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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

WILEY

Catchment-scale observations at the Niwot Ridge long-term ecological research site

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Abstract

The Niwot Ridge and Green Lakes Valley (NWT) long-term ecological research (LTER) site collects environmental observations spanning both alpine and subalpine regimes. The first observations began in 1952 and have since expanded to nearly 300 available datasets over an area of 99 km^2 within the north-central Colorado Rocky Mountains that include hydrological ($n = 101$), biological ($n = 79$), biogeochemical ($n = 62$), and geographical ($n = 56$) observations. The NWT LTER database is well suited to support hydrologic investigations that require long-term and interdisciplinary data sets. Experimentation and data collection at the NWT LTER are designed to characterize ecological responses of high-mountain environments to changes in climate, nutrients, and water availability. In addition to the continuation of the many legacy NWT datasets, expansion of the breadth and utility of the NWT LTER database is driven by new initiatives including (a) a catchment-scale sensor network of soil moisture, temperature, humidity, and snow-depth observations to understand hydrologic connectivity and (b) snow-albedo alteration experiments using black sand to evaluate the effects of snow-disappearance on ecosystems. Together, these observational and experimental datasets provide a substantial foundation for hydrologic studies seeking to understand and predict changes to catchment and local-scale process interactions.

KEYWORDS

alpine, catchment, climate, climate, ecology, high-resolution, hydrology

1 | DATA SET NAME

Niwot Ridge long-term ecological research dataset.

2 | INTRODUCTION

The Niwot Ridge and Green Lakes Valley (NWT) long-term ecological research (LTER) site encompasses several catchments spanning alpine and subalpine zones in the north-central Colorado Rocky Mountains. Such catchments provide a vital natural reservoir for mountain source waters and snowmelt generated runoff (Cayan, 1996; Mote, 2006; Mote et al., 2018). High elevation regions are among the most sensitive to climate change and present a valuable testbed for evaluating climate impacts on hydrology and ecology (Barnett et al., 2005; Cayan, 1996; Clow, 2010; Livneh et al., 2015; Livneh & Badger, 2020; Pepin & Losleben, 2002; Sexstone et al., 2018; Vano, 2020), but comprehensive in situ observations in these extreme environments are rare. Hydrologically relevant observations collected at the NWT LTER include: 68 years of daily and hourly observations of meteorology, 30+ years of snow depth and distribution observations, multiple surveys of soil characteristics, a spatially dense sensor array of collecting sub-hourly observations of catchment soil moisture and temperature, stream gauge observations, and several experiments designed to evaluate the drivers and consequences of long-term ecological and biogeochemical trends. The unique spatiotemporal density of hydrological and ecological observations paired with multi-decadal climate records make the data collected at the NWT LTER particularly well suited for research that seeks to understand catchment-scale ecohydrological processes in alpine and subalpine environments.

3 | SITE DESCRIPTION

The NWT LTER site is located in the southern Rocky Mountains of North America (40.05°N, 105.59°W; Figure 1). The sub-alpine Niwot Ridge Saddle catchment (Area: 0.6 km^2; Maximum elevation: 3528 m), located 5.6 km east of the continental divide, receives a majority (~80%) of its approximately 1035 mm of annual precipitation as snow (Bowman & Seastedt, 2001; Caine, 1995; Greenland, 1989; Jennings et al., 2019). The alpine Green Lakes Valley catchment (Area: 2.3 km^2; Maximum elevation: 3745 m), which feeds into the Green Lakes and Lake Albion, receives 1200 mm of precipitation, slightly more annual precipitation than the Saddle catchment (Jennings et al., 2019). Average daily temperatures of −8.8°C in the winter season and −0.5°C in the summer season (Jennings et al., 2019) support persistent snowpacks in the NWT LTER catchments through much of the year and a short growing season for the alpine vegetation (1–3 months; Jones et al., 2001). Annual records of daily gauged streamflow extending back nearly 40 years begin each year with the onset of snowmelt in the mid to late spring and continue into the fall.

The NWT LTER is regionally located adjacent to and interconnected with several other hydroclimate research sites that are not explicitly a part of the LTER but are valuable resources for hydrological and ecological research. The Niwot Ridge AmeriFlux tower (Blanken et al., 2016), located downslope of the Saddle catchment in the sub-alpine region of the LTER, was established in 1998 and generates atmospheric flux observations that have been used in conjunction with data produced at the NWT LTER to evaluate ecohydrological interactions (Knowles et al., 2015). Additional

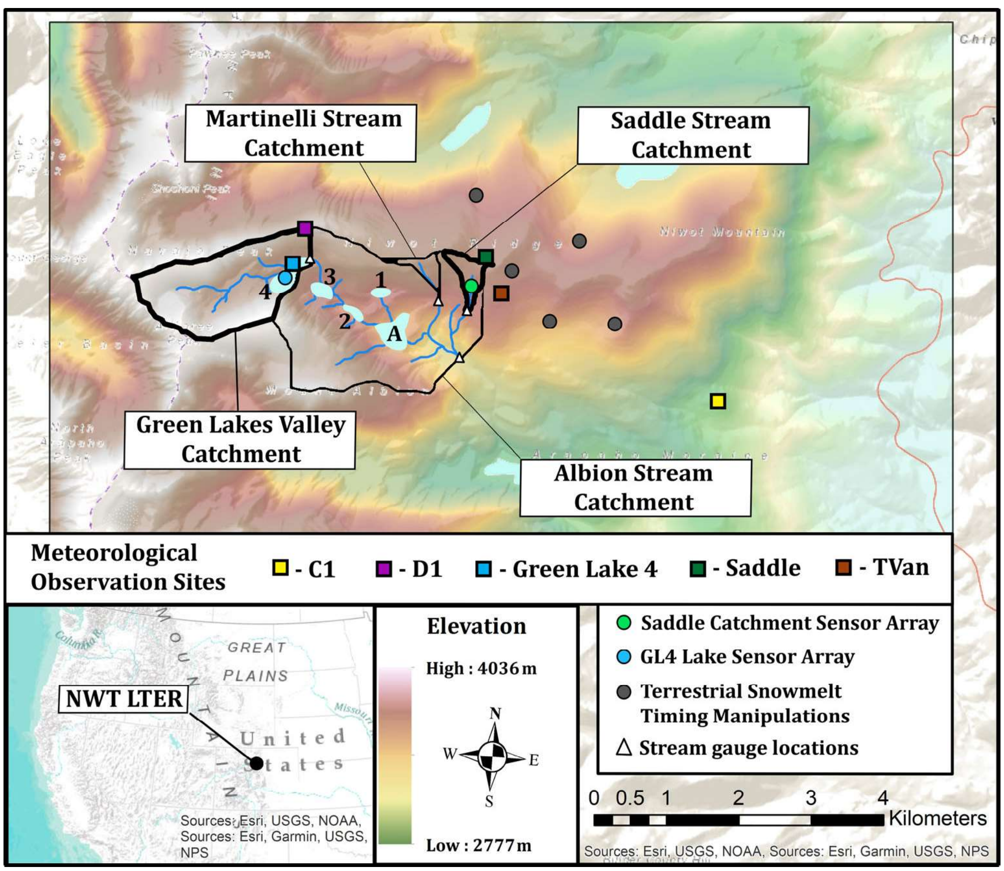

FIGURE 1 Map of Niwot Ridge and Green Lakes Valley long-term ecological research site—description. The NWT LTER coloured by elevation derived from a 10-m resolution digital elevation map. The boundaries of the Albion Stream, Green Lakes Valley, Martinelli Stream, and Saddle Stream catchments are highlighted with black borders, the stream path that connects the catchments is indicated in blue, and lakes are shown in light blue. The Green Lakes (1–4) are labelled with their identifying number and Lake Albion is indicated with an 'a'. The saddle catchment sensor array (green), GL4 Lake sensor array (blue), and terrestrial snowmelt timing manipulation experiments (grey) are shown with coloured dots. Coloured squares indicate the location of the meteorological observation sites and white triangles indicated the location of stream gauge for each catchment. The location of the NWT LTER within the continental United States is shown in the lower left inset

atmospheric, hydrological, and ecological observations are available for both the alpine and sub-alpine domain adjacent to the Niwot Ridge LTER at the Como Creek field site as part of the National Ecological Observatory Network (NEON). The Como Creek research site and the Critical Zone Observatory site, located in the higher elevation region of the NWT LTER, provide valuable observations of ecological composition and subsurface characteristics that are vital for subsurface hydrology research (Hermes et al., 2020; Leopold et al., 2008; Williams et al., 2009). Though these data are not the focus of this data note, we point to descriptions and links to data portals for all of these regional research sites found on the Niwot Ridge LTER website (https://nwt.lternet.edu/other-niwot-datasets) and acknowledge their importance to advances in hydrological research in the Niwot Ridge region.

4 | LONG-TERM HYDROCLIMATE DATASETS

Hydro-climate data were first collected at the NWT LTER in 1952 and have since expanded to nearly 300 available datasets over an area of 99.125 km^2 that include hydrological ($n = 101$), biological ($n = 79$), geographical ($n = 56$), and biogeochemical ($n = 62$) observations (Figure 2). Here we emphasize active datasets identified as being the most spatio-temporally unique and relevant to hydrological catchment research but encourage exploration and use of the hundreds of current and legacy datasets collected and stored on the publicly accessible NWT LTER database (https://nwt.lternet.edu/data-catalog). Emphasized hydrological datasets and other major datasets relevant to catchment hydrology (all of which have published data on the NWT LTER data catalogue) are described briefly in Table 1.

4.1 | Stream discharge and chemistry

Gauged stream discharge values are computed at daily resolution from stage observations for four major streams (Albion, Green Lake 4, Martinelli, and Saddle) in the NWT LTER alongside weekly to monthly observations of water chemistry (Table 1). Field measurements of stage are taken as the water depth at the centre of a 120° V-notch plate fixed to a timber weir structure (Caine et al., 2020). A stilling well is installed and removed each season due to harsh winter conditions, so seasonal recalibration of the rating curve is conducted and recorded in the metadata package for each of the streamflow datasets. Instantaneous discharge rates are calculated at a 10-min sampling rate using the calibrated stage-discharge relationship derived for each stream (Caine et al., 2020). Daily discharge volume is then calculated for each 24-h period by taking the mean of flow rates sampled at 10-min intervals. As with many of the long records of

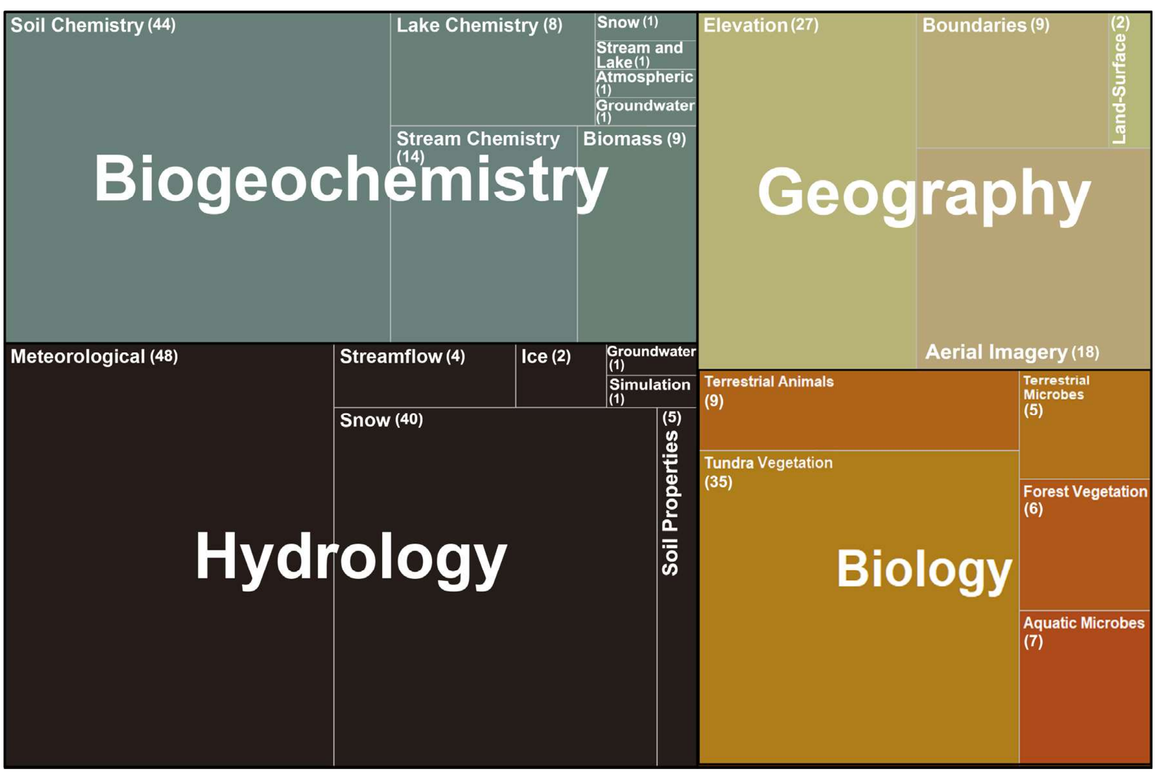

FIGURE 2 Proportion of Niwot Ridge LTER datasets available for each discipline. Description. All 298 datasets in the NWT LTER data catalogue were sorted into categories based on the abstract and observations contained within the datasets. Each dataset is categorized first by the major discipline that the observations fall under and then is sub-categorized based on the type of observations available in the dataset. We highlight here the diversity of the observations collected at the NWT LTER and note that a majority of the observations that fall outside of the 'hydrology' discipline are still hydrologically relevant and are potentially valuable tools for hydrological analyses

TABLE 1 Summary of hydrological observations at Niwot Ridge long-term ecological research site

Station ID	Observed variables	Length of record	Frequency of observations	Instrumentation	Uncertainty
Meteorology and climate					
C1	Precipitation, air temperature, relative humidity, barometric pressure, wind speed and direction, solar radiation[†]	1952–Present	Daily	Belfort precipitation gauge (Baltimore, MD), U.S. Weather Bureau standard unshielded 8-in rain gage, 594 hygrothermograph; Campbell Instruments meteorological recorders and sensors (Logan, UT), RM Young Anemometer (Traverse City, MI), Geonor precipitation gauge	*Barometric pressure*: accuracy ±0.3 hPa *Air temperature*: accuracy ±0.226–0.0028[†]reading (°C) at −80°C to +40°C *Relative humidity*: accuracy ± (1.0 + 0.008[†]reading) % RH at −20 to +40 (°C) *Wind speed*: accuracy ±0.3 m/s *Wind direction*: accuracy ±3° *Precipitation*: accuracy ±0.1 mm
D1		1952–Present	Daily		
Saddle		1981–Present (daily), 2009–Present (hourly)	Daily/Hourly		
Green Lake 4	Air temperature, relative humidity, wind speed, wind direction, solar radiation[†]	1997–2019	Daily		
Tvan	Heat flux, solar radiation, relative humidity, wind speed, wind direction, atmospheric pressure	2008–Present	Daily		
Snow water equivalent and snow depth					
Snow pits	Snow depth, snow density, and snow water equivalent along with measurement coordinates	1993–Present	Seasonal	1000-ml cutter, snow shovel	Uncertainty in manual measurements can vary depending on operation and conditions, but estimates from Dixon and Boon (2012) suggest that standard error of SWE ranges from 0.2 to 0.3 cm depending on instrumentation
Snow depth surveys	Snow depth and GPS coordinates for measurements	2013–Present	Annual	Garmin eTrex Legend GPS (Taiwan), avalanche probes	
Snowmelt timing manipulations	Snow depth	2018–Present	Hourly	Handheld snowdepth probe	
Soil moisture and temperature					
Saddle sensor node array	Soil moisture and temperature at 5 and 30 cm depths	2017–Present	10-min	Meter Group—GS1 soil moisture sensor, RT-1 soil temperature sensor (Pullman, WA)	*Soil temperature*: accuracy ±1°C from −40°C to −20°C, ±1°C from 5°C to 40°C *Soil moisture*: accuracy ±0.03 m^3/m^3
Snowmelt timing manipulations	Soil moisture, temperature, and electrical conductivity at 5 cm depth	2018–Present	Hourly	Meter Group—Teros 12 sensors (Pullman, WA)	
Streamflow					
Albion stream	Discharge volume	1981–Present	Daily	Leupold-Stevens float recorder, Omnidata recorder, Keller 1 psi pressure transducer, Campbell Instruments data loggers (Logan, UT)	Uncertainty in the instantaneous flow measurements have been estimated to be ±1 L/s due to compounding errors in stage measurements and calibration of rating curve (Caine et al., 2020). Estimates of discharge are subject to wider error during periods of high flow
Green Lake 4 Stream		1981–Present		Timber weir with a 120° V-notch plate, Omnidata data loggers, Campbell Instruments data loggers, Campbell	
Martinelli stream		1982–Present			
Saddle stream		1999–Present			

TABLE 1 (Continued)

Station ID	Observed variables	Length of record	Frequency of observations	Instrumentation	Uncertainty
				Scientific pressure transducers (Logan, UT)	
Lake and stream chemistry					
Green Lake 4	Temperature, dissolved oxygen (DO), photosynthetically active radiation (PAR), Chlorophyll-a	2018–Present	30-min	PME miniDOT sensors (Vista, CA), RBR solo3 T sensors (Ottawa, ON), LI-COR quantum sensor, Turner Designs Cyclops 7 submersible sensor (Sunnyvale, CA)	*pH*: accuracy ± pH 0.1 *Conductance*: accuracy ±0.5% *TOC and DOC*: accuracy ±1.5% *Spectrometry*: accuracy ±0.5 nm Ion/atomic concentration uncertainty is dependent on instrumentation and conditions. Detailed metadata of uncertainty can be found on the NWT LTER data portal for each individual data package
Albion stream	pH, conductance, ANC, NH4+, Ca++, Mg++, Na+, K+, Cl−, NO3−, SO4−−, PO4−−, Si, TOC, DOC, Tritium, d18O, DOP, TON, TDN, ANC	1982–Present	Weekly–monthly (irregular)	Manual titration, Accumet pH meter, Perkin Elmer AAnalyst 200 Atomic Absorption Spectrometer, Thermo Finnigan FLASH EA 1112 CHN Analyzer, Metrohm 930 Compact IC Flex, Biotek Synergy 2 Multi-Detection Microplate Reader, Shimadzu TOC-V, CSNMettler Toledo SevenEasy Conductivity Meter	
Green Lake 4 stream		1982–Present			
Martinelli stream		1984–Present			
Saddle stream		1994–Present			

Metadata summarized here is accessible through the NWT LTER Data Portal (https://nwt.lternet.edu/data-catalog). Observations of all variables described are available on the data portal along with documentation of data quality, collection practices, and instrumentation changes. We emphasize that uncertainty of individual datasets are based on time varying instrumentation and frequency of observations, and listed numerical values of uncertainty are used as a reference based on modern instrumentation. Uncertainty estimates are based primarily on documentation from instruments used to collect hydrometeorological data. †Values of air temperature, relative humidity, barometric pressure, windspeed, and solar radiation are reported with the minimum, maximum and average values for each collected time step. Quality-control flags are present for all data and documented for each data set in the NWT LTER data catalog.

hydroclimate data produced in the NWT LTER, there is time varying uncertainty of observations as instrumentation and data collection protocols evolve, but information on modern instrumentation and estimates of uncertainty are included in Table 1.

These long records of stream observations are valuable for the validation of the performance of hydrological (Biondi et al., 2012; Du et al., 2014) and hydrochemical (Molotch et al., 2008) model simulations of alpine and sub-alpine catchment hydrological processes. Furthermore, the combination of chemical and volumetric streamflow observations has been used to understand changes to the contribution of glacial melt to surface runoff (Barnes et al., 2014; Leopold et al., 2011) and changes in carbon respiration and nitrification (Barnes et al., 2014; Blanken et al., 2009; Knowles et al., 2015; Liu et al., 2004) for alpine tundra under a changing climate.

4.2 | Long-term climate observations

Daily observations of precipitation and temperature are available from 1952 to present for the D1 meteorological station that is located at the head of the Green Lakes Valley catchment and the C1 sub-alpine meteorological station located below tree-line. In addition to the raw observations, temporally infilled and continuous records of daily temperature (Kittel et al., 2019a, 2019b) and precipitation (Kittel et al., 2019c, 2019d) are available on the NWT LTER data catalogue. Data infilling follows the approach described in Jennings et al. (2019) in which missing data were infilled using least-squares linear regression models with daily observations from nearby meteorological stations. Daily precipitation and temperature observations beginning in 1981 for the Saddle meteorological station, located at the head of the Niwot Ridge Saddle catchment, were updated to hourly frequency in 2009. Observations of relative humidity, wind speed and direction, atmospheric pressure, and solar radiation are available at daily or hourly frequencies at the aforementioned meteorological stations in addition to more recently developed sites (Table 1).

5 | HIGH-RESOLUTION OBSERVATIONS

Within the last 5 years, two high-resolution observation arrays have been established and produce observations relevant to catchment-scale hydrology research: the Saddle Catchment Sensor Array and the Green Lake 4 Sensor Array. These datasets are highlighted here due to the uniquely high spatial and temporal density of observations collected as part of the research framework.

5.1 | Saddle catchment sensor array

A high-density array of sensor nodes, installed in 2017, collects observations of soil moisture and temperature within the Niwot Ridge Saddle catchment at a 10-min frequency. Sixteen sensor nodes are each equipped with a three-part transect of sensors that measures soil temperature and moisture at 5 and 30 cm depths, for a total of six observation points at each node, following methods outlined in Kerkez et al. (2012). These high spatiotemporal resolution soil observations in the Saddle catchment can help constrain uncertainties in the distribution of subsurface water (Grayson et al., 1997; Western et al., 2004) and can be used to further understand the role of catchment-scale soil moisture variability as it relates to runoff generation and hydrologic connectivity (Western et al., 2004; Williams et al., 2015).

5.2 | GL4 lake sensor array

To better document spatial and temporal variation in alpine lake systems, both within and among seasons (including under ice), an instrumented buoy line was deployed with sensors at fixed depths in Green Lake 4 (Figure 1) in early summer 2018. The sensor line was positioned in the area of greatest depth and contained eight RBR soloT sensors to record water temperature, three PME miniDOT sensors to record dissolved oxygen, one PME miniPAR sensor to record photosynthetically available radiation (PAR) and a Cyclops 7 from Turner Designs to optically measure in situ chlorophyll-a. Available data from summer 2018 and winter 2018–2019 have revealed the establishment and erosion of stratification in GL4, which previous 'snapshot' sampling did not detect. Given that alpine lakes such as GL4 are typically frozen for >200 days per year, this depth-stratified sensor array provides high-resolution limnological data and valuable insights into lake temporal dynamics during a period often difficult to sample directly.

6 | MANIPULATION EXPERIMENTS

Plot scale experiments, established in 2018, are conducted annually at the NWT LTER to evaluate the hydrologic and ecologic impacts of accelerated snowmelt and warmer alpine temperatures driven by climate change. Albedo and organic composition of snow/ice are modulated at several terrestrial and aquatic sites, paired with high-resolution observations of soil characteristics, snow depth, and biological composition.

6.1 | Terrestrial snowmelt timing manipulations

Beginning in 2018, 'black sand' experiments were conducted to reproduce and observe the effects of changing snow albedo on snowmelt timing and subsequent soil moisture by applying varying volumes of black sand to snow-covered plots equipped with soil moisture sensors (Blankinship et al., 2014; Bueno De Mesquita, 2019). Hourly observations of soil moisture, soil temperature, and electrical conductivity are collected at four locations for each of the five habitat sites along with sub-weekly (∼every 3 days) observations of snow depth for each of the sites. These terrestrial experiments are motivated in part by observed changes in snow albedo associated with dust-on-snow events, resultant from human activities (Neff et al., 2008), shown to impact the timing of peak snowmelt in the Western US (Deems et al., 2013; Livneh et al., 2015; Painter et al., 2010; Skiles et al., 2012). Furthermore, the snowmelt timing experiments build on a legacy of research at the NWT LTER focused on understanding the sensitivity of snowmelt and sublimation to radiative and turbulent fluxes (Cline, 1997), redistribution by wind (Berg, 1986), and topographic controls (Litaor et al., 2008).

6.2 | Megacosms: Experimental manipulation of ice cover and dissolved organic matter

In September 2019, an experimental array of 20 large-volume (2600 L) megacosms were positioned at a high-elevation (3290 m above sea level) site in the Boulder Creek Watershed. This represents the highest established megacosm experiment in North America and provides an aquatic analog to the Black Sand experiments that are conducted in the terrestrial plant communities. Half of the megacosms are made of a plastic, light in colour (control), while half are black (warmed), creating an albedo difference that is expected to drive variation in both ice-off date and water temperature (based on pilot experiments). The experiment also manipulates dissolved organic material (DOM) through the addition of willow-leaf packs, thereby mimicking forecasted advances in terrestrial vegetation around alpine lakes—which is expected to help mitigate the extreme UV effects common to such high-elevation environments. Each of the four treatments (light vs. dark tanks, enhanced vs. ambient DOM) are replicated five times in all factorial combinations (i.e., a 2×2 manipulation with five replicates per condition = 20 megacosms). Megacosms were seeded with lake sediment and zooplankton and are intended to run for 2 years. It is expected that higher temperatures, longer growing seasons, and higher DOM will function to 'soften' the harsh abiotic limitations inherent to alpine systems, leading to greater planktonic production (Chl-a and zooplankton biomass) and lower water clarity. Additionally, megacosm experiments are designed to observe expected shifts in zooplankton community composition and body size with warmer water and lessened UV stress, although whether these will be additive or interactive is uncertain.

7 | DATA

7.1 | Contributors and ownership of the data

A list of all contributors to the creation of the Niwot Ridge LTER data base is as follows: Katharine Suding, Nancy Emery, Pieter Johnson, Noah Molotch, Jason Neff, Brent Bednarik, Sarah Elmendorf, Sander Aplet, Stephanie Dykema, Jennifer Morse, Alexandra Rose, Jane G. Smith, Meagan Oldfather, Peter Blanken, Diane McKnight, Marko Spasojevic, William Bowman, Chris Ray, Scott Taylor, Steve Schmidt, T. Nelson Caine, Timothy Seastedt, Thomas Veblen, Eve-Lyn Hinckley, Will Wieder, Ben Livneh, Ryan Webb, Becca Barnes, Emily Farrer, Eric Frew, Katja Friedrich, John Knowles, Lara Kueppers, Daniel Liptzin, Iggy Litaor, Nicole Miller-Struttman, Kamini Singha, Carol Wessman, Andrew Badger, Courtney Collins, Anne Marie Panetta, Kyle Christianson, John Crawford, Jared Anderson-Huxley, John Berggren, Nels Bjarke, Laurel Brigham, Kelly Carscadden, Rachel Chai, Youchao Chen, J. Bryan Curtis, Chiara Forrester, Eli Gendron, Katherine Hale, Anna Hermes, Molly Huber, Hannah Miller, Stephanie Redfern, Will Reed, David Rey, Annika Rose-Person, Samuel Rossabi, Jenna Stewart, Angela Theodosopoulos, Kim Vincent, Caitlin White, Qinghuan Zhang, Patrick Gourgeron, Lara Kueppers, Detlev Helmig, Mark Williams, Robert Andrus, Joshua Grinath, Teal Potter, Curtis Beutler, Laurn Hallett, Dominik Schneider, Cliff Bueno de Mesquita, Amber Churchill, Nathalie Chardon, Youchao Chen, Rory Cowie, Jack Darcy, Josh Darling, Kelsey Elwood, Eva Gasarch, Ruth Heindel, Alice Hill, Holly Hughes, Cara Lauria, Matther Olivier, Devan Pensinger, Eric Sokol, Lara Vimercati, Katherine Wentz, Ashley Whipple, and Alana Wilson.

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DATA AVAILABILITY STATEMENT

The data collected at the Niwot Ridge and Green Lakes Valley are stored and publicly accessible through the Niwot Ridge LTER data catalogue (https://nwt.lternet.edu/data-catalog). All datasets include documentation of data collection practices, instrumentation, collection site information, and quality control information. In addition to the raw data, multiple temporally infilled and quality-control filtered datasets exist alongside documentation of the methods used to generate those datasets. This information is released under the Creative Commons license—Attribution—CC BY (https://creativecommons.org/licenses/by/4.0/). The consumer of these data ('Data User' herein) is required to cite it appropriately in any publication that results from its use. We want to emphasize that newer datasets described in this manuscript are available on the Niwot Ridge LTER data catalogue and are updated on a regular schedule as data are collected and processed. A search of the specific terms related to each of the datasets or experiments will return all relevant data packages on the data catalogue with each package containing information including title, creators, publication date, citation, abstract, spatial coverage, and metadata entries that describe methods and protocols for the data collection. Stream discharge data: Albion—10.6073/pasta/c97ebc3cd06ff3d8a19e31f56b23d10b; Green Lake 4—10.6073/pasta/24036687a2942822976dd5a4f94ca3f2; Martinelli—10.6073/pasta/64719f0f4fcaafc8860a8828e825d438; Saddle—10.6073/pasta/657d1d174636681d7a7430344b121175. Meteorological data:

D1—10.6073/pasta/1b62f2cda71579c4870ac5c1af71e6f3; C1—10.6073/pasta/6b8288f9498b00cf4f2156a3fefc1b72; Daily Saddle—10.6073/pasta/0bf785f2f77c3f558f633853a4465404; Hourly Saddle—10.6073/pasta/09ee081d2bf08f50c2a30e1e2b4c9d04; Infilled meteorology for Saddle, C1, and D1—10.6073/pasta/0bf785f2f77c3f558f633853a4465404. Saddle catchment sensor array: 10.6073/pasta/9415ac5a669c11c6501612a94f90e04a. GL4 sensor array: Temperature sensors—10.6073/pasta/3e1a61e877f1e63f013a3f890841f702; DO sensors—10.6073/pasta/d40ce19c07e89bbf5870f282a21a93e9; PAR sensors—10.6073/pasta/c99e2149c63fd58c463577f84adf4139; Chlorophyll-a sensors—10.6073/pasta/ef0a80b1500c692338df74730a6c6d82. Terrestrial snowmelt timing manipulations: Snow depth—10.6073/pasta/4a08e4abec654a9f725b07593bce8b8c.

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