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NWT LTER VIII
Year 1 Annual Report
2022-2023

Long-term Research on the Dynamics of High-Elevation Ecosystems:
A Framework for Understanding Rates of Ecological Response to Climate Change

***Note**: NSF project reports are not cumulative and should always be prepared for the specific project reporting period only.*

Accomplishments

What are the major goals of the project?

The overarching goals of NWT LTER VIII are to identify and describe the interacting abiotic and biotic mechanisms that cause differential rates of ecological response to climate change. We focus on how responses to rising air temperature – a climate driver at Niwot Ridge that has shown directional change over the past 70 years – are mediated by abiotic factors that have not changed in step with air temperature (e.g., precipitation, climatological growing season length, nutrients) and biotic processes (life history strategies, community dynamics, ecosystem legacies). Informed by 40+ years of long-term observations, experiments, and models, we leverage the natural heterogeneity of high-elevation mountain terrain to disentangle the abiotic and biotic drivers of ecological responses to climate change in alpine ecosystems. In NWT VIII, we are addressing the following five questions to understand variation in the rates at which different organisms, communities, and ecosystem processes are responding to rising temperatures at Niwot Ridge:

Q1: EXPOSURE – How do terrain-related differences in climate exposure and other physical factors affect ecological response? We hypothesize that ecological change will be fastest in microsites where organisms are most exposed to rising air temperatures and less limited by other abiotic factors.
Q2: ORGANISMAL STRATEGIES – Which species attributes predict how quickly individuals and populations respond to changing climate? We hypothesize differences in species thermal niches, resource use strategies, and potential for phenotypic plasticity will explain variation among species in the rates at which they respond to warming.
Q3: COMMUNITY TURNOVER – What community attributes predict how quickly species composition changes in response to changing climate? We hypothesize that the rate at which communities respond to climate change will vary with differences in the nature and specificity of biotic interactions across microsites.
Q4: ECOSYSTEM FUNCTION – How do soil attributes and community composition influence the rates at which ecosystem processes respond to a changing climate? We hypothesize legacies in soil attributes and plant and microbial communities will slow the rate at which ecosystem processes respond to rising air temperatures.
Q5: FORECASTING CHANGE – Does including climate exposure and rates of biological responses across a heterogeneous landscape improve model forecasts of ecological change? We hypothesize that including heterogeneous response rates across space and among ecological systems in ecosystem models improves our ability to forecast landscape-scale changes in function with climate change.

What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

Major Activities:

In Year 1 of NWT LTER VIII, we published 86 data sets and 12 peer-reviewed manuscripts, advanced 3 large collaborative experiments, established new research directions outlined in the NWT VIII proposal, participated in leadership and synthesis efforts across the LTER network, and contributed to 4 global synthesis projects and 1 within-NWT synthesis activity. These activities extend across or beyond the five specific questions of the NWT LTER VIII research framework.

Long-term data collection: We maintained all NWT long-term data sets and stayed current with publishing all available data sets from the previous sampling period according to our data management policies. A summary of our progress on our "Signature data sets" – those that are particularly critical for addressing the 5 questions in NWT VIII - are summarized in **Tables 1 and 2** in **Accomplishments – Supplemental File**; all published data sets are listed in **Products - Supplemental File**.

Integrative experiments: We recently completed two large "Growing Season Length Manipulation" (GSLM) experiments and initiated a new Turf Transplant experiment for NWT VIII.

- Alpine Tundra GSLM Experiment: In the summer of 2023, we conducted our final sampling efforts in the GSLM alpine tundra experiment, completing a 6-year investigation of the ecological impacts of early growing seasons in the alpine tundra. The experiment involved applying an "early snowmelt" treatment (through the application of black sand prior to snowmelt) to large (40 m x 10 m) plots at 5 different locations across Niwot Ridge. This year we repeated our annual collections of early vegetation production, plant species composition, arthropod diversity, snow depth, temperature, and moisture data in control and treatment plots at all 5 sites. We also conducted focused investigations of specific processes and interactions that we hypothesized to have changed with snowmelt manipulation that involved: (1) repeated sampling of soils during the spring snowmelt period to quantify changes in N cycling rates, C:N, and microbial biomass; weekly phenological measurements of 12 plant species to test if late-season species were more sensitive to early melt-out that earlier-season species; (3) root endophyte and bulk soil microbial community sampling to assess below-ground responses; (4) plant functional trait measurements to assess how interspecific trait variability might relate to vulnerability; and (5) soil collections to compare seed banks in experimental and control plots. We are currently processing all soil, root, trait, and seed samples.
- Alpine Lake GSLM Experiment: This experiment, which involved manipulating the ice-off data in aquatic mesocosms (700-gallon cattle tanks) over two consecutive years, was completed in 2021. Water chemistry samples have remained in storage due to laboratory facilities being closed during the COVID pandemic followed by the closure of primary lab facility at CU Boulder. We have recently established a new contract with an Oregon State University lab and are scheduled to ship these samples by the end of the calendar year. Zooplankton and periphyton data have been processed and will be analyzed with the water chemistry data when it becomes available.
- Turf Transplant Experiment: We initiated a pilot experiment to practice methods for excavating and transplanting 0.25 x 0.25 m turfs (plots of intact soil and vegetation) at Niwot Ridge. We successfully transplanted 20 plots between two locations, confirming the feasibility (and identifying challenges) with this experimental approach. We scouted over 20 sites in the summer of 2023 to identify suitable locations for the full experiment and installed temperature and soil moisture sensors at 22 locations. We finalized the specific locations for the experiment in fall 2023 and started planning pre-manipulation data collection strategies for summer 2024.

Information management: NWT 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 first reporting period, we added and/or updated 86 datasets (see **Products - Supplemental File**). NWT datasets were downloaded from EDI 7,548 times over the 11-month reporting period (excluding DataOne and robot records). This rate is twice that of our last reporting period, reflecting increased public access of NWT data. All IM procedures have been consistent with LTER network data access policy and generally follow guidance as laid out by DataOne's data management best practices hub.

<u>LTER Network Participation</u>: Three NWT investigators served in four different LTER Network leadership positions during Year-1 of NWT VIII. **Dr. Sarah Elmendorf** has served as the co-Chair of the LTER information management executive committee and a as member of an EDI/LTER unit working group that is working to enhance the QUDT vocabulary and applythis framework for semantic annotation of LTER datasets to enhance interoperability. **Dr. Marko Spasojevic** has been the NWT representative to the network-wide Diversity, Equity, Inclusion, and Justice (DEIJ) committee and served as the DEIJ representative to the network-wide Executive Committee. Ph.D. student **Joey Krieger-Lodge** served as co-chair of the LTER network-wide graduate student committee. **Dr. Nancy Emery, Dr. Will Wieder, Dr. Marko Spasojevic**, and **Joey Krieger-Lodge** all participated in the 2023 Science Council meeting at the Kellogg Biological Station.

<u>Synthesis</u>: NWT investigators have been involved in five LTER Network synthesis efforts this year. **Dr. Nancy Emery** co-leads the new LTER SPARC working group "Selection across scales—merging evolutionary biology and community ecology to understand trait shifts in response to environmental change," and **Dr. Katie Suding** and postdoc **Dr. Elisa Van Cleempet** participated in the "Ecosystem transitions: increased variability and regime shifts" working group. **Dr. Warren Sconiers** participated in the "Long-Term Ecological Research and Response of Primary Producers and Primary Consumers to Disturbances" working group. **Dr. Sarah Hart** and **Dr. Robert Andrus** were in involved in an informal synthesis of LTER tree data sets that emerged from the 2022 All-Scientist Meeting, and **Dr. Lauren Shoemaker** and **Dr. Alex Rose** participated in an informal collaboration across LTER sites on communicating biological concepts through artwork that led to a perspective article for *Plant Sciences Bulletin*.

Dr. Sarah Elmendorf and two NWT staff, **Dr. Jane Smith** and **Jen Morse**, are participating in three different global tundra synthesis projects. Elmendorf and Smith have installed root ingrowth bags into NWT ITEX plots for the "Warming effects on mycorrhizal abundance and diversity" synthesis group, and in the NWT Sensor Network Array for the "Belowground tundra phenology" project. Elmendorf and Morse are contributing temperature data from the NWT Sensor Network Array to the "Soil Temperature Project," which aims to develop a global dataset of microclimate variation. Elmendorf, Smith, and Morse have been actively involved in planning and organization meetings for each of these groups in addition to collecting and/or contributing NWT data. **Dr. Nancy Emery** collected data at NWT for a distributed experiment that is investigating latitudinal gradients in seed predation.

Dr. Chris Ray and **Ph.D. student Caitlin White** have led a within-site synthesis to characterize spatial clustering and temporal overlap of NWT temperature datasets from air, talus, soil, and lake monitoring, as well as snow cover and ice-off data, that would indicate periods of decoupling between air and subsurface temperatures. Over the past year they developed visualizations to illustrate relationships between aligned datasets and developed a repository of scripts for data harvesting, manipulation, and visualization.

Specific Objectives:

Over the first reporting period of NWT VIII, we have initiated the following **new activities to individually address each of the 5 questions** in our conceptual framework:

Q1: EXPOSURE – How do terrain-related differences in climate exposure and other physical factors affect ecological response? Several of our data sets include co-located, point-level microclimate measurements that allow us to characterize the extent to which individuals, populations, and/or communities are exposed to changing climate conditions. However, many of our long-term data sets do not have co-located sensors, and there large areas of the ridge where microclimate measurements have not been systematically collected. To address these gaps, we have initiated several efforts to improve our documentation of fine-scale spatial and temporal microclimate variation at Niwot Ridge and its relationships with topography, population dynamics, and community structure. First, we have added temperature and soil moisture sensors to ~1/3 of the long-term vegetation monitoring plots in the Saddle, with plans to add sensors to the remaining plots over the next 2 growing seasons. Second, we have installed sensors to monitor air, surface and subsurface temperature and humidity in 16 locations selected to represent the topographic heterogeneity of pika habitat (talus) at NWT. These data will support a model of subsurface temperature and humidity in taluses based on downscaled free-air data to estimate microclimatic conditions throughout the NWT landscape. Third, we installed TOMST soil moisture and temperature loggers in dry and moist meadow tundra habitat across the ridge to collect data that will inform the final design of the Turf Transplant Experiment. These additional sensors supplement our existing measurements and models of temperature and moisture across Niwot Ridge to increase our overall resolution of microclimate heterogeneity as needed to rigorously address Q1.

Q2: ORGANISMAL STRATEGIES – Which species attributes predict how quickly individuals and populations respond to changing climate? We have collected new data on plant, pika, and chickadee populations to begin documenting organismal responses to climate variation. In the alpine tundra, we have expanded a relatively new demographic study of a short-lived mountain herb, *Androsace septentrionalis*, to span 5 different locations that vary in slope, aspect, and elevation, which will allow us to characterize how demographic rates and life history traits vary with microclimate in this particularly tractable plant species. In pika, we deployed camera traps and acoustic recording units (ARUs) at four permanent stations along an elevational temperature gradient (from Cable Gate to D1) to monitor rates of change in the timing, frequency and nature of vocalizations, enabling us to document behavioral plasticity in response to temperature variation (e.g., increasing nocturnal or crepuscular surface activity in warmer locations). Finally, we collected temperature data alongside morphological measurements and blood sample collections from 10 chickadee nests to test for relationships between nest temperature, nest success, and bird physiology.

Q3: COMMUNITY TURNOVER – What community attributes predict how quickly species composition changes in response to changing climate? Many of the final data collection efforts in the alpine tundra GSLM experiment will address Q3 (see **Major Activities**), and the microclimate sensors that have been installed in locations where we are monitoring community and population dynamics (see Q1 activities above) will allow us to address this question with our existing and/or ongoing data sets in our terrestrial communities. This year we also completed several analyses that address this question (see **Accomplishments: Significant Results** and **Products**). New data collection efforts included a second year of sampling an experiment that is evaluating how biotic interactions influence the potential for range expansion into warmer microhabitats by transplanting individuals of one plant species (*Trollius albiflorous*) into the existing ITEX warming experiment (see **Accomplishments - Supplemental File, Table 2**). To increase our capacity to address Q3 in aquatic systems, we have analyzed samples of stream benthic macroinvertebrate communities and environmental variables at nine locations along elevational gradient within the North Boulder Creek watershed on Niwot Ridge where we have long-term hydrology and water chemistry data.

Q4: Ecosystem Function - How do soil attributes and community composition influence the rates at which ecosystem processes respond to a changing climate? In addition to collecting data in the Tundra GSLM experiment (see **Major Activities**) to address this question, we have been exploring the feasibility of using NEON hyperspectral flight data to scale up monitoring of taxonomic and functional turnover at Niwot Ridge. We have learned that we can leverage hyperspectral data to understand spatial variation in functional composition but have had little success relating interannual differences in spectral composition to functional turnover across time. We are continuing to investigate if these limitations are driven by technical parameters that could in theory be overcome (e.g., variability in the flight window that NEON uses) and/or more general limitations for using this approach in alpine tundra (e.g., temporal change in functional composition is too slow to be detected with hyperspectral data).

Q5: FORECASTING CHANGE – Does including climate exposure and rates of biological responses across a heterogeneous landscape improve model forecasts of ecological change? In Year 1 we completed two modeling studies that have highlighted the importance of incorporating fine-scale microclimate variation (Q1) and plant functional trait variation (Q2) in accurately forecasting ecosystem-scale responses to rising temperature. The main findings from these studies are summarized under **Significant Results.**

Significant Results:

While our full list of publications is provided in **Products**, here we **highlight some particularly important and exciting results that relate to the 5 key questions** we are addressing in NWT VIII:

Q1: EXPOSURE – How do terrain-related differences in climate exposure and other physical factors affect ecological response? As we increase our investigation of fine-scale spatial and temporal variation in climate across Niwot Ridge in NWT VIII, early results both confirm and challenge our intuition about microclimate heterogeneity in the alpine. Preliminary analyses of water temperature in ponds at NWT indicate that landscape position can lead to strong differences in pond temperature, even at similar elevations, confirming that slope and aspect have similar effects on water temperature as we have measured in terrestrial environments. Similarly, in alpine streams, water source (glacial, snowmelt, lake outlet, and mixed) heavily influences summer water temperature as well as other abiotic factors, confirming that both topography and water source mediate the temperature experienced by resident benthic macroinvertebrate communities (**Accomplishments - Supplemental File, Fig. 1**). On the other hand, we were somewhat surprised by recent results published by Monk and Ray (2022): leveraging the only known historical record of subsurface temperature in talus (the rocky habitat occupied by pika), we learned that subsurface temperature at two depths below the surface have increased more than free-air temperature over the past 50 years. This pattern suggests that organisms that rely on subterranean refugia, like pika and possibly certain seeds, invertebrates, and microbes that are restricted to subsurface habitat in talus, may be experiencing faster rates of temperature change than they would at the surface.

Q2: ORGANISMAL STRATEGIES – Which species attributes predict how quickly individuals and populations respond to changing climate? In a recently published manuscript (Oldfather et al., 2023), we combined co-located measurements of temperature, snow, and alpine plant community composition in the Saddle plots to investigate vegetation community trajectories over the last 30 years with warming temperature. Our analysis revealed striking patterns of directional change in the alpine vegetation at Niwot Ridge since 1990 with locations at both extremes of the snow gradients showing an approximately 25% shift in composition (**Accomplishments - Supplemental File, Fig. 2**). Importantly, community trajectories over the last thirty years changed across a snow depth gradient. Specifically, exposed parts of the landscape that experience little snow accumulation are shifting toward stress-tolerant, cold- and drought-adapted communities, while snowier areas shifted toward more warm-adapted communities.

Q3: COMMUNITY TURNOVER – What community attributes predict how quickly species composition changes in response to changing climate? A team of 11 NWT investigators, led by postdoctoral researcher **Dr. Jonathan Henn**, have conducted a large synthesis project examining alpine plant community responses to multiple global change drivers (**Accomplishments - Supplemental File, Fig. 3)**. This project quantified the change in abundance and probability of establishment through time for 43 species in experiments that included temperature, nitrogen, and snowpack manipulations and tested if plant responses could be predicted based on functional traits. Overall, plants with more acquisitive strategies (higher specific leaf area, taller, higher leaf nitrogen, lower leaf dry matter content) generally responded positively to global change treatments. However, trait changes at the community scale (i.e., community-weighted means) were not always aligned with those that predicted the responses of individual species, highlighting the importance of dominant species driving community-level responses. Together, this synthesis illustrates that functional traits differentially influence long-term changes in various facets of plant community composition and ecosystem function under various global changes.

Early results from the Alpine Tundra GSLM experiment suggest that extended growing seasons may have important implications for trophic interactions in alpine plant and insect communities. For example, snowmelt timing influences the assembly and structure of plant-pollinator networks, yielding different temporal dynamics that may lead to decreased within-season network stability in a changing climate. Growing season length also shapes the relationship between arthropod predators and insect herbivores: in 2023, we observed a significant negative relationship between predator diversity and herbivore abundance in treatment plots, but no relationship in control plots. While these results are preliminary, they provide early evidence that snowmelt timing and growing season length have important implications for species interactions and community structure, underscoring the importance of further investigating these processes in NWT VIII.

Q4: Ecosystem Function - How do soil attributes and community composition influence the rates at which ecosystem processes respond to a changing climate? Ph.D. student Jared Huxley has published an analysis investigating how the relationship between biodiversity and ecosystem function will shift with changing climate in the alpine plant community (Huxley et al., 2023). Using 13 years of data on plant species composition, functional traits, local abiotic variables, and ANPP (the measure of ecosystem function) from the NWT LTER Saddle Plots, as well as climate data from the Saddle climate station, this project found that the functional traits that drive ecosystem function (ANPP), as well as the underlying ecological mechanisms (e.g., mass-ratio and niche complementarity effects), change over time and with year-to-year variation in snow precipitation (**Accomplishments - Supplemental File, Fig. 4**). This work has informed (and further motivated) the manipulative approach we have planned to further investigate ecosystem responses to rising temperature in the Turf Transplant experiment.

Q5: FORECASTING CHANGE – Does including climate exposure and rates of biological responses across a heterogeneous landscape improve model forecasts of ecological change? In Year 1 we completed two modeling studies that have highlighted the importance of incorporating fine-scale microclimate variation (Q1) and plant functional trait variation (Q2) in accurately forecasting ecosystem-scale responses to rising temperature. In the first study (Jay et al. 2023), we ran ecosystem-scale Community Land Model (CLM) simulations with a novel hillslope hydrology configuration to represent topographically heterogeneous alpine tundra vegetation across a moisture gradient at Niwot Ridge (see **Accomplishments – Supplemental File, Fig. 5**). The results of this analysis emphasized substantial terrain-related differences in rates of climate exposure, highlighting the potential vulnerabilities of alpine vegetation in dry meadows and south-facing aspects. The second model builds on the hillslope hydrology configuration of CLM to explore the role of plant traits in mediating ecosystem response to projected climate change. Preliminary simulations suggest that potential shifts in plant traits (moving to more resource acquisitive or resource conservative strategies) explain a greater fraction of variance in ecosystem carbon and water cycle response to projected climate change than different climate change scenarios. That is, the biological uncertainty in shifting plant traits is greater than the scenario uncertainty in the physical climate system in determining ecosystem response to projected climate change. Thus, forecasting landscape-scale changes in function with climate change (Q5) will require refined understanding of rates of change organism strategies, community turnover, and ecosystem function, that we are evaluating in Q1-Q4.

Key outcomes or other achievements:

The NWT LTER continues to provide highly effective platform for a variety of research, education, and outreach activities that extend beyond the scope of the NWT LTER VIII award. Three recent NSF grants to

NWT investigators highlight how NWT data, infrastructure, and expertise is being leveraged to expand the scope of activities under way at the site:

1. **Dr. Isabella Olesky** (CU Boulder) has received an NSF Macrosystems award (Award #2306895) to study the implications of shorter winters for alpine lake phytoplankton phenology and function, which will use the long-term chemistry data, buoy data, and ice cover records from the NWT LTER for Green Lake 4.
2. **Dr. Lauren Shoemaker** (University of Wyoming) has an NSF EPSCoR grant (Award #2033292) to evaluate synchrony and stability of communities under global change factors using long-term vegetation data records from Niwot Ridge, in collaboration with Dr. Katie Suding and Dr. Nancy Emery.
3. **Dr. Nancy Emery, Dr. Scott Taylor,** and **Dr. Julian Resasco** (CU Boulder) are co-PI's on an award from the Division of Graduate Education at NSF (Award #2105635) to design and test the efficacy a first-year graduate student program designed to promote the inclusion of students from diverse identities as well as provide discipline-specific training in field methods. The NWT LTER is providing training in field methods for this project.

In addition to these NSF research awards to faculty, four NWT graduate student researchers received funding from NSF Graduate Research Fellowships, and a fifth student received a Ford Foundation Fellowship through the National Academy of Sciences. NWT faculty and students have also received funding from a variety of local institutions, agencies, and organizations to support research, education, and outreach activities that benefit from NWT LTER data, infrastructure, and personnel.

What opportunities for training and professional development has the project provided?

Undergraduate Researchers: NWT provided research opportunities to 12 undergraduate students this year. Two of these positions were REU's. In the summer of 2023, we again partnered with the Research Experience for Community College Students (RECCS) program through the Cooperative Institute for Research in Environmental Sciences (CIRES) to host our 2 REU students from regional community colleges. One of these students chose not to complete the program due to a change in circumstances early in the summer, but the other completed a project that involved measuring microplastic quantities in water samples they collected from alpine lakes and streams at NWT. Two undergraduate students, **Miles Moore** and **Trevor Randall**, completed undergraduate Honor's theses using NWT data, receiving summa cum laude and magna cum laude academic distinctions, respectively.

NWT researchers participated in several events that engaged groups of undergraduate students in field biology and alpine science. **Dr. Warren Sconiers** organized field activities for a group of RECCS students to practice the scientific method at Niwot Ridge. Sconiers guided the students through the process of developing research questions and testing hypotheses, instructed them in field methods and appropriate statistical tests, and provided the equipment and logistical support they needed to collect their data. The NWT LTER provided the students with Wilderness First Aid Training certification and additional logistical support that allowed them to safely complete their work. Sconiers also organized a field trip for 80 first-year biology students in his Introductory General Biology course to visit the CU Mountain Research station and interact with NWT researchers to learn about the LTER and research opportunities on Niwot Ridge.

Graduate Students: A total of 18 graduate students (16 PhD, 2 MS; one MS student is listed as "Other Professional" in the Personnel table) from 5 institutions received research training in field, laboratory, and/or computational methods, stipends, funding for research and/or presenting their work at scientific conferences, and/or logistical support through the NWT LTER last year. Students also received support from IM Dr. Sarah Elmendorf to learn best practices in data management as well as individual mentoring in data publication and analysis. Students presented NWT results at the AGU, ESA, and American Society of Mammologists annual meetings, as well as other more specialized and/or local conferences. Three Ph.D. theses and one M.S. theses involving NWT research were successfully defended and published by graduate students this year, and three additional NWT publications had graduate students as first author (see **Products**).

Graduate students that are financially supported through the NWT LTER complete formal training in science communication and participate in outreach and education activities. CU Boulder students complete a semester-long practicum on science communication and "engaged scholarship" taught by Outreach Coordinator **Dr. Alex Rose** every fall semester. Four NWT LTER graduate students participated in the course this year and developed demonstrations about their NWT research that they presented to public audiences on campus, at a "Meet a Scientist" event at the Lafayette Public Library, and opportunistically at other venues.

The NWT LTER continued its collaboration with the **NSF-Funded Fired Up** program for the second year in 2023. This program a research project in Innovative Graduate Education that is testing if immersive early field experiences for incoming graduate students promotes a sense of belonging, supports inclusivity, and fosters student confidence in pursuing large-scale research questions in the environmental sciences. NWT investigators **Dr. Nancy Emery, Dr. Scott Taylor, and Dr. Julian Resasco** are co-PI's on this project (see **Key Outcomes and Other Achievements**), and over 15 NWT faculty, staff, and graduate students participated in in 2023 to teach field methods, ensure student safety in the alpine, and share information and opportunities with the NWT LTER.

Postdoctoral Researchers: The NWT LTER supported the research training and professional development of two postdoctoral researchers over Year 1 of NWT VIII. **Dr. Jonathan Henn** led a data synthesis project evaluating the role of functional trait variation in driving community responses to global change drivers using several long-term NWT data sets. He has also conducted field sampling in NWT experiments related to his interests in functional traits and swing-season (early, late) effects on plant communities. **Dr. Katya Jay** has been working on simulations with the Community Land Model (CLM) using the hillslope hydrology model that is parameterized, validated, and evaluated with data collected across Niwot Ridge, and was the lead author on a publication addressing Q5 this year. A third postdoc that was funded through a different source, **Dr. Courtenay Ray**, conducted some preliminary analyses of synchrony patterns in the ITEX experiment.

NWT continued ongoing collaborations with two researchers who have postdoctoral positions at other institutions. Former NWT postdoc **Dr. Elisa Van Cleempet** has used remote sensing to estimate microclimate variation across Niwot Ridge and evaluate the potential of using hyperspectral data to identify taxonomically and functionally distinct plant communities at the site, and was a lead author of an LTER synthesis project this year. Former NWT graduate student **Dr. Robert Andrus** continues to be a key collaborator in our analysis of subalpine forest responses to climate change and has participated in an informal synthesis group among LTER sites (see **Accomplishments: Major Activities – Synthesis**).

Technicians and Other Temporary Staff: In the first year of NWT VIII, 6 different temporary technician positions supported data collection on subalpine tree growth and seed production, stream benthic macroinvertebrate diversity and abundance, pika habitat occupancy, and alpine plant community composition, productivity, phenology, and functional traits variation. The majority of these positions provide students with experience in field, laboratory, and computational methods, and opportunities to work with a range of investigators in the NWT LTER. At least one of these students is pursuing an undergraduate Honor's thesis that will use NWT data, and another has applied to graduate school to pursue their interests in forest science and management.

Permanent staff: The NWT LTER employed 7 staff in permanent positions over the past year: D**r. Sarah Elmendorf** (Information Manager, 80% time), **Dr. Alex Rose** (Outreach and Education Coordinator, 25% time), **Dr. Jane Smith** (lead vegetation technician; 100% time during field season, 60% in off-season), **Jen Morse** (~25% time; also an MS student), **Sammy Yevak** (lead aquatic technician, 100% time), **Thomas Austin Willbern** (assistant general technician, 100% time), and **Alexa Esler** (project coordinator, 50% time). Elmendorf is also an active researcher with NWT and regularly participates in global tundra synthesis efforts and publishes using NWT data sets. Morse, Yevak, and Willbern also receive professional development training through the Institute of Arctic & Alpine Research (INSTAAR), the administering unit at CU Boulder, and NWT covers their training expenses in wilderness safety and rescue (e.g., NOLS Wilderness First Aid certification, NOLS Wilderness First Responder, Avalanche safety training). Our permanent staff receive training in data management and curation, both directly from Elmendorf as well as online training courses and curriculum offered through CU Boulder, and are encouraged to participate in projects that align with their personal interests and long-term career goals. Our permanent staff are regularly included on publications and are first authors on data sets they have collected, curated, and published.

How have the results been disseminated to communities of interest?

In the final year of NWT VII and first year of NWT VIII, NWT researchers produced 12 publications in peer-reviewed journals, 4 manuscripts that have been accepted and are awaiting publication, and 6 theses (3 PhD, 1 MS, and 2 undergraduate Honor's theses) (see **Products**). NWT investigators have presented our work at invited academic seminars, international conferences (ESA, AGU), and local outreach events (e.g., Museum of Boulder, Colorado Native Plant Society). We have also shared our results with a variety of stakeholders (Forest Health Council Legislative Committee, Rocky Mountain National Park, Lassen Volcanic Park, Estes Valley Watershed Coalition, City of Boulder Watershed, and the Natural Areas Association) through invited talks and individual meetings (see **Impacts**). **Dr. Will Wieder** and postdoc **Dr. Katya Jay** have led two workshops on using the Community Land Model, both of which highlighted their work using NWT data.

What do you plan to do during the next reporting period to accomplish the goals?

Long-term data collection: We plan to continue our ongoing data collection efforts as planned, publish 2023 data sets on time, and continue to extend sampling to align with the plans we outlined in the NWT VIII proposal (see "Planned for Year 2" column in **Accomplishments - Supplemental File, Tables 1 & 2).**

Integrative experiments: Year 2 of NWT VIII will focus on analyzing and synthesizing the results of the Alpine Tundra and Alpine Lake GSLM experiments, which we expect to include writing several manuscripts that will be submitted for publication. As the GSLM experiments wrap up, our primary experimental focus will shift to getting the Turf Transplant Experiment under way. During the 2024 growing season, we will establish all plots and collect "pre-experiment" data on all possible variables (plant community composition, individual abundances and traits of focal plant taxa, pollinator observations and traits, soil microbial community diversity and biogeochemistry). In the fall of 2024, a large team will work together to excavate and transplant turfs within a 1- or 2-week time period, after plant senescence but prior to snowfall. This will be a massive undertaking that will require a great deal of personnel support and careful logistical coordination across the NWT LTER team and will therefore be a primary focus of our planning and field activities over the next year.

Specific projects for Q1-Q5: We have outlined a number of specific goals that address each of our questions as planned in our NWT VIII proposal. Some of the specific activities we have prioritized for Year 2 are the following:

- **Q1:** Analyze subalpine tree, pika, chickadee, and aquatic data sets to quantify topographic variation in climate exposure, as well as more general analyses of microclimate variation across the ridge as data becomes available from newly installed sensors.
- **Q2:** New data collection efforts on functional trait, phenotypic plasticity, and life history variation in plant and pika populations, to understand how these attributes shape demographic and distribution responses to warming.
- **Q3:** Initiate a new investigation of plant interactions with root endophytes and their role in driving rates of species turnover with warming, and extending our study of the role of microclimate and biotic interactions in determining the rates of shrub expansion across Niwot Ridge.
- Q4: Continue analyses of variation in ANPP and its relationship with soil temperature, water, and species composition.
- Q5: Build expertise in calibrating parameters in the FATES ecosystem demography model to start examining potential rates of plant community change and shifts in community weighted mean traits.

Information management: NWT IM goals for the next year include: (1) continued publication of datasets collected during the 2023 field season, (2) developing reproducible code for ongoing publication of infilled, quality-controlled, long-term meteorological dataset s; and (3) the development and delivery of a short-course on data quality control and visualization targeting graduate students and staff scientists. We are also collaborating with other LTER Information Managers to harmonize unit definitions across the LTER network, with the ultimate goal of including these annotations on all units for published Niwot datasets going forward. Finally, the information manager will continue to provide mentorship and statistical advice on student and postdoc-led projects.

Broader Impacts: We will maintain our emphasis on training graduate students in science communication and engaging in the outreach and education activities that have become the foundation of our broader impacts (see **Impacts: K-12 Outreach & Education**). Inspired by our success engaging middle school students with the *Tempestry Project*, we are excited to expand the work we're doing in schools and during out-of-school time with data-driven art as a method for improving data literacy in K-12 students more broadly. This work has been extremely well-received by a variety of audiences and has allowed us to expand our community and school partnerships, as well as initiate collaborations with regional artists and art teachers. Our Diversity, Equity, and Inclusion committee will continue to focus on creating safe and inclusive environments, both in the field and in other science environments, for members with diverse backgrounds and identities. In Year 2, we will be conducting our NWT-wide community climate survey (performed every 3 years); the data from this survey will be used to assess the effectiveness of our existing practices and identify areas that we need to prioritize for improvement over the next 3 years. Finally, we will be further developing the NWT-led Consortium of local stakeholders by continuing to co-develop collaborative projects and creating an online "Data Dashboard" that provides visualizations of specific NWT data sets that practitioners have requested.

NOTE: You may upload PDF files with images, tables, charts, or other graphics in support of the Accomplishments section. You may upload up to 4 PDF files with a maximum file size of 5 MB each.

Products

Journals:

Brigham, Laurel M. and Bueno de Mesquita, Clifton P. and Spasojevic, Marko J. and Farrer, Emily C. and Porazinska, Dorota L. and Smith, Jane G. and Schmidt, Steven K. and Suding, Katharine N. (2023). Drivers of bacterial and fungal root endophyte communities: understanding the relative influence of host plant, environment, and space. 99. (5). *FEMS Microbiology Ecology, 99.* Published. 1574-6941. doi: https://doi.org/10.1093/femsec/fiad034

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Gill, A. L. and Grinder, R. M. and See, C. R. and Chapin, F. S. and DeLancey, L. C. and Fisk, M. C. and Groffman, P. M. and Harms, T. and Hobbie, S. E. and Knoepp, J. D. and Knops, J. M. and Mack, M. and Reich, P. B. and Keiser, A. D. (2023). Soil carbon availability decouples net nitrogen mineralization and net nitrification across United States Long Term Ecological Research sites. 162. (1). *Biogeochemistry, 162.* Published. 0168-2563. doi: https://doi.org/10.1007/s10533-022-01011-w

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Jay, K. R. and Wieder, W. R. and Swenson, S. C. and Knowles, J. F. and Elmendorf, S. C. and Holland-Moritz, H. and Suding, K. N. (2023). Topographic Heterogeneity and Aspect Moderate Exposure to Climate Change Across an Alpine Tundra Hillslope. 128. (11). *Journal of Geophysical Research: Biogeosciences, 128.* Published. 2169-8953. doi: https://doi.org/10.1029/2023JG007664

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Oldfather, Meagan F. and Elmendorf, Sarah C. and Van Cleemput, Elisa and Henn, Jonathan J. and Huxley, Jared D. and White, Caitlin T. and Humphries, Hope C. and Spasojevic, Marko J. and Suding, Katharine N. and Emery, Nancy C. (2023). Divergent community trajectories with climate change across a fine-scale gradient in snow depth. *Journal of Ecology.* Published. 0022-0477. doi: https://doi.org/10.1111/1365-2745.14223

Shepherd, Rachel M. and Brigham, Laurel M. and de Mesquita, Clifton P. and Gattoni, Kaitlin M. and Gendron, Eli M. and Hahn, Philip G. and Schmidt, Steven K. and Smith, Jane G. and Suding, Katharine N. and Porazinska, Dorota L. (2023). Trophic group specific responses of alpine nematode communities to 18 years of N addition and codominant plant removal. *Plant and Soil.* Published. 1573-5036. doi: https://doi.org/10.1007/s11104-023-06281-3

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Varner, Johanna and Carnes-Douglas, Zoe J. and Monk, Emily and Benedict, Lauren M. and Whipple, Ashley and Dearing, M. Denise and Bhattacharyya, Sabuj and Griswold, Loren and Ray, Chris (2023). Sampling a pika's pantry: Temporal shifts in nutritional quality and winter preservation of American pika food caches. 14. (5). *Ecosphere, 14.* Published. 2150-8925. doi: https://doi.org/10.1002/ecs2.4494

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Books:

Book Chapters:

Thesis/Dissertations:

Reed, Will J. (2022). *Alpine Plant Community Composition and Species Distributions at Niwot Ridge: The Roles of Variability and Predictability. University of Colorado, Boulder*

Theodosopoulos, Angela Nicole (2022). *Haemosporidian Infection Dynamics and Immune Gene Variation in a Population of Hybridizing Chickadees*. University of Colorado, Boulder.

Trevor Randall (2023). *Arthropod Predator Diversity in the Alpine Tundra in Response to Artificially Extended Summers*. University of Colorado, Boulder.

Anderson-Huxley, Jared D. (2023). *The Causes and Consequences of Biodiversity Change in the Alpine Tundra of Western North America*. University of California, Riverside.

Conference Papers and Presentations:

Other Publications:

Technologies or Techniques:

Patents:

Inventions:

Licenses:

Websites:

Other Products:

NOTE: You may upload PDF files with images, tables, charts, or other graphics in support of the Products section. You may upload up to 4 PDF files with a maximum file size of 5 MB each.

Participants

What individuals have worked on the project?

(Uploaded as separate table)

What other organizations have been involved as partners?

Type	Name	Location	Contribution
Other – Federally Funded Research Institute (NSF)	National Center for Atmospheric Research CLM Group	Boulder, CO	In-kind support Collaborative research
Other – Federal Government (USGS)	North Central Climate Adaptation Science Center	Boulder, CO	Collaborative research Personnel exchanges
Academic Institution	CU Boulder Mountain Research Station (MRS)	Nederland, CO	In-kind support Facilities Collaborative research Personnel exchanges
Other – Federally Funded Instrumentation Network (NSF)	National Ecological Observatory Network	Boulder, CO	In-kind support
Other – Federally Supported Research Network (DOE)	Ameriflux Network	Lawrence Berkeley National Lab, Berkeley, CA	In-kind support
Other – Federal Government (National Park Service)	Rocky Mountain National Park	Estes Park, CO	Collaborative research
Other Nonprofits	Denver Botanic Garden	Denver, CO	Collaborative research
Academic Institution	Colorado Forest Restoration Institute	Fort Collins, CO	Collaborative research
Local government	City of Boulder Watershed	Boulder, CO	Collaborative research
Other nonprofits	Colorado Pika Project	CO	Collaborative research
Other – Cooperative Network	National Atmospheric Deposition Program	Madison, WI	Facilities Personnel exchanges
Other – Federal Government	NOAA Earth Systems Research Laboratories	Boulder, CO	In-kind support
Other – Federal Government	National Water and Climate Center SNOTEL Program	Portland, OR	In-kind support
Academic Institution	CU Science Discovery	Boulder, CO	In-kind support Facilities Personnel exchanges

Type	Name	Location	Contribution
Other nonprofits	Cal-Wood Academy	Jamestown, CO	Facilities Personnel exchanges
Academic Institution	Cooperative Institute for Research in Environmental Sciences (CIRES), CU Boulder	Boulder, CO	Facilities Personnel exchanges
Other nonprofits	Wild Bear Ecology Center	Nederland, CO	Personnel exchanges
Other nonprofits	Winter Wildlands Alliance	Boise, ID	Personnel exchanges
Academic Institution	CU Boulder Earth Lab	Boulder, CO	
Local Government	Boulder Valley School District	Boulder County, CO	Personnel exchanges
Other – Federal Government (USDA)	US Forest Service	Washington, DC (headquarters)	Other
Other – Federally Supported Center (NSF)	National Center for Ecological Analysis and Synthesis	Santa Barbara, CA	Financial support Collaborative research
Other – Federally Funded Critical Zone Observatory Network (NSF)	Dynamic Water Critical Zone Thematic Cluster	Arlinton, MA	Collaborative research
Other – Federally Funded Synthesis Center (NSF)	Environmental Data Science Innovation & Inclusion Lab (ESIIL)	Boulder, CO	In-kind support Collaborative research Personnel exchanges

Have other collaborators or contacts been involved? Yes

Dr. Isabella Olesky joined CU Boulder as an Assistant Professor in the fall of 2023 and has already become an important member of the NWT LTER community. Dr. Olesky's research expertise in alpine limnology and biogeochemistry fills an important gap in the NWT research program, and her interests in studying the interacting effects of nitrogen deposition, warming, and ice phenology on mountain lake ecosystem ecology is well-aligned with the goals of NWT VIII. Dr. Olesky has not been at CU Boulder long enough to contribute a full person-month with NWT and is therefore not listed in the "Participants" table above, she has already contributed to key decisions about our water chemistry sample analysis and received an NSF macrosystems grant that will leverage NWT alpine lake data and other NWT resources.

Impacts

You have the option of selecting “nothing to report” in this section.

What is the impact on the development of the principal discipline(s) of the project?

While we have only completed one year of NWT VIII, our work is already having impact in the disciplines that collectively study the environmental impacts of global change, particularly in alpine systems. Our conceptual framework is unique it that it explicitly evaluates the ecological mechanisms that determine the speed with which biota and ecosystem processes respond to climate change. Our focus on rising air temperature - a key climate driver that risen particularly fast at NWT and in mountain systems worldwide – singles out this key variable as having particularly critical consequences for organisms adapted to high-elevation, cold-dominated environments. At the same time, we are leveraging topographic complexity of NWT terrain to understand how the effects of rising temperature are mediated by spatial heterogeneity in exposure and interacts with abiotic factors and biotic processes to facilitate or constrain the rate at which individuals, populations, communities, and ecosystem processes respond. The published results and preliminary analyses that we have generated over this first reporting period representing important advances in our understanding of the complexities of temperature change in alpine systems, as well as the incredible importance of understanding those complexities to accurately forecast the future of these ecosystems.

What is the impact on other disciplines?

NWT’s contributions to the Fired UP Innovative Graduate Education research project (see **Accomplishments – Opportunities for Training and Professional Development** and **Key Outcomes or Other Achievements**) are leading to impacts in the discipline of Biology Education. Over the past year, results from the project have been presented at the 2023 Gordon Research Conference on Undergraduate Biology Education Research and the 2023 Society for the Advancement of Biology Education Research Conference, and an abstract has been accepted for the 2024 National Association for Research in Science Teaching Conference. The researchers have been invited to submit a paper on this project for a special issue in DBE-Life Sciences Education on equity, inclusion, access, and justice in biology education.

What is the impact on the development of human resources?

The Niwot Ridge LTER formed the **NWT Diversity, Equity, and Inclusion** (DEI) committee in summer 2020. During the first year of NWT VIII the committee has continued its efforts to make Niwot a more welcoming and equitable space. First, we have updated our DEI plan with a focus on four broad areas: 1) Ensure that the Niwot LTER is a welcoming and inclusive environment; 2) Recruit, retain, and support a more diverse team of students, investigators, staff, and collaborators; 3) Collaborate meaningfully with local communities; 4) Frequent assessment and evaluation of efforts. To achieve these goals, the DEI committee hosted a Field Futures workshop for the Niwot Community in spring 2023, which provided structured, interactive activities to teach participants how to prevent, intervene, and report harassment and assault. We have also continued to stock and maintain a gear closet to reduce financial barriers to participants having access to high-quality field gear and clothing, which we consider a necessity for safe work in the alpine. While we typically conduct an annual End-of-Season survey to check in on the social climate at Niwot during the previous summer field season, this year we are instead conduct in our second (more detailed) Social Climate Survey, which we plan to implement every 3 years. This was first conducted in 2020 and will inform our DEI efforts over the next few years. Lastly, Niwot personnel are active in the Network Wide DEIJ committee where we share our previous efforts (i.e., code of conduct, end of season surveys).

Please see the **Accomplishments** section of this report for a summary of the training and professional development opportunities that the NWT LTER has provided to participants over the past reporting period.

What is the impact on teaching and educational experiences (K-12 Outreach & Education)?

The NWT LTER's contributions to outreach and education during the first year of NWT VIII has involved continuing well-established programs and extending ourselves in new directions. This year we continued our model of 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 effectively 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. Dr. Alex Rose is our lead outreach and education coordinator; she teaches the "Science Communication and Outreach" to new NWT graduate students each fall and coordinates the majority of NWT K-12 programming.

Snow School - Bringing Alpine Science and Winter Recreation to Denver Area Youth (Elementary School Program): 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 our team of outreach staff and LTER scientists and graduate students taught snow science to children on snow shoes – many of whom had never put on snow shoes before. We reached 416 children in 1st through 6th grade, 32% of whom receive free or reduced lunch. This year's Snow School programming included Rose visiting each classroom after the field trip to lead activities that involved graphing Snow-Water Equivalency (SWE) and snowpack data collected by students in the field and curriculum around winter adaptations in alpine animals.

Tempestry Project - Using Fiber Arts to Visualize Long-Term Climate Trends (Middle School Program): In Year-1 of NWT VIII we developed a new initiative at Casey Middle School in Boulder, Colorado focused on using art as an entry point for data interpretation. Specifically, Rose worked with 24 8th graders in a college and career preparation program (AVID) to explore trends in maximum temperature (T_{max}) over the past 100 years in Boulder, Colorado and in Mazatlán, Sinaloa, Mexico. In partnership with the AVID teacher, the 8th grade science teacher, and the school art teacher, Rose helped students create 4 embroidered "Tempestries" representing maximum daily temperature in Mazatlán and Boulder in 1923 and 2021. Students presented their fiber arts to an appreciative audience of diplomats, climate scientists, and public audience members from around the world at the *Right Here, Right Now* United Nations Global Climate Summit on the CU Boulder campus last December. These students were the sole youth representatives at the conference.

Mountain Research Experience – Place-Based Ecology and Conservation for Under-Served Communities (High School Program): In the summer of 2023, we were again able to conduct the Mountain Research Experience for high school students by collaborating with Cal-Wood Environmental Education center. This collaboration reached 14 participants from low income, Latinx, and first-generation college student backgrounds from the Denver-Metro area. The Center was the site of the 2020 Cal-Wood fire, and we spent the week discussing sub-alpine forest ecology, forest management, and wildfire impacts and restoration.

Researchers from Niwot LTER and The Nature Conservancy helped teach the students about forest management, fire ecology and restoration.

General K-12 and Community Outreach Events (all ages): Using graduate students trained in science communication, we staffed several large (1000+ attendees) public outreach events including a large Earth Day celebration in Lafayette, Colorado. We brought demonstrations of our science developed by graduate students in the science communication and outreach course, as well as a co-created community data art installation about climate change in Colorado. NWT scientists also engage on a regular basis with individual K-12 classrooms upon request. For example, this past year Dr. Eve Hinckley and Ph.D. student Zachary Schwartz taught a lesson on alpine soils and soil analysis methods to a 4th grade class at Creekside Elementary (a public school in Boulder, CO), and Dr. Chris Ray hosts 7 children and 2 educators at Niwot Ridge each year to collect data on microsite temperature and pika habitat use on "Wild Bear Pika Day."

What is the impact on physical resources that form infrastructure?

Nothing to report.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

Nothing to report.

What is the impact on society beyond science and technology?

Niwot investigators have engaged in several opportunities to connect the results generated by the NWT LTER to relevant audiences in land management and conservation. We have pursued these relationships deliberately by establishing a new Consortium that we have organized with 5 local stakeholders, and opportunistically as we have been asked to present our work to specific groups. Some of our most notable interactions with non-profit organizations, government agencies, and other land management practitioners over the past year are the following:

NWT-Led Consortium: Members of the consortium (Denver Botanical Gardens, Colorado Forestry Restoration Institute, Rocky Mountain National Park, City of Boulder Water, and the USGS North Central Climate Adaptation Science Center) met in January 2023 at the Denver Botanical Gardens York Street Campus. Plans were put in motion for joint student internship projects, a data dashboard, and ways to communicate science findings to our various stakeholders. In spring 2023, one graduate student received summer GRA support to collaborate with the Denver Botanic Gardens on a studying evaluating how rising temperatures influences seed dormancy and germination rates, seedling survival, and early seedling growth in a subset of alpine plant species on Niwot Ridge.

Boulder Ecosystem Resilience: **Dr. William Wieder** served on the advisory board for the Boulder Ecosystem Resilience Project and is working to connect city and county land managers with students in the aeronautics team at the Saint Vrain Valley School District Innovation Center.

Boulder County Nature Association: **Dr. Eve Hinckley** presented results from the NWT LTER at the annual ecosymposium for this organization in the fall of 2023. Her presentation focused on patterns of pH and sulfur in NWT water quality records and discussed how government regulations and warming temperature are interacting to influence the physical, chemical, and ecological processes operating within the Boulder County watershed.

Colorado's Forest Health Council: **Dr. Sarah Hart** presented results from NWT LTER long-term subalpine forest plots to the Legislative Committee of the Colorado's Forest Health Council that addressed the effects of vapor pressure deficit on forest demography.

Natural Areas Association: **Dr. Nancy Emery** gave a presentation and participated in a panel discussion at the 2023 Natural Areas Conference. The topic of the conference, which is organized by the Natural Areas Association, was "The Power of Long Term Ecological Research (LTER): Informing Natural Areas Management." Along with other LTER scientists from Konza Prairie, Kellogg Biological Station, and Cedar Creek, Emery presented work from the NWT LTER in the "Prairies & Grasslands" breakout session to an online audience of >90 land management and conservation practitioners.

Changes / Problems

Changes in approach and reason for change:

Based on a new temperature data and field observations from the 2023 field season, we have decided to modify the design of the Turf Transplant Experiment from the plan that had been outlined in our NWT VIII proposal. Our original design had proposed transplanting turfs along fine-scale gradients in soil moisture between three pairs of “cold” and “hot” sites. Through a series of group field excursions, small group meetings, and iterative data analysis sessions, we recognized that (1) we were limited in the number of paired sites that provided the temperature differential between “hot” and “cold” that we are targeting (~2-3°C difference in mean summer soil temperature) without introducing other confounding variables (e.g., shading from subalpine trees), and (2) it was going to be very difficult to find similar soil moisture gradients within sites. Given these constraints, we have modified the design to consist of two pairs of hot-cold sites: one pair of dry meadow communities, and a pair of moist meadow communities. We will transplant turfs between the hot and cold sites within each community type (i.e., dry meadow will only be transplanted into dry meadow).

Actual or Anticipated problems or delays and actions or plans to resolve them:

The only significant change to our originally proposed timeline is a one-year delay in the installation of the turf transplant experiment. Given the enormous amount of work that will be involved in setting up this experiment, we decided to use this first year to evaluate candidate sites more carefully. This summer we focused on scouting multiple potential locations, collecting preliminary temperature and moisture data at candidate sites, and considering different options for plot placement and replication at different locations. Based on this information, we have now selected the sites for the turf transplant experiment, and we will set up plots early in the 2024 growing season and collect “pre-transplant” data prior to moving turfs in fall 2024.

A second, minor change to our timeline was the delay of pollinator surveys this year (see **Accomplishments – Supplemental File, Table 2**). The investigator leading this effort experienced a significant injury early in the season that made it impossible to coordinate this work. The pollinator surveys are a new campaign for NWT VIII, and so we do not consider it particularly problematic that it did not occur this year, and we expect it to resume as planned next year.

We had previously developed a backlog of water chemistry samples due to laboratory shutdown during the COVID-19 pandemic followed by our primary lab facility permanently closing. This year we have identified a new laboratory for these analyses and expect to process all backlogged samples over the next year (see **Accomplishments – Supplemental File, Table 1**).

Changes that have a significant impact on expenditures:

Nothing to report.

Significant changes in use or care of human subjects:

Nothing to report.

Significant changes in use or care of vertebrate animals:

Nothing to report.

Significant changes in use or care of biohazards:

Nothing to report.

NWT VIII: YEAR 1
ACCOMPLISHMENTS SUPPORTING FILE
– Supplementary Tables & Figures –

Table 1. NWT Signature Climate and Geophysical Data Sets. Measurement details, Year-1 progress, and Year-2 plans for NWT's long-term datasets that characterize the climate drivers and geophysical responses that motivate research and will be used to test H1-H5. *Abbreviations:* MRS = CU Boulder Mountain Research Station; GLV = Green Lakes Valley.

Dataset	Measurement Details	Accomplishments in Year 1	Planned for Year 2
Climate	1952-ongoing (C1, D1); 1982-ongoing (Saddle): Climate measures collected on chart recorders and data loggers.	Ongoing maintenance and continuation of data sets; substantial progress made in gap-filling past datasets.	Ongoing sampling; equipment maintenance and repair as needed; data processing with the goal of publishing data sets within 6 months of collection.
Snow depth, snow water equivalent (SWE)	1992-ongoing: Saddle grid plots (88 plots, measured bi-weekly), with periodic measurements of snow density at select locations; annual intensive snow survey in GLV at peak SWE.	Ongoing maintenance and continuation of data sets.	Ongoing sampling; equipment maintenance and repair as needed; data processing with the goal of publishing data sets within 6 months of collection.
Stream, lake, snow chemistry	1982-ongoing: Major cations and anions, pH, conductance, reactive silicate (Si), SO4, dissolved organic nutrients (DOC, DON, DOP).	Ongoing maintenance and continuation of data sets. Backlogged samples from 2020 and 2021 (due to COVID shutdown and closure of primary lab facility) are scheduled to be shipped to the Oregon State University lab in November 2023. These data sets will be published once samples are processed.	Finish processing and publish data from backlogged samples through 2023; collect 2024 data; ongoing maintenance and repair of equipment as needed.
Streamflow	1981-ongoing: Daily streamflow discharge records.	Ongoing maintenance and continuation of data sets.	Publish 2023 data; collect 2024 data; ongoing maintenance and repair of equipment as needed.
Lake ice cover	1981-ongoing: Measurements of ice cover thickness and ocular estimates of ice cover (spring, fall); used to calculate ice-free duration.	Replaced one camera and added a second at lake GL4 to monitor ice-off. Ongoing maintenance and continuation of data sets.	Publish 2023 data; collect 2024 data; ongoing maintenance and repair of equipment as needed.

Table 2. NWT Signature Ecological Data Sets. Measurement details, Year-1 progress, and Year-2 plans for NWT's ecological observations that motivate the five primary questions and research plans in NWT VIII. We prioritize data sets that encompass multiple spatial locations for H1, species that vary in specific characteristics for H2, species pairs or multispecies communities in H3, responses with links between composition and function in H4, and parameters for the models we propose in H5. *Abbreviations:* MRS = CU Boulder Mountain Research Station; GLV = Green Lakes Valley; GSLE = Growing Season Length Experiment.

Dataset	Measurement Details	Accomplishments in Year 1	Planned for Year 2
Tundra vegetation	Saddle Grid, 1989-ongoing: Annual survey of 88 1 m^2 plots, spaced at 50 m intervals; point quadrat species cover, NDVI; aboveground biomass and NDVI collected in adjacent 0.125 m^2 plots. ITEX, 2006-ongoing: Annual survey of 48 1 m^2 plots in moist meadow with experimental warming x snow x nitrogen manipulations; point quadrat species cover and NDVI; incorporated *Trollius albiflorus* range expansion transplant experiment in 2021. GSLE, 2018-2023: annual point quadrat species cover surveys in 80 0.5 m^2 subplots and 60 1 m^2 warming treatment plots; annual NDVI in subplots Snowbed, 2012-ongoing: Annual monitoring of snowmelt timing and intermittent vegetation surveys in 15 1 m2 plots spanning local snow cover gradients at 4 different elevations. ANPP experiment - 2022-ongoing: annual measures of productivity (using NDVI and plant aboveground biomass harvest).	2022 data published and 2023 data collected for all data sets. Saddle Grid - installed TOMST surface and subsurface (5 cm) temperature/ moisture sensors in 30 plots and began using NDVI in addition to biomass harvesting to estimate plant productivity ITEX - Completed species composition surveys and collected *Trollius albiflorus* demographic and trait data. ANPP - added 17 0.5m^2 plots to expand replication across habitat types.	2023 data will be curated and published; 2024 data will be collected; Saddle Grid – Install TOMST loggers into an ~30 additional plots ITEX – Analyze *T. albiflorus* experimental results to date and determine data collection plan for 2024. ANPP: analyze 2023 ANPP data and decide on future sampling efforts based on results.
Subalpine forest	5-year tree surveys - 1982-ongoing: 12 stands (>100 years old) distributed across a moisture gradient (xeric to hydric),~400 trees (>4cm DBH) per stand; 9 stands mapped and monitored 9 times in the last 40 years; 3 new permanent plots installed near treeline in 2016. Annual tree surveys - 2015-ongoing: Monitoring soil moisture, seed production, germination, litter production, and seedling establishment annually; mortality and ingrowth every 3 years in 7 plots. Dendrometer measurements - 2020-ongoing: Annual monitoring of diameter growth using dendrometer bands in 5 plots.	2023 measurements collected for annual tree surveys and dendrometer data sets.	2023 data will be processed and published; 2024 dendrometer band, seed trap, litter production, and regeneration data will be collected.

Table 2. NWT Signature Ecological Data Sets. (con'd)

Dataset	Measurement Details	Accomplishments in Year 1	Planned for Year 2
Pika population	1980-1990, 2004-ongoing: Representative population sampling. 2016-ongoing: occupancy survey.	2023 population sampling and occupancy survey completed; installed 16 new, 3-sensor microclimatic monitoring stations to increase spatial resolution of subsurface temperature and humidity in talus.	2023 data will be processed and published; 2024 demographic study, habitat occupancy survey, microclimatic monitoring and acoustic monitoring will be conducted; 2016-2023 occupancy data will be analyzed.
Zooplankton and Primary Production	2012-ongoing: Weekly sampling with conical net from deepest location during ice-free season and monthly sampling during ice-on season; zooplankton identified to species and classified as by developmental stage; body length measured for 50-100 individuals/taxon/ sample.	2022 and 2023 chlorophyll-a data published; 2023 zooplankton data collected; preliminary analyses conducted evaluating zooplankton richness and body size in relation to ice phenology.	2023 zooplankton data and 2024 chlorophyll-a (primary production metric) will be published; 2024 zooplankton data collected; analysis of zooplankton diversity and phenology will be completed and submitted for publication.
Flux towers	2007-ongoing: Alpine eddy covariance flux towers.	2022 data submitted to AmeriFlux (currently under final review); 2023 data collected; 15 new soil moisture sensors added (9 at T-Van east site, 6 at T-van west site); data collection system upgraded with new CR1000X dataloggers at each tower to comply with new sensors; completed data processing review of eddy covariance flux calculations by AmeriFlux ("site visit lite")	2023 data will be curated and published; 2024 data will be collected; 24 soil samples will be collected for hydraulic conductivity, soil water retention, texture, and fine root biomass analysis by the Regional Environmental Soil Hydrology Project (ReESH) at Indiana University
Sensor Network Array	2017-ongoing: 16 nodes distributed throughout Saddle Catchment; each node is instrumented with sensors that measure soil moisture and temperature at 2 depths (5cm, 30cm) in 3 subplots, co-located with snow depth and air temperature, and vegetation plots surveyed annually for species composition (using point intercept method) and NDVI. Soil NO3- and NH4+ data collected annually. Time lapse cameras (phenocams) capture images every 30 min. during the growing season.	2023 data collection completed; 2022 vegetation and soil NO3- and NH4+ data published; 2022 microclimate data undergoing QA/QC; root processing from 2022-2023 ingrowth cores in process to assess belowground NPP; NDVI measured at multiple points during the 2023 growing season to characterize within-season variation.	2023 data will be processed and published; 2024 data will be collected; equipment will be maintained and repaired as needed.

Table 2. NWT Signature Ecological Data Sets. (con'd)

Dataset	Measurement Details	Accomplishments in Year 1	Planned for Year 2
Chickadee Nest Boxes	2018-ongoing: 150 nest boxes distributed across an elevational transect from the subalpine forest to the MRS. Breeding, fledging, and genetic data collected annually.	2023 nest box survey completed; blood and morphological data collected from 56 adults and 111 chicks; 2018-2020 blood parasite data published; temperature data collected from 10 nests (inside and outside of nest boxes)	Increase the number of nest boxes with temperature sensors; collect 2024 morphological and genetic data from all occupied nest boxes.
Pollinators	New in NWT VIII: 2 vane traps and 5 bee bowl triplets (red/blue/white) installed along 50 m transects at 5 m intervals at 6 sites; sampled 3x/summer; air and soil temperature sensors to be installed along transects. Methods piloted in 2021.	2023 data collection postponed from Year-1 to Year-2 due to injury of leading investigator.	Conduct pollinator surveys during the spring 2024 growing season; process insects in fall 2024.
Pond and stream macro-invertebrates	New in NWT VIII: D-frame kick net sampling to collect macroinvertebrates from benthos and water column; co-located measures of water temperature, pond bathymetry/stream geomorphology, depth, temperature, DO, conductivity, and pH. Methods piloted and initial environmental data collected in 2021.	2021 environmental data published; 2022 data collected with analysis under way; no new data collected in 2023 to prioritize completing 2022 analysis.	2022 data will be published, and 2021 and 2022 data sets will be analyzed and results used to define a longer-term sampling plan in targeted ponds and stream locations.

Fig. 1. Water source and elevation mediate temperature exposure in alpine benthic macroinvertebrate stream communities at Niwot Ridge. New measurements of benthic macroinvertebrates at 9 locations spanning an elevation gradient and different water sources in the North Boulder Creek Watershed indicate that sites differ in a range of abiotic factors, including means and variation in summer water temperatures (panel a), hydroperiod and discharge (panel b), and water chemistry parameters such as conductivity (panel c). Preliminary analyses of benthic stream invertebrate data that was newly collected as part of the current grant cycle shows that community structure differs in relation to water sources and corresponding abiotic factors (panel d). All panels use the same legend showing water sources (top right). Analyses and figures provided by **Dr. Daniel Preston.**

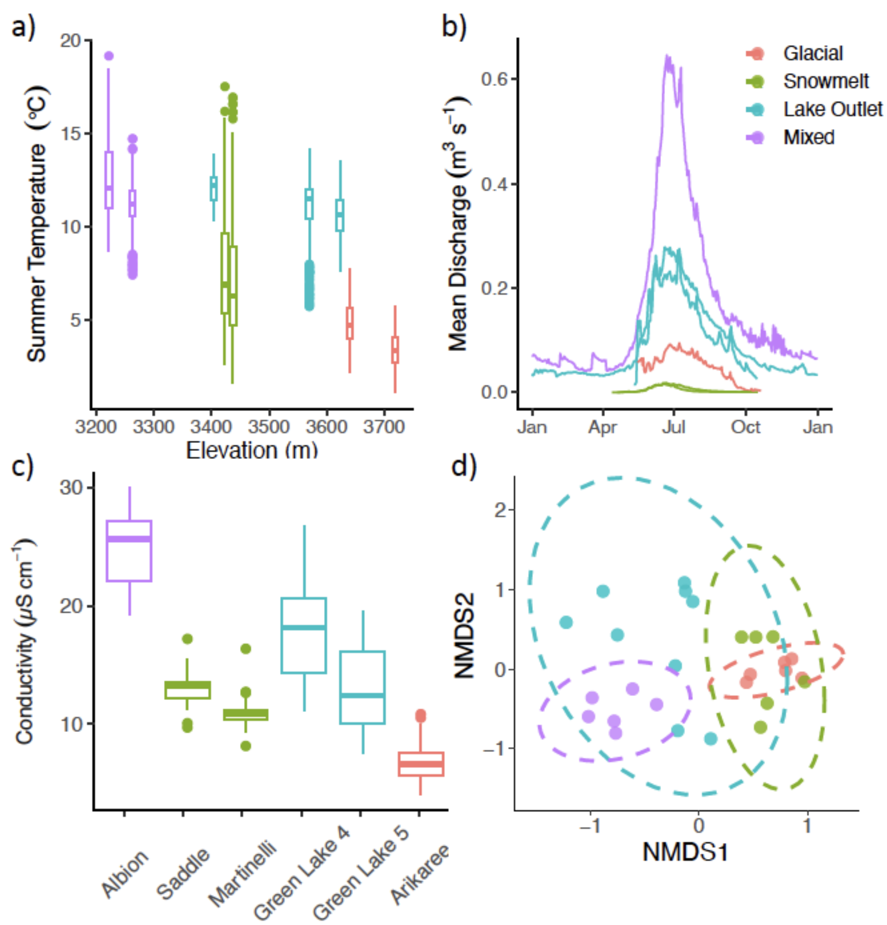


Fig. 2. **Alpine plant responses to rising temperature varies across a gradient in snow depth.** Community-weighted (a) mean annual temperature niche (°C), and (b) water use efficiency values (WUE; Δ δ13C) through time for the three snow depth groups. Points indicate a community-weighted mean for each plot in each time-point. Dashed lines indicate non-significant trends ($p > 0.05$) through time; solid lines indicate significant trends through time. 95% confidence intervals based on ordinary least squares linear regression are shown as shaded areas around the trend lines. From **Oldfather et al. (2023), Divergent Community Trajectories with Climate Change Across a Fine-Scale Gradient in Snow Depth.** ***Journal of Ecology*****: doi 10.1111/1365-2745.14223.**

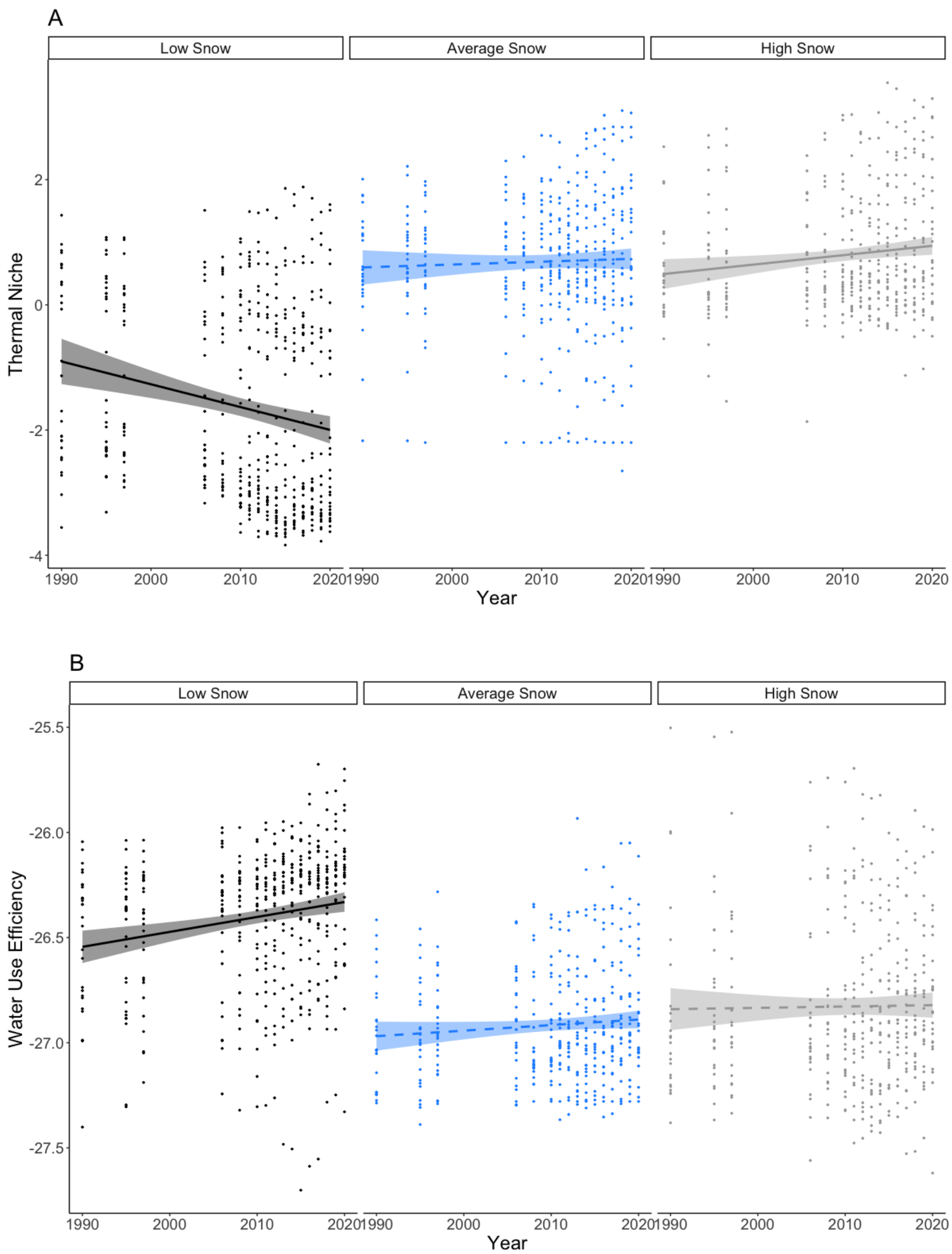


Fig. 3. Plant functional traits and species-specific responses drive alpine plant community responses to global change drivers. To better understand how species respond to global change (simulated nitrogen deposition, increased snowpack, and warming), we synthesized data frpom six long-term experiments at the NWT LTER with a comprehensive functional trait database. Here we show the comparison of trait effects on establishment probability, changes in abundance, and slopes of community weighted mean values (CWM) across the global change treatments. Traits on the x-axis are arranged based on negative to positive CWM change in control plots. Solid points indicate where effects are different from zero (95% confidence interval does not overlap with zero), while triangles indicate a different effect than in the control plots (the effect in the control plots does not fall within the 95% confidence interval for the effect in the treatment plot). Figure and analyses conducted by **Dr. Jonathan Henn.** Manuscript is in preparation to be submitted to *Ecology Letters.* Full author list: Jonathan Henn, Kurt E. Anderson, Laurel M. Brigham, Clifton P. Bueno de Mesquita, Courtney G. Collins, Sarah Elmendorf, Matthew Green, Jared Huxley, Nicole E. Rafferty, Annika Rose-Person, and Marko J. Spasojevic.

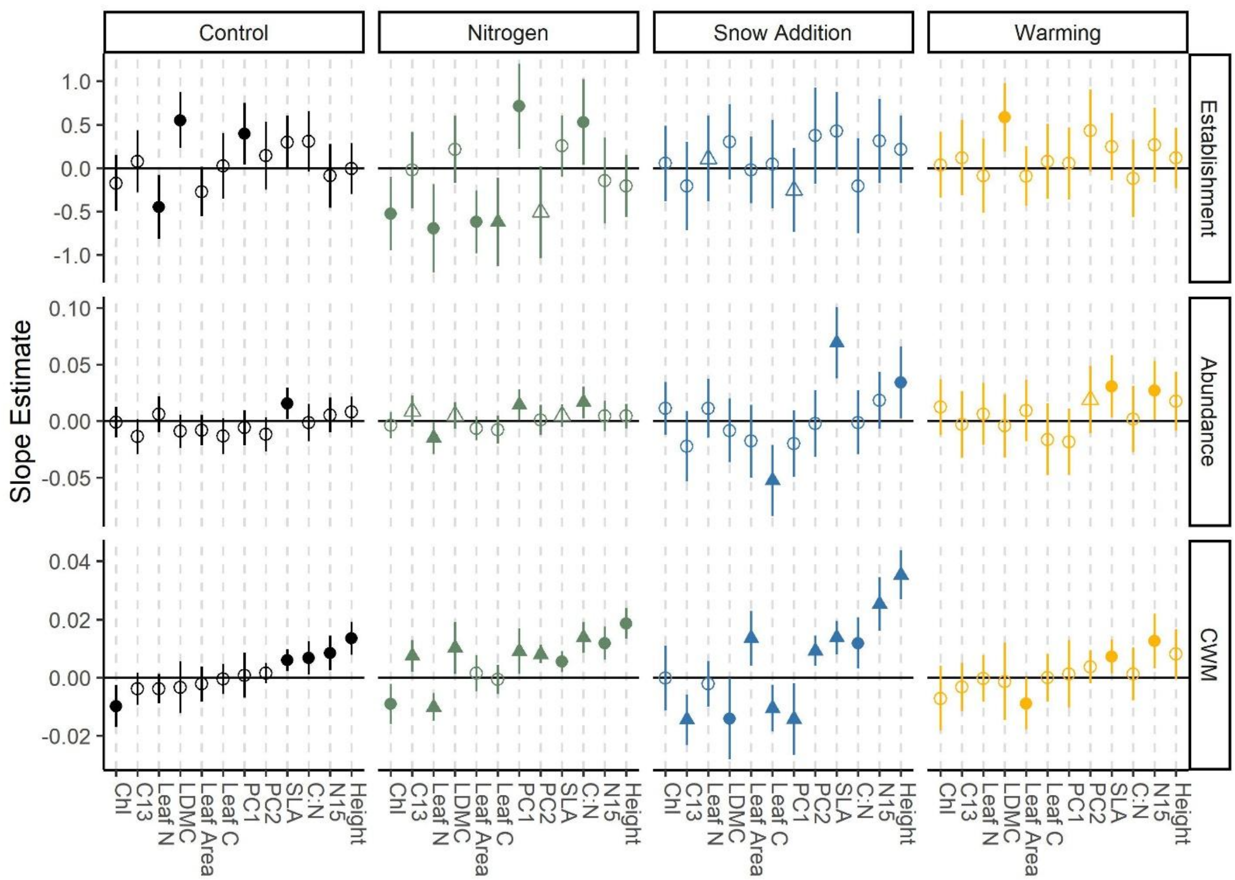


Fig. 4. The functional traits that underpin the relationship between biodiversity and ecosystem function vary with annual climate conditions. Using 13 years of data on plant species composition, plant traits, local scale abiotic variables, above-ground net primary productivity (ANPP), and climate from NWT LTER long-term data sets, we found that (a) the functional trait model that best predicts ANPP depends on the amount of snow that occurs each year. he alpine tundra of Colorado (USA) to investigate temporal dynamics in the B–EF relationship. The three panels in the bottom row illustrate the relationships between the Annual NPP R-squared values and annual snow precipitation for trait models incorporating (b) Leaf Area, (c) Height, and (d) δ15N. Lines of best fit from linear regressions between snow precipitation and Annual NPP 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. **Figure from Huxley et al. (2023). Plant functional traits are dynamic predictors of ecosystem functioning in variable environments.** ***Journal of Ecology.*** **doi:10.1111/1365-2745.14197.**

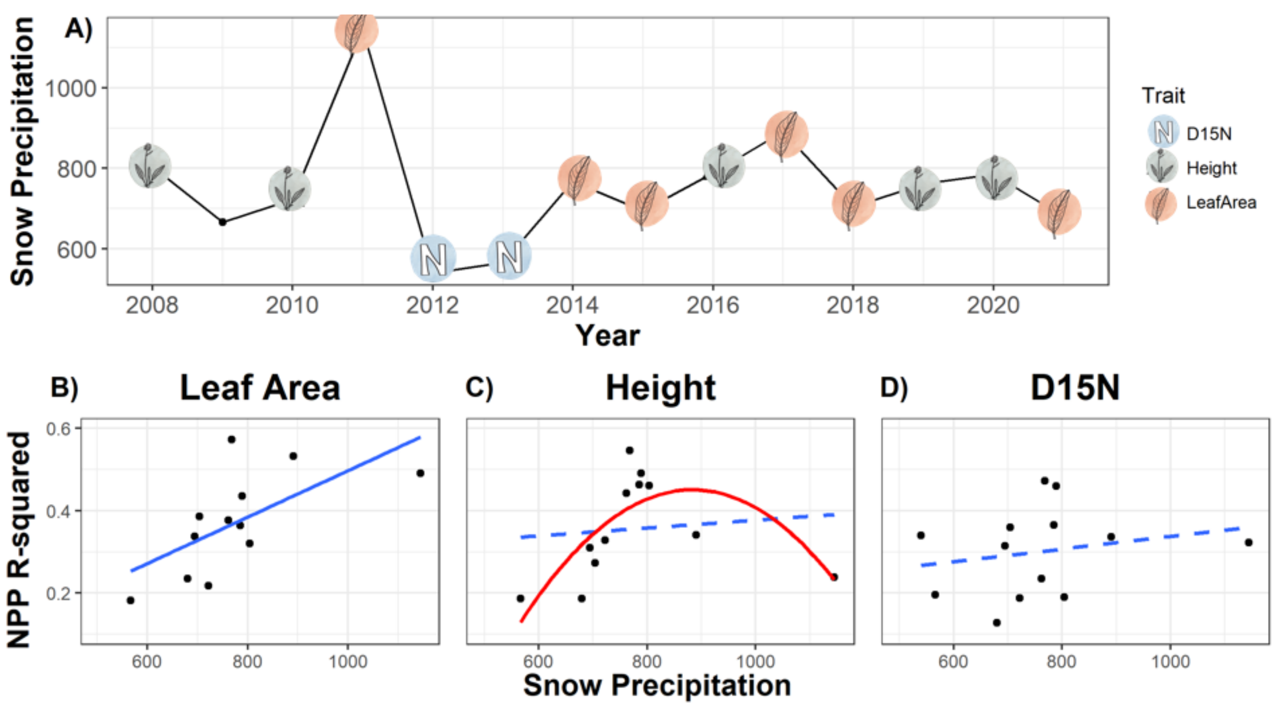
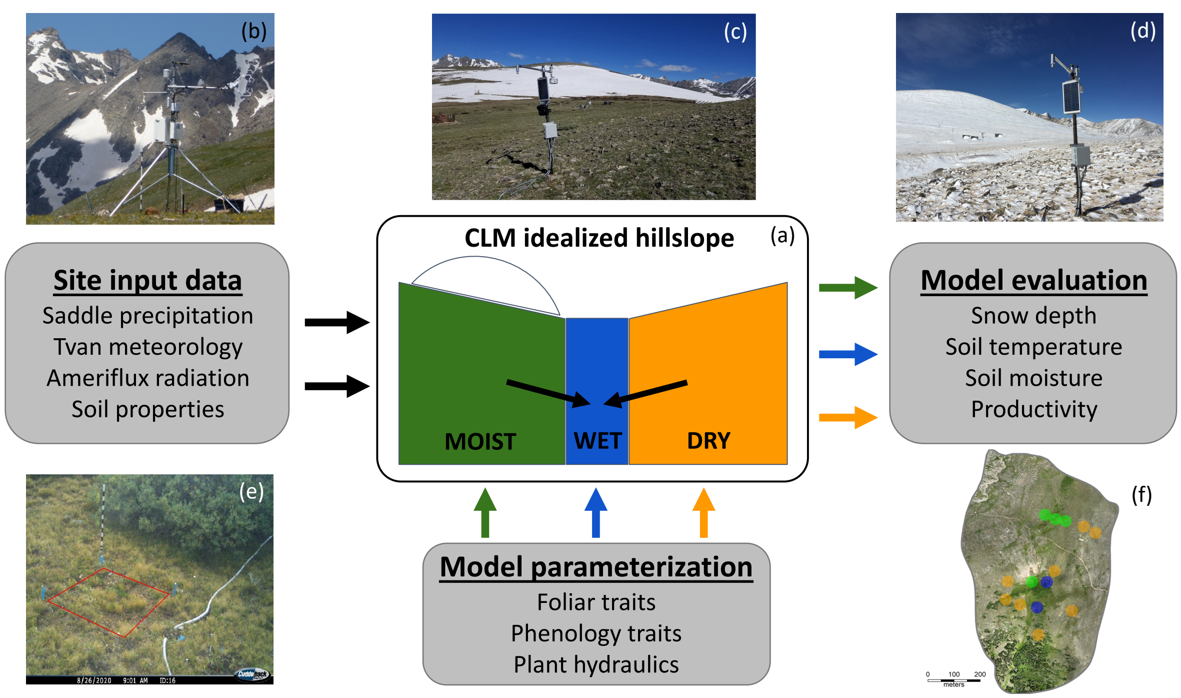


Fig. 5. Diagram of our model workflow for single-point simulations with hillslope hydrology configured for an alpine tundra hillslope. The Community Land Model (CLM) can be run at point scales and with site-specific configurations to test ecological hypotheses using a combination of atmospheric forcings, plant traits, and observational data for evaluation. (a) Shows the Niwot Ridge idealized hillslope, with separate columns for moist, wet, and dry meadow vegetation. Black arrows indicate the direction of hydrologic connectivity with a lowland (wet meadow) column connected to two upland (moist and dry meadow) columns. Forcing data included (b) meteorological measurements from two alpine flux towers, (c) precipitation measurements from the Saddle site, and (d) shortwave radiation measurements from the US-NR1 AmeriFlux Tower site. Moist, wet, and dry meadows were parameterized using plant functional trait data and (e) phenocam observations from Niwot Ridge. We evaluated our results using observational data from Niwot Ridge including snow depth measurements, soil temperature and moisture from the Sensor Network Array, and aboveground NPP measurements from biomass harvests. Photo credits: (b) J. Knowles; (c) W. Wieder; (d) J. Morse; (f) O. Wigmore & NWT LTER. Figure from **Jay et al. (2023). Topographic Heterogeneity and Aspect Moderate Exposure to Climate Change Across an Alpine Tundra Hillslope.** ***Journal of Geophysical Research: Biogeosciences*** **128(11): e2023JG007664.**



NWT VIII: YEAR 1
PRODUCTS SUPPORTING FILE
- Published Datasets-

Table 1. NWT Published Datasets.

Title	Package ID	DOI
Aboveground net primary productivity calibration of indirect measurements, 2022.	knb-lter-nwt.308.1	doi:10.6073/pasta/23be5cabe2b9712a8e4f5ce04859756c
Aboveground net primary productivity data for Saddle grid, 1992 - ongoing.	knb-lter-nwt.16.7	doi:10.6073/pasta/56491d9a56214ca7d7f3f26487faf510
Air temperature and relative humidity data for A1 HOBO logger, 2013 - ongoing.	knb-lter-nwt.3.7	doi:10.6073/pasta/b3d4132f47e51f1e7a6708be84e1dab5
Air temperature and relative humidity data for B1 HOBO logger, 2012 - ongoing.	knb-lter-nwt.5.6	doi:10.6073/pasta/b143d2ea59c9fd094f6808d025050b1c
Air temperature data for C1 chart recorder, 1952 - ongoing.	knb-lter-nwt.411.15	doi:10.6073/pasta/13e297de163be8d607550e3d040ba9dc
Air temperature data for D1 chart recorder, 1952 - ongoing.	knb-lter-nwt.412.13	doi:10.6073/pasta/f78dea915bafea757940b6a7d203b5b7
Air temperature data for Saddle chart recorder, 1981 - 2017.	knb-lter-nwt.413.14	doi:10.6073/pasta/befff1f7b1d3ac9e99d807467ce09c0a
Alpine species transplant experiment within the sensor network, 2019 - 2021.	knb-lter-nwt.260.2	doi:10.6073/pasta/7186ca55ffe364f3079f423c218a13e1
Annual snow survey, Green Lakes Valley, Niwot Ridge, Colorado, 2013 - ongoing.	knb-lter-nwt.929.3	doi:10.6073/pasta/4e39f916aec3334a60850ccce0458eaf
ANPP, NDVI and canopy height in black sand extended growing season experiment, 2019 - ongoing.	knb-lter-nwt.265.3	doi:10.6073/pasta/42e9e319615f4f08831e7b177e3cfe97
Benthic macroinvertebrate, water temperature, and stream environmental data for Green Lakes Valley, 2021.	knb-lter-nwt.310.1	doi:10.6073/pasta/eea7fc67dde2504a951434715b1a0b6e
Chickadee breeding and parasite survey from Boulder, Sugarloaf, and MRS nest boxes, 2019 - 2021.	knb-lter-nwt.263.1	doi:10.6073/pasta/fa5a11934f3526c5391879f76b1b569e
Chlorophyll-a data for the Green Lake 4 buoy, 2018 - ongoing.	knb-lter-nwt.267.4	doi:10.6073/pasta/5e659c5f72a20ac3af7090cf2cba59d5
Climate data for C1 data logger (CR1000), 2015 - ongoing, 10 minute.	knb-lter-nwt.252.3	doi:10.6073/pasta/0e76bbf6d8771678e5f75905c6f4165a
Climate data for C1 data loggers (CR23X and CR1000), 2000 - ongoing, daily.	knb-lter-nwt.401.8	doi:10.6073/pasta/bd825fe6d00d3cec3a2623cca4b55ef5
Climate data for D1 data logger (CR1000), 2014 - ongoing, 10 minute.	knb-lter-nwt.273.2	doi:10.6073/pasta/520427aedc0e568a5f17157c49da6a1b
Climate data for D1 data loggers (CR23X and CR1000), 2000 - ongoing, daily.	knb-lter-nwt.402.6	doi:10.6073/pasta/4dfce38fb126d46a928e29c3764314ba
Climate data for saddle catchment sensor network, 2017 - ongoing.	knb-lter-nwt.210.5	doi:10.6073/pasta/efec07ed03c2857ce2b6f2f2bd3b2b5e

Table 1 (con'd).

Title	Package ID	DOI
Climate data for saddle catchment sensor network, 2017 - ongoing.	knb-lter-nwt.210.6	doi:10.6073/pasta/25348fb210f66a1f18b31ba14b32c05a
Climate data for saddle data logger (CR1000), 2014 - ongoing, 10 minute.	knb-lter-nwt.274.2	doi:10.6073/pasta/e3ab756c6f3933814fbe94b456184f2d
Climate data for saddle data loggers (CR23X and CR1000), 2000 - ongoing, daily.	knb-lter-nwt.405.7	doi:10.6073/pasta/dc266e27577baf856ea576422dcbc226
Dissolved oxygen data for the Green Lake 4 buoy, 2018 - ongoing.	knb-lter-nwt.175.4	doi:10.6073/pasta/c88e9145afc953e9719c27d6111563f7
Fecal glucocorticoid metabolite levels of American pika (Ochotona princeps) and habitat characteristics of their associated territories found in rock glaciers adjacent to Niwot Ridge and within Rocky Mountain National Park, 2018 - 2019.	knb-lter-nwt.309.1	doi:10.6073/pasta/b15009b35926522f75e43e1e9a861d64
Gap-filled precipitation data for Saddle, 1981 - ongoing, daily.	knb-lter-nwt.315.1	doi:10.6073/pasta/b78fc5dbec3fcdfe4a53a009fce2e13d
Homogenized, gap-filled, air temperature data for Saddle, 1986 - ongoing, daily.	knb-lter-nwt.314.1	doi:10.6073/pasta/d3460079bb2cb633f994a2f4075049ef
Ice thickness at Green Lake 4, 1984 - ongoing.	knb-lter-nwt.199.5	doi:10.6073/pasta/d7aa271b4bfc3d532f60df540eb7b620
Increased temperature, N and snowpack experiment for north of saddle, 2006 - ongoing.	knb-lter-nwt.13.6	doi:10.6073/pasta/bde85da4484103fff1927f976d7ac23f
Lake ice clearance and formation data for Green Lakes Valley, 1968 - ongoing.	knb-lter-nwt.106.6	doi:10.6073/pasta/e89a9a6984ebbcdbbc85c16d65298dd2
"National Atmospheric Deposition Program (NADP) SITE CO02 https://nadp.slh.wisc.edu/sites/ntn-CO02/"		https://nadp.slh.wisc.edu/sites/ntn-CO02/
"National Atmospheric Deposition Program (NADP) SITE CO90 https://nadp.slh.wisc.edu/sites/ntn-CO90/"		https://nadp.slh.wisc.edu/sites/ntn-CO90/
PAR data for the Green Lake 4 buoy, 2018 - ongoing.	knb-lter-nwt.189.4	doi:10.6073/pasta/9b5abafd602c097c793dabcd9f5e0bb9
Pika demography data for west knoll and Indian Peaks wilderness, 2008 - ongoing.	knb-lter-nwt.8.5	doi:10.6073/pasta/3ef3608f4e04c99874bfc7abc4395eee
Plant species composition data for Saddle grid, 1989 - ongoing.	knb-lter-nwt.93.7	doi:10.6073/pasta/1b4e85930251df1eba3d417fd4f6cd04
Plant species composition for sensor network array, 2017 - ongoing.	knb-lter-nwt.191.5	doi:10.6073/pasta/d040fbb7d96339126d0d13211369db59
Plant species composition in black sand extended growing season experiment, 2018 - ongoing.	knb-lter-nwt.225.5	doi:10.6073/pasta/1e98735687843c217368a5ea7a1b38ff

Table 1 (con'd).

Title	Package ID	DOI
Plant species composition in black sand extended growing season experiment, 2018 - ongoing.	knb-lter-nwt.225.7	doi:10.6073/pasta/1e286dce0fe357e55ba03c17f1ddfef7
Plant species composition in ITEX subplots in black sand extended growing season experiment, 2018 - ongoing.	knb-lter-nwt.261.3	doi:10.6073/pasta/3ff9a40fa0781e3ebf56336c138a6983
Pollinator visitation, flower count, and seed set in Black Sand plots, 2020.	knb-lter-nwt.286.1	doi:10.6073/pasta/920fe947b69eea415bdca0af3b3e33c9
Potentilla demographic and environmental data for Rainbow Meadows, Elk Meadows, and Cabin Clearing, 2018 - 2020.	knb-lter-nwt.256.1	doi:10.6073/pasta/6a404a63a42bd63a64d9991e46ea14c9
Potentilla demographic and environmental data for Rocky Mountains of Colorado (Niwot LTER & RMBL), 2018 - 2020.	knb-lter-nwt.256.2	doi:10.6073/pasta/4f5913f9095b74945700d1dae93c0f16
Potentilla flowering phenology for Cabin Clearing, Elk Meadows and Rainbow Meadows, 2019.	knb-lter-nwt.257.1	doi:10.6073/pasta/0a771270b78eed4834ed7933c8f77776
Potentilla plot soil moisture for Cabin Clearing, Elk Meadows and Rainbow Meadows, 2019.	knb-lter-nwt.258.1	doi:10.6073/pasta/77aa957a0c8a00dcf1311108196dfa41
Precipitation data for C1 chart recorder, 1952 - ongoing.	knb-lter-nwt.414.14	doi:10.6073/pasta/759b07d4276f65b39e4bd3adee650b47
Precipitation data for C1 chart recorder, 1952 - ongoing.	knb-lter-nwt.414.15	doi:10.6073/pasta/1c93c092cc9728e1d8d8b497b90eab3a
Precipitation data for D1 chart recorder, 1964 - ongoing.	knb-lter-nwt.415.16	doi:10.6073/pasta/5a5de35cba70fa1c419a44707f7ba333
Precipitation data for Saddle chart recorder, 1981 - ongoing.	knb-lter-nwt.413.13	doi:10.6073/pasta/69048358b06838f54df1ca482f87e6f0
Precipitation data for Saddle chart recorder, 1981 - ongoing.	knb-lter-nwt.416.14	doi:10.6073/pasta/a46163b488c489faea22192d33537183
Silver film response to sulfate reduction activity in alpine and subalpine wetlands, 2022.	knb-lter-nwt.316.1	doi:10.6073/pasta/f89874c9c42517fd9dec64e703b460f1
Snow cover profile data for Niwot Ridge and Green Lakes Valley, 1993 - ongoing.	knb-lter-nwt.98.18	doi:10.6073/pasta/654f9ff43b79a80f864ddf645ec07536
Snow depth data for Saddle grid, 1992 - ongoing.	knb-lter-nwt.31.20	doi:10.6073/pasta/3ee9e9f8b6437dc627d01c066724b33c
Snow depth data for saddle snowfence, 1992 - ongoing.	knb-lter-nwt.34.14	doi:10.6073/pasta/e81b5ea0c41c1b884d19bce844743a2d
Snow grain data for Niwot Ridge and Green Lakes Valley, 1995 - ongoing.	knb-lter-nwt.97.17	doi:10.6073/pasta/2e9afb46ea313fa3ac6ddbd34cf23051
Snow water equivalent data for Niwot Ridge and Green Lakes Valley, 1993 - ongoing.	knb-lter-nwt.96.19	doi:10.6073/pasta/06635298ea4364c6d55ad14146257f0d

Table 1 (con'd).

Title	Package ID	DOI
Snowbed experiment species composition and hobo data for Niwot Ridge, 2012 - ongoing.	knb-lter-nwt.172.6	doi:10.6073/pasta/db304e014854dc22f226a546c79449e1
Soil moisture and snowdepth measurements in the Black Sand experiment for East Knoll, Audubon, Lefty, Soddie and Trough, 2018 - ongoing.	knb-lter-nwt.181.6	doi:10.6073/pasta/89de017fd3148d43102eb3d6fe9ae33f
Soil moisture, temperature, and electrical conductivity data from the black sand extended growing season length experiment, 2018 - ongoing, hourly.	knb-lter-nwt.238.4	doi:10.6073/pasta/b76253df86d025a61c21d1260dac77f0
Soil moisture, temperature, and electrical conductivity data from the black sand extended growing season length experiment, 2018 - ongoing, hourly.	knb-lter-nwt.238.5	doi:10.6073/pasta/95adf6e90b2ba0e032c480c23e2ca1b8
Streamflow data for Albion camp, 1981 - ongoing.	knb-lter-nwt.102.18	doi:10.6073/pasta/cc7e183b27383d894709fcc3e2e8cc74
Streamflow data for Saddle Stream 16, 2020 - ongoing.	knb-lter-nwt.239.2	doi:10.6073/pasta/f2bec079a9dbee45715fc8db1804176e
Streamflow data for Saddle stream, 1999 - ongoing.	knb-lter-nwt.74.8	doi:10.6073/pasta/7de15f073c80e868423bf81970d2d5a0
Streamflow for Green Lake 4, 1981 - ongoing.	knb-lter-nwt.105.17	doi:10.6073/pasta/8854555349a948660f8f681a041049c8
Streamflow for Martinelli basin, 1982 - ongoing.	knb-lter-nwt.111.15	doi:10.6073/pasta/817f8beba7b66e35790aa118cca50114
Supplemental soil moisture and temperature data from the saddle catchment sensor network, 2019 - 2021.	knb-lter-nwt.262.2	doi:10.6073/pasta/500605538621e56577c2a8b8b4f0e68f
Temperature data for Green Lake 4 inlet and outlet, 2019 - ongoing	knb-lter-nwt.259.3	doi:10.6073/pasta/667b65a1ff17f08a786e332e5bc9d03b
Temperature data for the Green Lake 4 buoy, 2018 - ongoing.	knb-lter-nwt.188.4	doi:10.6073/pasta/ce2c273eae068f5fa80df4ddd82f2643
Time lapse camera photos for Green Lakes Valley, 2011 - ongoing.	knb-lter-nwt.270.4	doi:10.6073/pasta/1c9881c581b14bfd268d3e46a7a9ab4d
Time-lapse camera (phenocam) imagery of black sand extended growing season length experiment, 2022.	knb-lter-nwt.307.1	doi:10.6073/pasta/93de0f9a44684672ff9c32b3e39a498f
Time-lapse camera (phenocam) imagery of sensor network plots, 2017 - ongoing.	knb-lter-nwt.192.4	doi:10.6073/pasta/926c925a2e5a9ca7962bc12e5bc5592e
Water quality data for Green Lakes Valley, 2000 - ongoing.	knb-lter-nwt.157.8	doi:10.6073/pasta/2b9271ce9c27c939696fff96553a7bd2
Zooplankton community composition and trait data for Green Lakes Valley, 2009 - ongoing.	knb-lter-nwt.161.6	doi:10.6073/pasta/9eda64cdaf74c5df938d765fa04649eb