Mountains are among the most fragile environments on Earth. They are also rich repositories of biodiversity and water and provide many ecosystem goods and services on which downstream communities rely.

The presence of a seasonal snowpack in mountain environments may amplify climate signals because of the redistribution, storage and release of liquid water, solutes, and particulates from the seasonal snowpack. Moreover, meteorological, hydrological, cryospheric, and ecological conditions change greatly over relatively short distances in mountain areas because of their rugged terrain, and thus the boundaries between these systems are sensitive to small environmental changes. In the past, we have noted that the harsh conditions characteristic of these environments suggest that some organisms in mountain ecosystems are on the edge of their tolerance. Yet, with notable exceptions such as the pika, this may not be a generality. There appear to be winners as well as losers in these interactions, and discovering which of the organisms and the biogeochemical processes mediated by them in high elevation catchments are sensitive to small changes in climate and other environmental parameters is an important activity.

The Niwot Ridge LTER focuses on this tight coupling between climate and ecosystem processes in mountain landscapes. A key premise of our work is that the stability of the coupled climate-ecological system translates into marked benefits in terms of the maintenance of biodiversity and protection of downstream water availability and quality. Changes in climate and depositional drivers may have the potential to decouple climate-ecosystem linkages, affecting connectivity among landscapes and decreasing the capacity of mountain systems to deliver important ecosystem services (Figure 1).

Niwot Ridge was established as a site in the Long-Term Ecological Research Program in 1980. Located approximately 35 km west of Boulder, Colorado, our site encompasses extensive alpine tundra, glacial lakes, cirques and talus slopes, all above 3000 m elevation.
Research Activities and Findings

The overall goal of the Niwot Ridge LTER is to relate changes in the amount and timing of snow and snowmelt, along with increasing N deposition and increasing dust deposition, to changes in resource connectivity and resource limitations in a heterogeneous landscape. Our work is structured around two working hypotheses.
H1. Earlier and decreased snowmelt will decrease hydrologic landscape connectivity. Increased air temperatures in combination with increased dust and N deposition will result in a decrease in hydrologic connectivity across landscape units because of less snowfall and earlier snowmelt. Increases in N and dust deposition will disproportionately affect microbial populations in barren soils and lead to soil acidification.

H2. Decreased hydrologic connectivity will affect biotic diversity across the heterogeneity of the alpine landscape. Here, we are particularly interested in the interactive effects of climate (snow, temperature) and nutrient availability (nitrogen, phosphorus) (H1). We expect that changes in resource flow will disproportionately affect ecological communities in transitional zones. These changes will cause soils will become more "leaky" in alpine tundra, resulting in a decrease in the DOC:NO$_3$ ratio in streams.

We organize our annual report around the first two hypotheses (Sections I and II, Figure 1). We consider ecological responses across the mountain alpine ecosystem, including vegetation, small mammals, and microbes in alpine tundra (Section IIa), microbes in unvegetated talus (Section IIb), and phytoplankton and zooplankton in lakes (Section IIc).

We include a third section, which we title Integration and Syntheses, about new efforts to synthesize long-term data and models to include both drivers and responses. We end with details about our continued efforts in long-term monitoring and information management (Section IV) and our efforts in outreach and engagement (Section V).

I. Environmental Drivers (Findings Related to H1)
Alpine ecosystems are particularly susceptible to climatic and resource variation due to their short growing seasons, sparse vegetation, and thin soils. Increased nitrogen deposition in wetfall and changes in climate currently affect Green Lakes Valley (GLV) within the Colorado Front Range. Previous research at NWT LTER conducted within the alpine zone links chronic N inputs to a suite of ecological impacts, resulting in increased nitrate export.

In 2015, NWT completed a comprehensive analysis of temperature and precipitation data. Long-term monitoring at Niwot Ridge began in the 1950s with the installation of meteorological stations at the C1 subalpine forest site (3,022 m) and the D1 alpine site (3,739 m), the longest high-elevation continuous climate record in the US (McGuire et al. 2012). Annual precipitation (approx. 75% of which is snow) has increased in the alpine (D1) due to the exposure of high elevations to orographically-generated snow related to regime change in the Pacific Decadal Oscillation (PDO) in the mid-1970s (Fig. 2). After the step increase in the 1970’s associated with the PDO, snowpack has shown no discernable trend (consistent with regional patterns; Clow 2010) and we expect the step increase to dissipate as the PDO shifts to a negative phase (Pederson et al. 2011). Subalpine precipitation patterns (two-thirds of which falls as snow) have gone unchanged since the 1950s. Regionally, projected trends in precipitation for both zones are uncertain, but directional changes, if any, are predicted to be small (Hoerling et al. 2013).

While changes in precipitation may reflect decadal-scale variation, there is growing evidence of persistent long-term warming trends at NWT (McGuire et al. 2012, Kittel et al. 2016), consistent with high-mountain environments globally (Rangwala and Miller 2012, Pepin et al. 2015). We find that the subalpine is experiencing daytime warming in the winter, spring and summer (as indicated by maximum temperatures, Fig. 2), with nighttime cooling in the fall months. Maximum and minimum daily temperatures are substantially colder in the higher alpine zone, with the alpine experiencing daytime and nighttime warming in the spring and summer months (Fig. 2), and colder temperatures in the fall. A consequence of the warming is a shift towards earlier timing of seasonal snowmelt and a longer growing season.
Climate change is affecting the hydrology of high-elevation mountain ecosystems, with implications for ecosystem functioning and water availability to downstream populations. We used precipitation and evapotranspiration (ET) from both subalpine forest and alpine tundra portions of Green Lakes Valley, as well as discharge fluxes at the catchment outlet, to quantify climate effects on water balance (Knowles et al. 2015b). Between 2008 and 2012, the water balance closure averaged 90% annually, and the catchment ET was the largest water output at 66% of precipitation. Interestingly, we found alpine ET was greatest during the winter, in part because of sublimation from blowing snow, which contributed from 27% to 48% of the alpine, and 6% to 9% of the catchment water balance, respectively. In contrast, the subalpine ET peaked in summer.

Correctly accounting for dissimilar hydrological cycling above and below alpine treeline is critical to quantify the water balance of high-elevation mountain catchments over periods of climate variability. We found that alpine areas generate the majority of the catchment discharge, despite in the case of Green Lakes Valley, covering only 31% of the catchment area (Fig. 3). Although the average annual alpine runoff efficiency (discharge/precipitation; 40%) was greater than the subalpine runoff efficiency (19%), the subalpine runoff efficiency was more sensitive to changes in precipitation. Inter-annual analysis of the evaporative and dryness indices revealed persistent moisture limitations at the catchment scale, although the alpine alternated between energy-limited and water-limited states in wet and dry years. Each ecosystem generally over-generated discharge relative to that expected from a Budyko-type model. The
alpine and catchment water yields were relatively unaffected by annual meteorological variability, but this interpretation was dependent on the method used to quantify potential ET.

**SUBSURFACE ICE MELT AND LAKE ICE.** Subsurface ice preserved as ice lenses and within rock glaciers as well as glacial and lake ice provide sensitive indicators of climate change and serve as a late-season source of meltwater. Permafrost conditions reported from Niwot Ridge in the 1970s are generally absent today, but ice lenses form and melt seasonally. Ice is present permanently within the Green Lake 5 rock glacier and at nearby favorable sites (Leopold et al. 2015). The Arikaree Glacier has shown a marked decline in cumulative mass balance during the past 12 years after a 30-year period when net mass balance was approximately 0. Surface temperature measurements from rock glaciers have not shown strong trends during the past 15 years. We suspect that almost all of the 2.5-mm year\(^{-1}\) increase in stream discharge from the upper GLV in September and October has been derived from melting of subsurface ice.

Duration of seasonal lake ice increases with elevation in GLV, but duration has decreased at all seven lakes that have been monitored during the last three decades (Fig. 4). This decrease has been most marked at the lowest elevation where it amounted to a reduction of about 1 d year\(^{-1}\) and least at Green Lake 5 where the loss has been at a rate of 0.5 d year\(^{-1}\). Using data from the same seven high elevation lakes (3126 to 3620 m) in the Green Lakes Valley, we also found that spring ice-off dates have shifted 7 days earlier over the last 33 years (Preston, et al., in review). Climate data indicate that spring precipitation and summer temperatures are strong predictors of ice cover phenology, with dryer springs and warmer summers causing earlier ice-off.

**WINTER GAS EXCHANGE BETWEEN THE ATMOSPHERE AND SNOW-COVERED SOILS.** We also find shifts in winter gas exchange due to changes in microbial activity under the snowpack as the timing and extent of seasonal snow cover changes (Liptzin et al. 2015). Gases can react chemically or physically with other gases in the snowpack or in the aqueous phase. We find that carbon dioxide, nitrous oxide, methane, nitrogen oxides, ozone, gaseous elemental mercury, and volatile organic carbon compounds have been changing, although the mechanisms (biological or chemical) that create these concentration gradients still need to be determined. Changes driven by biological reactions may be the result of periods of exponential growth of a winter microbial community throughout much of the snow-covered season.
II. Biotic Responses (Findings Related to H2)

Our initial expectations of strong biotic responses to changes in temperature, N and dust deposition, and snowmelt dynamics have been tempered by the findings of substantial biotic resilience to these drivers. In alpine tundra, our findings tentatively point to the role of feedbacks with soil organic matter and small-scale heterogeneity as mechanisms for this resilience.

II.A) Tundra Responses

SCALE DEPENDENCE AND INTERACTIVE EFFECTS ON ECOSYSTEM CHANGE AT HIGH ELEVATION.

Changes along elevation gradients in mountain systems can be used as a proxy for predicting vegetation distributional changes in time. In alpine ecosystems changing climatic controls affect meso-scale (10–100 m) transitions at the lower and upper boundaries of vegetation (with forest and subnival zones, respectively) where sharp elevational gradients reflect a combination of temperature and snowfall gradients that influence the distribution of vegetation types along forest–tundra and tundra–subnival ecotones. Climatic changes also affect micro-scale (1–10 m) transitions among plant communities within the alpine belt where wind redistribution and topography contribute to temperature and snowpack gradients, influencing the distribution of plant species within alpine tundra. We are also finding that changing climatic controls influence both meso-scale transitions at the upper and lower boundaries of alpine vegetation and micro-scale transitions among plant communities within tundra (Suding et al. 2015).

Micro-scale heterogeneity appears to buffer response in many cases, while interactions between climate and other changes may often accelerate change. Interactions with microtopography and larger edaphic gradients have the capacity to both facilitate rapid changes and reinforce stability, and these interactions will affect the responsiveness of vegetation to climate change at different spatial scales.

Along the elevational gradient from forests to tundra to unvegetated talus, course-scale vegetation patterns are also changing in response to extended summer trends. Aerial photograph time-series analysis combined with ground verification indicates tundra expansion at high elevation into
unvegetated soils; 9-21% of the bare areas have been colonized by tundra since 1970. Colonization is most rapid in high-elevation areas with lower snowpack (Fig. 5). Forest expansion has been much slower and has mostly consisted of infilling lower elevation areas (Fig. 5). Shrubs (largely *Salix* species) have also colonized alpine tundra; in some areas shrub increase has been rapid (Formica et al. 2014). These changes are consistent with increased growing season length allowing tundra expansion uphill into unvegetated barren soils (Suding et al. 2015), where microbial communities may be facilitating plant colonization in some areas (Bueno de Mesquita et al. 2015). We expect that these changes in vegetation – particularly the expansion of tundra vegetation into high elevation unvegetated areas – will increase dissolved organic matter export into lakes and enhance aquatic primary production.

**SOIL RESPIRATION VARIABILITY ACROSS A MOISTURE GRADIENT.** To advance our understanding of carbon cycling across the micro-scale gradient of alpine tundra vegetation communities, we characterized the spatio-temporal variability of soil respiration (*R*₃) from 17 sites across a broadly representative soil moisture and vegetation gradient, within the footprint of ongoing eddy covariance measurements at Niwot Ridge (Knowles et al. 2015a). In every year, measured *R*₃ was greatest from mesic tundra, followed by wet and then dry tundra locations (Fig. 6). Increasing soil moisture invoked a bidirectional *R*₃ response from areas of dry and mesic tundra (directly proportional) compared to wet tundra (inversely proportional), and the optimum *R*₃ conditions were between 0.30 and 0.45 m³ m⁻³ soil moisture, which mainly coincided with soil temperatures below 8°C. We also developed simple models to predict *R*₃ from concurrent measurements of soil moisture and temperature, and from nighttime eddy covariance measurements. Both models were significant predictors of *R*₃ in all years and for all ecosystem types (where applicable), but the models did not adequately capture the intra-seasonal *R*₃ variability. The median cumulative growing season *R*₃ flux ranged from 138.6 g C m⁻² in the driest year (2013) to 221.4 g C m⁻² in the wettest year (2011), but the cumulative growing season fluxes varied by a factor of five between sites. Our results suggest that increased or more intense precipitation in the future has the potential to increase alpine tundra *R*₃, although this effect will be buffered to some degree by compensatory responses from dry, mesic, and wet alpine tundra.

**INDIRECT AND INTERACTIVE EFFECTS OF CLIMATE AND NITROGEN.** In an on-going global change experiment, we are testing indirect and interactive effects of changes in nutrient availability, temperature, and precipitation patterns on alpine tundra ecosystems (Farrer et al. 2015). Nitrogen fertilization, warming (passive warming chambers), and enhanced snowpack (snowfences) treatments have been in place since 2006 in all factorial combinations in a moist meadow tundra community. Annual measurements include species composition and productivity. In some years, microbial biomass, N mineralization (buried bags), and summer and winter N cycling (resin bags) have been measured.
We found that N and snow increased the abundance of Deschampsia (grass) and decreased the abundance of Geum (forb) over time, which caused strong indirect effects on diversity but not ecosystem function. Few interactive effects were found. Indirect effects on diversity were consistently stronger than direct effects and tended to increase over time. Direct effects predominated for three of four ecosystem functions we measured (productivity, N mineralization, and winter N availability). The only indirect effects on ecosystem function were that N and snow indirectly affected microbial biomass N by influencing Geum abundance. Overall, results suggest that explicitly accounting for changes in dominant plant abundance may be necessary for forecasting plant community response to environmental change, but predicting ecosystem function without knowledge of plant responses to global change may be possible.

**PLANT-MICROBE INTERACTIONS AND RESPONSE TO N DEPOSITION.** Given the high rates of N deposition NWT is experiencing, we asked how abiotic (N) and biotic (plant host and neighborhood) effects interact to influence root-associated bacterial (RAB) community assembly. Using 454 pyrosequencing, we examined RAB communities from two dominant alpine tundra plants, *Geum rossii* and *Deschampsia cespitosa*, under control, N addition and *D. cespitosa* removal treatments, implemented in a factorial design. We hypothesized that host would have the strongest effect on RAB assembly, followed by N, then neighbor effects. The most dominant phyla were Proteobacteria (mostly Gammaproteobacteria), Actinobacteria, Bacteroidetes and Acidobacteria. We found RAB communities were host specific, with only 17% overlap in operational taxonomic units. Host effects on composition were over twice as strong as N effects. *D. cespitosa* RAB diversity declined with N, while *G. rossii* RAB did not (Fig. 7). *D. cespitosa* removal did not influence *G. rossii* RAB community composition, but *G. rossii* RAB diversity declined with N only when *D.
*cespitosa* was absent (Fig. 8). Thus, we find RAB of both hosts are sensitive to N enrichment, and RAB response to N is influenced by host identity and plant neighborhood (Dean et al. 2015).

**SUBSURFACE MICROCLIMATE MAY BUFFER PIKA MORTALITY.** The American pika (*Ochotona princeps*) is considered a sentinel species for detecting ecological effects of climate change. Pikas are declining within a large portion of their range, and ongoing research suggests loss of sub-surface ice as a mechanism. At NWT we conducted the first analysis of physiological stress in pikas living in and adjacent to habitats underlain by ice. Fresh fecal samples were collected non-invasively from two adjacent sites (one with sub-surface ice and one without) and analyzed for glucocorticoid metabolites (GCM). We also measured sub-surface microclimates in each habitat. Results indicate lower GCM concentration in sites with sub-surface ice (Fig. 9) (Wilkening et al. 2015), suggesting that pikas are less stressed in favorable microclimates resulting from sub-surface ice features. GCM response was well predicted by habitat characteristics associated with sub-surface ice features, such as lower mean summer temperatures. These results suggest that pikas inhabiting areas without sub-surface ice features are experiencing higher levels of physiological stress and may be more susceptible to changing climates. Although post-deposition environmental effects can confound analyses based on fecal GCM, we found no evidence for such effects in this study. Sub-surface ice features are key to water cycling and storage and will likely represent an increasingly important component of water resources in a warming climate. Fecal samples collected from additional watersheds as part of current pika monitoring programs could be used to further characterize relationships between pika stress and sub-surface ice features.

**INSECT POLLINATOR MISMATCH UNDER CLIMATE CHANGE.** Indirect effects of climate change can also occur through changes in mutualisms that evolve through the matching of functional traits between partners, such as tongue length of pollinators and flower tube depth of plants. Using a long-term dataset, we found that in two alpine bumble bee species, decreases in tongue length have evolved over 40 years
(Miller-Struttman et al. 2015). Long-tongued pollinators specialize on flowers with deep corolla tubes, whereas shorter-tongued pollinators generalize across tube lengths. Co-occurring flowers have not become shallower, nor are small-flowered plants more prolific. Declining floral resources because of warmer summers appear to favor generalist foraging, leading to a mismatch between shorter-tongued bees and the longer-tubed plants they once pollinated.

II.B) Unvegetated Talus Responses

**PLANT-MICROBE INTERACTIONS AND COLONIZATION OF UNVEGETATED TALUS SOILS.** We are finding new evidence that plant and microbial communities and populations will respond to future changes in the talus environment, especially with regard to the potential uphill movement of plants and microbes in response to climate change and nitrogen deposition (Schmidt et al. 2015). These areas are currently undergoing a shift from a microbe-dominated ecosystem to one where microbe-plant interactions will play a critical role in reducing nutrient losses to downstream ecosystems.

We investigated the influence of soil bacterial clades on the distributions of bryophytes and 12 vascular plant species in the talus areas at the very highest elevation zone on Niwot (Bueno de Mesquita et al. 2015). We used an information-theoretic criterion (AICc) modeling approach to compare SDMs with the following different sets of predictors: abiotic variables, abiotic variables and other plant abundances, abiotic variables and soil bacteria clade relative abundances, and a full model with abiotic factors, plant abundances, and bacteria relative abundances. We found that inclusion of either plant or bacteria biotic predictors generally improved the fit, deviance explained, and predictive power of the SDMs for the majority of the species. Interactions were both positive and negative, suggesting the presence of competition, parasitism, and facilitation. Plant–plant co-occurrences appear to be a stronger driver of plant distributions than plant–bacteria co-occurrences, but we find that bacteria can explain parts of plant distributions that remain unexplained by abiotic and plant predictors.

To simulate the effects of plants on the microbial community in this largely unvegetated zone, we tested the effects of C, P and N on heterotrophic respiration of talus soils. Results indicate that the addition of plant carbon (e.g., as litter) will increase microbial activity, particularly in combination of N and P (Fig. 10)(Schmidt et al. 2015). We expect that added inputs of C via plants will increase microbial immobilization and N retention as colonization proceeds over time.

![Figure 10. Effects of added C, N and P on heterotrophic microbial activity (total CO2 respired) in microcosms of soil from the subnival zone of the Niwot Ridge LTER site. Only microcosms receiving C in combination with N and/or P had total levels of CO2 accumulation that were significantly different from the control soils. Full respiration curves from the microcosms receiving C and P were previously published (King et al. 2008).](image-url)
II.C) Aquatic Responses in Lakes

We found that aquatic ecosystem structure and function within GL4 varied consistently with the timing of ice-off, such that years with earlier ice-off correlated with slower flushing rates and increases in stratification, conductivity, most major ions, pH, nitrogen concentration, primary production and Daphnia density (Preston et al., in review) (Fig. 11). Mechanistically, observed changes in lake ecosystem structure are likely explained by the effects of climate on hydrology: warming and drying reduce summer stream flow but enhance local glacial and permafrost ablation, increasing late season solute transport through the catchment. The observed links among hydrological, chemical and biological responses to climate warming highlight the ability of lakes to integrate larger-scale ecosystem change and bolster the mechanistic framework for predicting high elevation ecosystem shifts driven by forecasted climate trends.

![Figure 11](image)

**Figure 11.** Correlations of ice-off dates at Green Lake 4 with lake flushing rate (a), thermal stratification (b), pH (c), log-transformed conductivity (d), calcium (e), magnesium (f), log-transformed sodium (g), potassium (h), log-transformed chloride (i), sulfate (j) log-transformed nitrate (k) and log-transformed silica (l). Flushing rate is calculated as lake volume divided by discharge rate. Lake stratification is the difference in water temperature between the surface and 9 m depth. All values are means per year taken over the course of the ice-free summer period (~June/July to August/September, depending on year). Plots with regression lines and 95% confidence bands indicate statistically significant linear regressions (p < 0.05).
To examine a wider geographical range than and complement the long temporal monitoring of Green Lake 4, we expanded sampling into Rocky Mountain National Park (ROMO), just north of NWT. The sampling protocol from the GL4 LTER study was mimicked in ROMO for cross comparison of aquatic communities (Fig. 12). Fifteen lakes were sampled across an elevational gradient multiple times during the ice-off season to capture seasonal variations in lake productivity and community composition. We visited eleven of the lakes three times, and four of the lakes twice during the ice-off period. Water samples were collected from the epilimnion and the hypolimnion of the deepest point of 15 lakes to examine phytoplankton, chlorophyll-a, and water quality (including major ions, dissolved organic carbon, nitrogen, and phosphorus). A vertical zooplankton tow was also conducted at the deepest point of each lake to examine zooplankton assemblages. A vertical profile of water temperature, pH, conductivity, and dissolved oxygen was recorded at one-meter increments from the surface to the bottom of each lake. The remaining water chemistry, chlorophyll-a, phytoplankton, and zooplankton samples will be analyzed throughout the academic year.

**III. Integration and Synthesis.** In 2015, we completed our effort to synthesize and integrate findings of Niwot Ridge in special issue in *Plant Ecology and Diversity*. The issue will be published in 2016, and consists of 15 articles that cover our work in education, hydrology, microbial ecology, limnology and plant ecology. The focus of this special issue is to synthesize alpine research undertaken in the last 20 years at high altitude research sites that comprise the NWT LTER (Figure 12). It is a timely update of the benchmark volume on alpine ecology by Bowman and Seastedt (2001) that presented a summary of work carried out over 40 years on the structure and functioning of the Niwot Ridge alpine terrestrial and aquatic ecosystems. In this Niwot Ridge monograph, the focus is on aspects of temporal changes in the abiotic system and ecosystem structure and functioning, and on reporting new kinds of research and synthesis that have been developed since 1995.

Niwot researchers were also active at the LTER All-Scientists Meeting, helping organize sessions about temporal and spatial variation in NPP, climate synthesis, and linkages with NEON.
IV. Long-term Monitoring and Information Management

CLIMATE. In 2015 we continued to maintain records of meteorological observations from eleven climate stations of varying complexity on and adjacent to Niwot Ridge. The stations range from 2199 to 3814 m in elevation. Six stations are on Niwot Ridge (D1, Saddle, Subnivean, Fahey, Soddie, and C1). Three are in the City of Boulder Watershed (Arikaree, Green Lake 4, and Albion). Two are located below Niwot Ridge in the foothills above the city of Boulder (A1 and B1). Our longest continuous climate records are temperature (measured with thermohygrograph) and precipitation (measured with a Belfort Universal Rain Gauge) from our D1 and C1 stations, located at 3739 and 3022 m respectively on Niwot Ridge, which have been running from 1952 to the present. The D1 site is the highest continuously operating weather station in North America. Methods of observation include electronic environmental sensor data collected with Campbell Scientific or Onset Hobo data loggers at ten minute or hourly time intervals, relayed to a central server via remote RF communication and direct download with a laptop or other communications device, as well as mechanical chart measurements from thermohygrographs and Belfort Universal Rain Gauges, collected by hand on a weekly or biweekly basis. Site instrumentation maintenance and data collection are performed by NWT field manager Jennifer Morse, and field technicians Hillary Buchanan and Henry Brandes.

SNOW AND HYDROLOGY. In 2015 we continued our long-term collection of snow and hydrologic data on Niwot Ridge and the Green Lakes Valley in the City of Boulder Watershed. These data measurements include precipitation, stream discharge, water chemistry from a number of sources and locations, ground water well depth to water levels and water temperature, soil moisture and temperature, lake ice thickness, stream temperature, snow depth measurements, snow melt quantity and chemistry, and snow pit measurements of temperature, grain size, density and chemistry. The majority of these measurements are taken by hand, though soil moisture, temperature, and some stream gauge data are taken with automated electronic sensors and data loggers. Hand measurements and site maintenance were performed by Niwot researcher Nel Caine; field manager Jennifer Morse; field technicians Hillary Buchanan, Henry Brandes; graduate student Kelsey Daily; the Snow Intern program through the University of Colorado Geography Department; and volunteers during the annual NWT LTER Green Lakes Valley Snow Survey.

Stream discharge data is collected through both hand and electronic pressure transducer measurements at six locations: Green Lake 4 outlet, Martinelli, Saddle Stream, Albion, Watershed Flume, and Como Creek weir. Stream flow data for Green Lake 4 and Albion are our longest records, and data are available for these locations beginning in 1981.

Water chemistry data are produced through lab analysis of water samples collected by hand from the field. Sources include surface water, talus water, soil lysimeters, ground water wells, snow melt lysimeters, and snow collected from snow pits and melt water for analysis. Each sample is analyzed for inorganic nutrients (calcium (Ca2+), magnesium (Mg2+), sodium (Na+), potassium (K+), manganese (Mn), ammonium (NH4+), lithium (Li), chloride (Cl-), nitrate (NO3-), nitrite (NO2-), sulfate (SO42-), ortho-phosphate (PO43-), bromide (Br-), fluoride (F-) and silica (Si)) DON, DOC, DOP, 18O, deuterium and fluorescence index. Water chemistry is analyzed for the following samples:
• **Surface water** samples are collected at bi-weekly to monthly intervals (seasonally dependent) at all discharge measurement sites, as well as ten other sampling sites: Saddle Stream 007, Soddie Stream, Como Creek at s-curve, Como Creek at C1, Arikaree, Navajo Bench, rock glacier, Green Lake 5, and Green Lake 5 wetlands inlet and outlet.

• **Talus water** samples are collected at three sites on the northwestern slopes above Green Lake 4, and one site on the southern slopes above Green Lake 4.

• **Soil lysimeters** are sampled throughout the summer following snowmelt through mid-September when the majority of lysimeters have gone dry. At higher elevations in the Green Lakes Valley we began sampling in July. For lower elevations sampling could begin as early as mid-June. There are fifteen sampling locations on Niwot Ridge and the City of Boulder Watershed comprising sixty-one soil water lysimeters.

• **Ground water well** samples are collected monthly in winter and weekly in spring, summer, and fall from three different sites comprising twenty six wells. Two sites are located on Niwot Ridge at our Saddle and C1 stations, and a third site is located below the Martinelli snow field in the City of Boulder Watershed.

• **Snowmelt lysimeters** are located at the Subnivean and Soddie meteorological sites. Samples are collected daily from a total of eight lysimeters during snowmelt, roughly mid-May through the end of June.

• **Snow pit** samples are collected weekly during the winter from the Subnivean and Soddie sites. Samples are representative of the snow pack from the surface of the snow to the ground. Snow pit samples were also collected from six sites in the Green Lakes Valley in mid-May during the annual Green Lakes Valley Snow Survey.

**VEGETATION.**

**Saddle (alpine) and treeline surveys.** We continued recording alpine plant species composition in the 88 permanently marked Saddle grid vegetation plots, along with collection of net primary productivity (NPP) samples in designated locations near grid plots. Species composition and NPP have been measured yearly in the Saddle from 2010 to 2015; less frequent sampling was conducted from 1989 (the year of establishment of the saddle grid) to 2008. Sampling of permanently marked treeline transects was conducted in 2015 by Dave Buckner (ESCO Associates), for a total of 6 consecutive years of sampling.

**Snowbed elevation transect.** We continued monitoring plots established in 2012 to survey plant communities in areas of late-melting snow along an elevational gradient at Niwot Ridge. The goal is to document changes in plant community composition due to warming temperatures and earlier snowmelt, which will cause transitions from primarily snowmelt-fed, growing season length-limited communities to rain-fed communities with longer snow-free periods for growth. Plots at five different snowbed sites were censused for vegetation composition using the point intercept method. We also established 20 new experimental plots at each snowbed site in order to investigate the effects of N and P nutrient additions on plant colonization in currently unvegetated snowbed areas. Nutrient additions were applied for the first time in the summer of 2014. These plots will be revisited annually to continue treatment applications and survey plots for plant colonization.

**LAKES.** During the 2015 field season, we conducted weekly lake sampling over a period of 7 weeks from mid-July until the end of August. These analyses are performed every year at specific depths and locations in Green Lake 4 to capture important characteristics of the lake system and possible changes. Target depths and/or locations include the inlet and the outlet of Green Lake 4 as well as surface water, 3 m and 9 m. The following baseline limnological data were collected: 1) chlorophyll-a, 2) phytoplankton; 3) dissolved organic carbon (DOC) concentration, 4) dissolved organic matter (DOM) quality by fluorescence, 5) dissolved anion and cation concentrations, 6) hydrogen ion concentration (pH), 7) dissolved oxygen (DO),
8) conductivity, and 9) temperature. To characterize changes in the zooplankton community and how they correlated with phytoplankton patterns, we used a vertical net tow at the deepest point of the lake during each visit. Samples were preserved for subsequent identification and enumeration.

To identify phytoplankton and zooplankton, we are using a unique flow cytometer paired with a Digital Imaging System called a FLowCAM. By acquiring and storing a digital image of each particle detected, different particle types in a heterogeneous sample can be automatically identified, differentiated and quantified. The examination of numerous samples at larger volumes in a shorter amount of time, as well as automated identification of particles using a recognition algorithm and calculation of concentration, size, volume etc. are only some of the advantages this instrument is bringing about.

Continuing in 2015, Katherina Hell, a Professional Research Assistant, led the field sampling of the lakes in Green Lakes Valley. Katherina is also in charge of sample processing and analyses, including phytoplankton and chlorophyll-a sample processing and analysis, data management, and mentoring of students working on the project (e.g. students from REU programs, volunteer high school students and prospective graduate students). Graduate student Kim Vincent was also involved with the lake sampling.

**INFORMATION MANAGEMENT:** Hope Humphries, NWT’s Information Manager, attended the annual meeting of LTER Information Managers, held during the All Scientists Meeting in Estes Park, CO, August 30 to September 2. New long-term data sets posted to the NWT website in 2015 include pika demography data, snowbed plant species composition data, saddle stream water chemistry data, hourly saddle climate data, and atmospheric ozone concentration data. Humphries, field manager Jennifer Morse, and graduate student Dominik Schneider have continued work on the application of quality assurance/quality control (QAQC) criteria in the use of the GCE Data Toolbox for processing raw climate data, including generation of data at different time intervals.

The redesign of NWT’s website was finished and the new website was launched in March 2015, containing new webpages produced by Eric Parrish, web developer, for data, locations, personnel, publications, news, research information, videos, outreach, webgraphs, and photo galleries, among others. The website is averaging 780 page views per week since the launch. Our steerable TundraCam ([http://instaar.colorado.edu/tundracam/](http://instaar.colorado.edu/tundracam/)), continues to be a popular destination for users of the website, and visitors also comment favorably on the near real-time display of climate data from multiple NWT sites.

**V. Education and Outreach.**

NWT LTER serves a broad audience through a wide variety of educational programs and online resources. Here we outline 2015 NWT education and outreach activities for K-12 students and teachers, undergraduate students, colleagues within and outside the LTER Network, resource managers, journalists, and the broader community. We also welcome our new outreach and education director, Alex Rose.

The University of Colorado’s newest promotional video features Niwot Ridge LTER technician, Henry Brandes, and graduate student, Kelsey Dailey, doing field work at dawn on Niwot Ridge. The video will air at halftime for basketball and football games (Figure 14).

We have also engaged with the public on site at the LTER by giving research tours and presentations to more than 800 individuals who have used the Mountain Research Station facilities.
After the massive flooding events of 2013 destroyed many homes in mountain communities, LTER researchers connected with community stakeholders in mountain communities to help with strategic planning for resiliency and adaptability.

**PLANT-IDENTIFICATION APP.** After a year-long collaborative project with Computer Science undergraduate students (Jamie Miller, Brian Bauer, Morgan Garske, Jacob Rail, Andrey Shprengel, Jack Skinner) in CS’s Senior Design Course and postdoc Jane Smith from INSTAAR, ENVS PhD student Nathalie Chardon recently launched the Luminous ID app (luminousid.com). This app serves as both an alpine plant field guide, and can recognize the alpine cushion plant *Silene acaulis*. The field guide currently consists of flowering plants occurring on Niwot Ridge, and the filtering function allows users to quickly narrow down a list of possible species. The identification algorithm encoded within the app immediately tells users if they’ve taken a picture of *S. acaulis*, and this information is uploaded to a server along with GPS coordinates of the user’s location. As *S. acaulis* is a common alpine species found throughout the northern hemisphere, this will be incredibly useful in mapping the species' widespread distribution. Coupled with climate and topographical data, the data generated from this citizen science project will be invaluable in answering questions about the distributional constraints on this species.

**CURRICULA AND OUTREACH FOR K-12 STUDENTS.** Using our two schoolyard books, My Water Comes from the Rocky Mountains and My Water Comes from the San Juan Mountains, as the primary educational tools, we have partnered with nine educational organizations and two school districts in the Front Range and Four Corners regions of Colorado to link our research to K-12 curricula. The books and associated classroom and teacher professional development curricula have reached an estimated 15,000 children and 90 teachers (Ray et al. 2015).

In Boulder County, several of the most popular components of the My Water curriculum have been adapted to be included in a kit designed for teaching about weather and the water cycle. This kit is now in use in every 5th grade science classroom in the Boulder Valley School District. Our schoolyard LTER program is also enhanced by online curricula about hydrology and pika biology, available to teachers worldwide via [www.Science-Live.org](http://www.Science-Live.org).

Three LTER Graduate Students worked with 25 middle school students and their teachers during the summer of 2015 as part of the Nederland Summer School’s “Camp Reach” program. Students came from an underserved mountain community close to the Mountain Research Station and graduate students taught them about ecology, ecosystems, graphing skills, soil science, and math.
We partnered with the Boulder Creek Critical Zone Observatory and CU's Science Discovery Program to support development of a summer camp, "Our Watershed", that taught approximately 60 9-14 year olds from the Colorado Front Range and Denver Metro Area about water sources and uses in the Boulder Creek Watershed.

In response to flooding in mountain communities in 2013, LTER researchers developed STEM curricula for these communities' schools around landscape vulnerability, adaptability and resilience (Fig. 15).

Over 200 middle and high school students were welcomed annually into LTER laboratory facilities on the CU campus during open houses.

In partnership with CU Science Discovery, 12 high school students from Colorado, Tennessee, and Paris, France attended a week long field course called the Mountain Research Experience. The students worked closely with LTER PIs and graduate students to get hands-on experience studying alpine and sub-alpine ecology and ecosystem processes.

**MENTORING UNDERGRADUATE STUDENTS.** REU programs organized by the Mountain Research Station REU Site supported 11 MRS REU students and 4 NWT REU students during 2015. Most of these students were mentored by NWT faculty. Students lived at the MRS and participated in intensive classes as well as independent and group studies and a final, oral presentation to the group. A strong emphasis was placed on recruiting diverse REU students from backgrounds under-represented in STEM fields.

Field courses on topics ranging from Limnology to Winter Ecology brought approximately 50 undergraduates to the Mountain Research Station for several weeks this year.
References Cited.


