

Mountain Views

Chronicles of the Consortium for Integrated
Climate Research in Western Mountains
CIRMOUNT



Informing the Mountain Research Community

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Fourth Lake in the Palisades, Sierra Nevada, California. Photo: Jeff Wyneken

Front Cover: Finger Lake and Sawtooth Range, Sierra Nevada, California. Adrienne Marshall.

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Back Cover: Unnamed tarn below Sierra crest, John Muir Wilderness. Photo: Steve Sadro.

Read about the contributing artists on page 91.

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EDITOR'S INTRODUCTION

My first job with the U.S. Forest Service was as a seasonal Wilderness Ranger during the early 1970s in the Three Sisters Wilderness on the Willamette National Forest in the Cascades Mountains of Oregon. I was one of two rangers hired to uphold the newly minted Wilderness Act, and between the two of us, we were rather unsure of our on-the-ground responsibilities. Soon it became clear that we had plenty to do if we hung out around the mountain lakes, for that was where backpackers and horsepackers came, fished, and camped. Our job evolved to be one of protecting mountain waters: moving campsites and latrines back from lake shores and inlet streams, designating horse camps away from lakes and drainages, removing fish guts from the water, hauling garbage from campsites near lakeshores, and instructing campers not to use soap in the lakes or throw wash water in the lake. We trusted that as these practices became standard, the pure mountain lakes would stay just that far into the future.

In the decades since, I have continued to enjoy mountain lakes in the areas I've worked and played. I don't much think of what's below the surface, enjoying only the cool splash on a hot day, and the reflected glory of mountain crests on still waters. This winter, when I was thinking to feature mountain lake research in the spring 2016 issue of *Mountain Views Chronicle*, I happened

to talk with Jill Baron (USGS). She had recently been a collaborator and co-author in an important new study and publication that synthesized the condition of mountain lakes around the world. In typical Jill manner, she enthusiastically offered to be a guest editor and to gather relevant articles for a special feature on mountain lakes. As a result—thanks to Jill and the authors she rallied, you can read in this issue ten *Brevia* articles on recent mountain lake research. In contrast to my short-sighted hopes of the 1970s, and my blind eye more recently, all is not well below the surface of our mountain lakes. As Jill's Guest Editorial summarizes, lakes are changing rapidly in the face of diverse anthropogenic forces, and they are routinely trending in the direction of increased productivity and loss of biodiversity. On the brighter side, at least we now have tools and methods to measure key indicators of lake condition and health, to reconstruct historic condition and response to change, and to elaborate mitigation measures. For added inspiration, read the interview with lake researcher, David Porinchu, who shares his love of lakes and their mysteries with

colleagues. And, reflecting the beauty so many people find in mountain lakes, we highlight lakes in our art sections of this issue.

In addition to the features on mountain lakes, I appreciate the other contributions to this issue: an article on multi-scale forest-drought research, perspectives on the Anthropocene in our *Voices in the Wind* section, and several features from colleagues who relate field experiences, from Alaska to California to the Swiss Alps, while conducting on-the-ground research.

Finally I'm happy to remind you that, with thanks to the organizing work of Andy Bunn (WWU), Dave Peterson (USFS PNW), and Scotty Strachan (UNR), 2016 is a MtnClim conference year. This biennial CIRMOUNT flagship conference convenes October 17-21 at the Sleeping Lady Resort, Leavenworth, WA. We hope to see many of you there to once more discuss serious science in an informal setting. See page 87 for more information, and find the conference website at: <http://www.mtnclim.org/>.

Connie Millar



Gibbs rock glacier (Eastern Sierra Nevada, California, viewed from Dana Plateau) shows classic ridge and furrow morphology that betrays its active ice layer embedded below the rocky mantle. Kidney Lake is unusual in receiving water both from the rock glacier and from the Gibbs ice glacier to the east (left) of the rock glacier. As the *Brevia* of Fegel et al. in our mountain lakes feature indicates, waters from these two types of glaciers differ significantly in chemistry and microbial diversity throughout the West, pointing to different histories and process behaviors of the two glacier types.

GUEST EDITORIAL

The Fate of Mountain Lakes

Jill Baron

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Mountain lakes show up rarely in historical accounts of the American West. A few records described dams installed to raise lake levels, and there are more than a few accounts of the fishing, or lack thereof. But largely, mountain lakes are left out of the utilitarian descriptions of the mineral resources, the timber, and the water conveyed by rivers in the many accounts of the

Western Frontier. Mark Twain provided the exception. Twain had a lifelong love of Lake Tahoe: “As it lay there with the shadows of the mountains brilliantly photographed upon its still surface I thought it must surely be the fairest picture the whole earth affords (Roughing It, 1872).” And in *The Innocents Abroad* (1869), none of the famed European lakes ever matched the beauty of Tahoe.

Twain had it right, of course and not just for Lake Tahoe.

Mountain lakes are beautiful. They are important to many of us for spiritual renewal and are destinations for thousands seeking joy in the sight of these shining jewels.

Mountain lakes are also biologically important. Since 1887 we have known lakes as hotspots of nutrient cycling, elaborate food webs and biodiversity (SA Forbes, *The lake as a microcosm*). Oligotrophic mountain lakes support hundreds of algal species and astonishing varieties of invertebrates including shrimp, clams, snails, leeches, midges, copepods, cladocerans, and rotifers. The bigger, older lakes such as Lake Tahoe support invertebrates that are known nowhere else.

We take stock of the state of mountain lakes in this issue of *Mountain Views Chronicle*. They are changing rapidly from a triad of driving forces: non-native species, cultural eutrophication, and climate change. Using a variety of surveys and paleolimnological evidence, all the authors report exciting



Loch Vale, Rocky Mountain National Park, Colorado. Photo: National Park Service.



Taylor Rock Glacier with Sky Pond and Lake of Glass, Loch Vale Watershed, Rocky Mountain National Park, Colorado. Photo: Melannie Hartman.

science, and all the results point to rapid change. Sadly, regardless of the driver, the response may be the same: increased productivity and a loss of biodiversity.

Alien species were intentionally introduced in the 19th century. According to a 2001 paper by Knapp, Corn, and Schindler, 60% of the estimated 16,000 naturally fishless western lakes were stocked, and 95% of all large western lakes. Kokanee salmon and lake trout were introduced to larger lakes for sport fishing, and, like the old woman who swallowed a fly, a progression of additional non-native species, like mysid shrimp, were introduced to stimulate the production of those fishes.

Most mountain lakes are found on public lands, and you may think that protection from land use change keeps them “pristine.” Those lakes may look serene and lovely on top, but they hide human secrets below. Examination of the history of atmospheric deposition using paleolimnological techniques reveals a history of metals, organic compounds, and nutrients carried in on the winds. Western mountain lakes accumulated heavy metals from the gold rush, both from direct runoff and the more pervasive atmospheric deposition of mercury, cadmium, zinc, lead, and copper transported in by rain and snow. Nutrients like

phosphorus, made airborne in dust storms by grazing and land use change, are recorded from the time of Euro-american settlement of the Great Basin and Southwest in the 1800s. Organochlorines and other nasty chemicals (Dieldrin, anyone?), and the nutrient nitrogen entered some mountain lakes in precipitation in the 1900s. Nitrogen deposition is still affecting mountain lakes, and phosphorous from dust and other sources may be increasing. The lasting effect is one of nutrient enrichment, or eutrophication, in many lakes of the western mountains.

Lakes are warming faster than the air, and mountain lakes are among those lakes warming the fastest. Warmer temperatures favor different species and assemblages, and greater primary production than cold temperatures. Glacier retreat, another direct response to warming, influences lake chemistry and productivity by releasing nutrients.

My favorite lakes are in the Loch Vale watershed in Rocky Mountain National Park. My colleagues and I have observed, experimented with, and modeled them since 1983. The lakes reflect their human history. Non-native trout dominate the food web. Primary productivity and diatom communities shifted abruptly ca. 1960 caused by nitrogen deposition. The mid-

20th century marked a shift from oligotrophic to mesotrophic conditions. Since at least the mid-1980s summer lake temperatures have risen steadily, and phosphorus appears to be more available than in the past. In 2010 we began to observe an abundance of the kind of common green algae that the UC Berkeley Museum classifies as “pond scum.” Are our high elevation lakes now becoming eutrophic?

Loch Vale lakes are not alone. The collective knowledge we are gaining suggests a profound change in the small alpine and subalpine water bodies we hold so dear.



Sky Pond, Loch Vale Watershed, Rocky Mountain National Park. Photo: Melannie Hartman.

BREVIA

Rapid and Highly Variable Warming of Lake Surface Waters Around the Globe

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Over the past decade, there have been many regional reports of lakes warming around the world. However, until recently scientists had not had the opportunity to rigorously consider data globally to determine the speed, magnitude, or geographic patterns of these temperature changes in lakes.

After years of working together to collate and analyze all the relevant lake temperature data, collected by hand and by satellite, the Global Lake Temperature Collaboration (GLTC) published the first synthesis of temperature trends in lakes worldwide (O'Reilly et al. 2015, Sharma et al. 2015; Figs. 1, 2). Focusing on summer surface temperatures between 1985 and 2009, which allowed us to analyze the most lakes, we found that the average rate of lake warming has been 0.34° C per decade (0.61° F per decade). This average warming rate is faster than oceans (0.12° C per decade) or air (0.25° C per decade), but there is a great deal of variation from lake to lake. Knowing that the average rate is 0.34° C per decade clearly does not tell you whether your local lake is warming at the same rate.

The variation in warming trends among lakes surprised us; we had expected to see some geographic clustering or patterns associated with physical factors such as elevation. We expected

to be able to say "this region is warming faster than that region," or "lakes above or below this elevation warm at these rates," but in fact, simple patterns like that were the exception rather than the rule. Instead, the rate of warming depends both on the regional changes in climate and also on the size and shape of the lake. Some lakes very close to each other were warming at very different rates in our study. For higher elevation lakes that freeze in the winter, we found that shallow lakes warmed faster than the global average, at 0.55° C per decade. Larger lakes found at higher elevations in cold climates warmed at rates closer to the average global, 0.36° C per decade. Altogether, global differences in local climate and the physical differences among the lakes themselves created quite a mosaic of warming rates, though with the general pattern that 90% of lakes in our study showed warming trends.

So the next perplexing question for us was: why are some lakes warming faster than air temperatures? The data gave us some important clues—we needed to look not just at air temperature but also at solar radiation and winter ice cover. In the summer, lakes warm from rising air temperature and exposure to solar radiation. Strong warming rates were seen in areas of the world where cloud cover is decreasing and solar radiation is increasing. Meteorologists refer to areas receiving less solar radiation through time as points of global "dimming," while those receiving increased radiation are those experiencing "brightening" (Wild 2011, Eastman and Warren 2012). Patterns of dimming and brightening have primarily been driven by changes in how clean the air is, for example, increases in aerosols by human activities decrease how much solar radiation reaches a lake. But lakes experiencing changes in solar radiation exposure were not the only ones warming faster than surrounding air. Some of the rapidly warming lakes were those that normally have ice cover in the winter. As air temperature increases, ice duration has been decreasing (Magnuson et al. 2000), and ice is a critical structuring force in lakes. Ice acts as an insulator; every day that ice is on top of the water, the lake temperature stays more or less the same, around 4° C. Every day that the ice is off is another day that the lake is exposed to warming from solar radiation and air

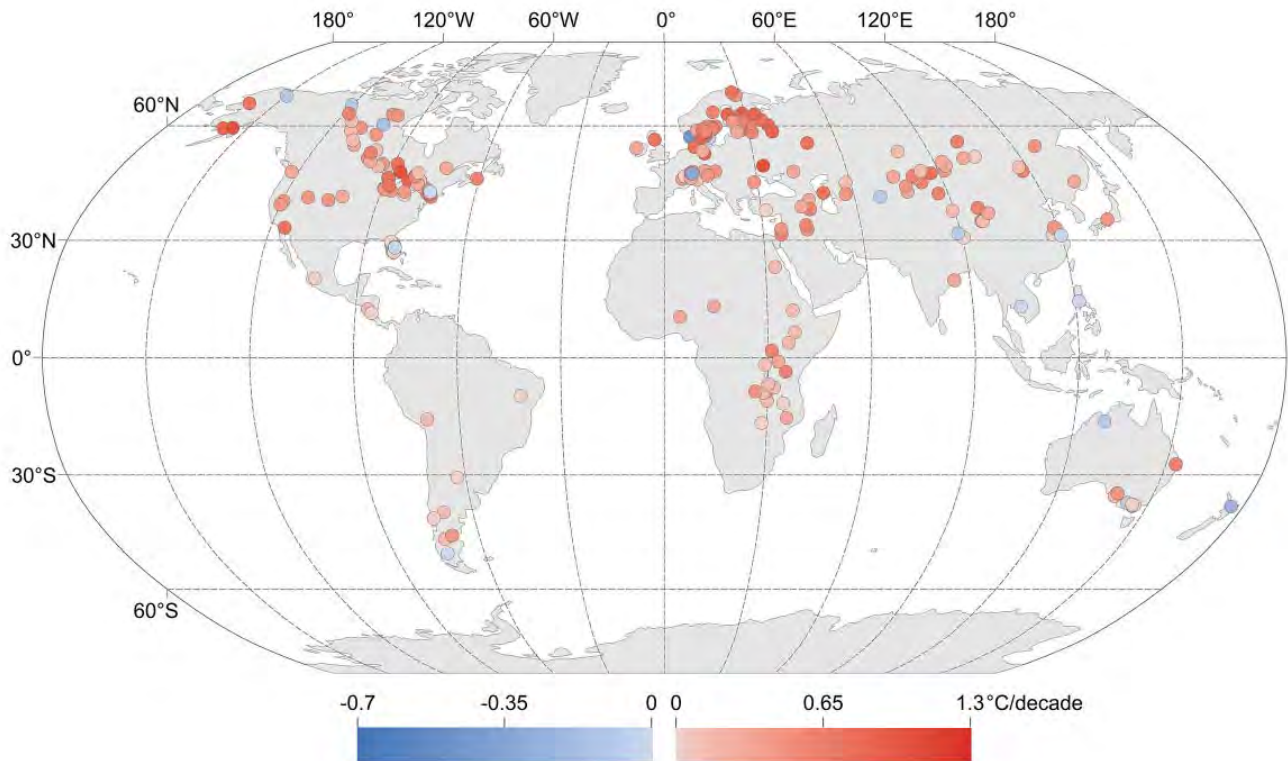


Figure 1. Global trends in summer surface temperature for lakes, including hand-collected, buoy, and satellite data.

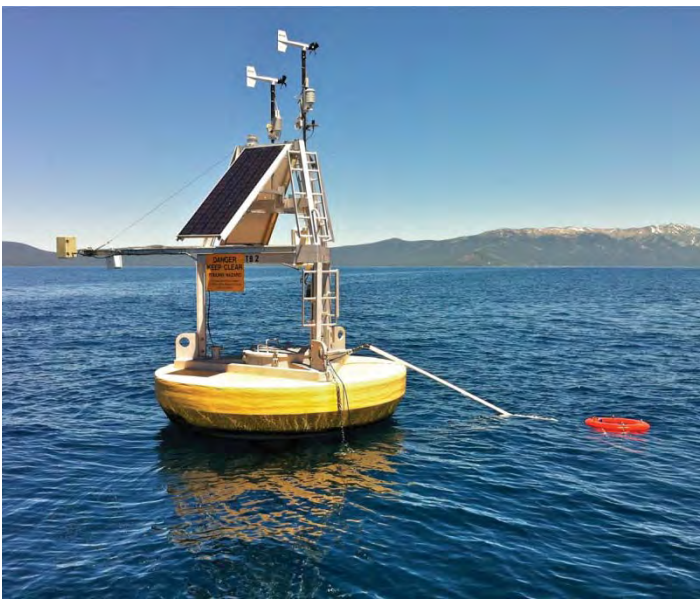


Figure 2. A buoy on Lake Tahoe instrumented to collect temperature data. Photo: Simon Hook.

temperatures, and the temperature can jump above 4° C, creating a steeper lake warming trend over time.

What do warming waters mean for people and the other organisms that rely on water? Temperature sets the stage for basically everything we care about in lakes.

The vast majority of human water uses rely on surface waters—our lakes and rivers—from drinking water and crop irrigation to cooling for energy production and manufacturing. In the most drastic cases, evaporation can simply make the lake disappear as it has in some lakes of the Canadian High Arctic. John Smol, Marianne Douglas, and their colleagues have been working on the same Arctic lakes for several decades and these lakes are now gone (Smol and Douglas 2007). They have carefully examined sediment cores that record thousands of years of environmental conditions; this current disappearance of water is unprecedented. They call this "crossing the final ecological threshold," when the whole ecosystem is just no longer there. To be clear, we would expect this event only in shallow lakes with high evaporation, but it also illustrates to us how much lake levels can drop and reduce water supply in regions that badly need water, like Bolivia, Australia and the southwestern United States.

Water quality is probably the most widespread concern as lakes warm. Warming can exacerbate nuisance algal blooms, especially in lakes that are already having problems with nutrient pollution (Rigosi et al. 2014). Some of these blooms are toxic to humans and wildlife. But even blooms that are not toxic can threaten water quality. When the algae die, bacteria busily eat all those dead algal cells, consuming oxygen at high rates. To make things worse, warmer water physically holds less oxygen. Lower oxygen is stressful for fish and also can create the chemical conditions that release harmful metals normally bound in lake sediments. When the lake gets a big layer of water on the bottom that has no oxygen in it, fish kills can occur. In the Salton Sea in California, large fish kills have resulted from a convergence of large algal blooms that die and deplete the oxygen, warm water, and strong winds that push the lake water around and suddenly expose fish to anoxic water (Marti-Cardona et al. 2008).

In Lake Baikal in Siberia, conditions are very different but warming is also expected to have large ecological effects, primarily through shortening duration of ice (Moore et al. 2009). Baikal is the world's oldest, largest (by volume), deepest, and most biodiverse lake in the world. It holds 20% of the world's liquid freshwater; you could pour all of the North American Great Lakes combined into Baikal. It has many animals and plants that are found nowhere else and they are famously well adapted for cold conditions and a long period of winter ice cover. The Baikal seal is the only exclusively freshwater seal, and it is the top predator in the lake (Fig. 3). It depends directly on the

ice, because it gives birth on the ice and protects the pups from predators by building ice caves. The ice needs to last long enough for the pups to handle themselves when the water opens up. Meanwhile on the bottom of the ice, large blooms of algae feed the tiny invertebrates at the base of the food web, never reaching what would be considered "nuisance" levels but giving much-needed sustenance in this naturally low-productivity lake. Losing ice may reshuffle this food web quite a bit.

It can be tempting to focus our attention on the cases of high warming rates, but we should be careful to consider some of those lakes that are already warm, where even modest warming can simply make the conditions too hot. In Africa's Lake Tanganyika, and other warm tropical lakes, lake organisms may be living very close to their physiological thresholds, easily becoming physically stressed by small temperature changes. In addition, the physical conditions in warm lakes can change more dramatically with small temperature increases than they do in cooler lakes. For Tanganyika, warming has already reduced its overall productivity by reducing summer water mixing that would normally re-suspend the nutrients important for fueling algal growth (O'Reilly et al. 2003). Decreases in algal growth mean less food for the fish, and fisheries in this lake provide up to 60% of the animal protein to the four surrounding countries. Scientists are already documenting major declines in fish catches, which has negative consequences for the local communities for both food and income.



Figure 3. The Baikal seal is the world's only exclusively freshwater seal. Lake Baikal, Siberia. Photo: Kantor/Greenpeace.

Sometimes climate change feels like an inexorable force, the course of which individuals feel powerless to change. Even as our nations and municipalities work toward cutting greenhouse gases, it will take an uncertain amount of time to reverse the climate changes already underway. However, in the meantime, knowing that our ecosystems are stressed by climate change, individuals and organizations can identify what human impacts are more directly under our control to reduce on shorter time scales. For example, as we worry about nuisance algal blooms, we can more aggressively seek to curb nutrient pollution, knowing that warming is going to make this problem worse (Brookes and Carey 2011). Or if we are concerned about climate impacts on wildlife and fish, we may want to monitor populations more carefully and be mindful of the need to revisit management of harvest regularly as these populations adjust to a changing climate.

This new understanding of the global scope and patterns of warming in lakes gives us a foundation for many new studies that will tell us where we can expect warming to lead to more nuisance algal blooms, reduced water levels, and other impacts on water for humans, wildlife and the ecosystems in which we are all embedded. We envision this work proceeding much more rapidly on this new foundation, so that we can better manage the world's freshwater resources.

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An Uncertain Synergy between Atmospheric Deposition and Warming: High-Elevation Lakes of Grand Teton National Park

Sarah Spaulding

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Spaulding, S.A., Otu, M., Wolfe, A.P. and Baron, J. 2015. Paleolimnological records of nitrogen deposition in shallow, high-elevation lakes of Grand Teton National Park, Wyoming, U.S.A. Arctic, Alpine and Antarctic Research 47:701-715.

Reactive nitrogen (Nr) from anthropogenic sources has been altering ecosystem function in lakes of the Rocky Mountains over recent decades. The response of biota in shallow lakes to atmospheric deposition of Nr, however, has received little attention. Benthic algae are dominant in shallow, high-elevation lakes and are less sensitive to nutrient inputs than planktonic algae (Fig 1). Because the benthos is typically more nutrient rich than the water column, shallow lakes are not expected to show evidence of anthropogenic Nr. Yet, when the sedimentary evidence of Nr deposition in shallow, high-elevation lakes of Grand Teton National Park was quantified through sediment chronology and algal community response, it is clear that shallow lakes have changed in recent decades. Shallow lakes are now

included on a growing list of impacted high-elevation localities in western North America. Recent changes in these lakes are most correlated with anthropogenic Nr. Less certain, however, is whether a combined effect of Nr deposition and warming is accelerating species shifts in benthic diatoms. An outcome of this study is the implication for reinforcing effects of Nr deposition and climatic warming in shallow lakes.

Lake sediments record direct evidence of atmospheric deposition of reactive nitrogen (Nr) across the Northern Hemisphere (Wolfe et al. 2001, 2013, Holtgrieve et al. 2011, Kopáček and Posch 2011). Nr is deposited primarily as nitrate (NO_3^-) and ammonium (NH_4^+), which alters surface water chemistry and induces a distinctive suite of shifts in species composition, particularly diatom species composition (Burns 2003, Fenn et al. 2003, Porter and Johnson 2007). The release of Nr to the biosphere during the past 150 years has escalated due to increased combustion of fossil fuels, as well as the production and application of synthetic N fertilizers (Vitousek et al. 1997, Holtgrieve et al. 2011). Nitrogen



Figure 1. Ramshead Lake, Grand Teton National Park, was one of the potential sites for this study. The lake sediment record, however, was interrupted by coarse avalanche debris.

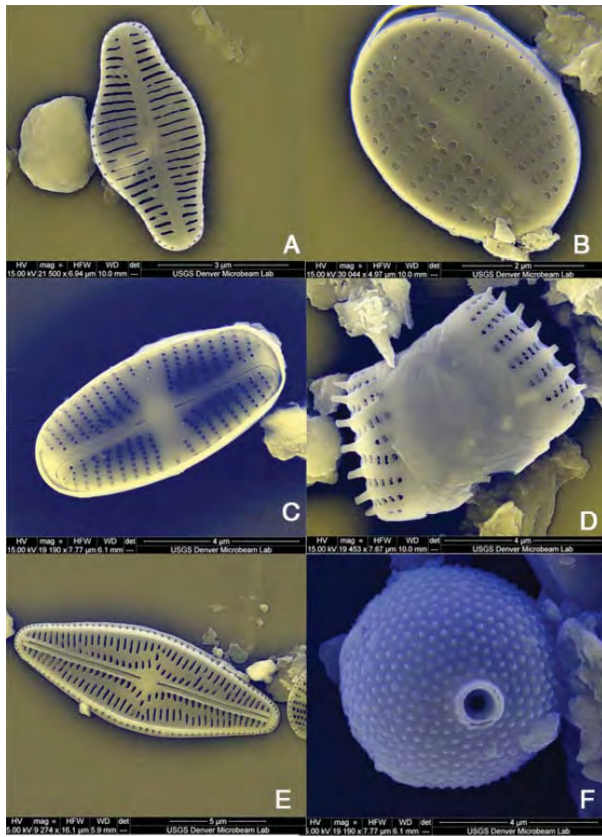


Figure 2. Example of benthic diatom species, imaged in scanning electron micrographs. A) *Chaetopinnularia* sp., Ramshead Lake B) unknown monoraphid diatom, C) *Sellaphora* sp., Holly Lake, D) *Staurosira* sp., Ramshead Lake, E) *Brachysira* sp., Amphitheater Lake, F) chrysophyte cyst, Holly Lake.

is frequently a limiting nutrient for primary producers, and as a result, inputs in excess of natural supply may induce changes to species composition, biodiversity, community dynamics, and nutrient cycling in both aquatic and terrestrial ecosystems. Chronic deposition of anthropogenic Nr to oligotrophic lakes of the northern hemisphere has altered nutrient dynamics primarily by exacerbating phosphorus (P) limitation (Elser et al. 2009).

High-elevation lakes of western North America are vulnerable to both acidification and eutrophication from Nr introduced through atmospheric deposition (Nanus et al. 2009, Sheibley et al. 2013). Annual precipitation is dominated by snow, and orographic effects cause precipitation to increase with altitude, leading to higher rates of Nr deposition with increasing elevation (Williams and Tonnesson 2000). High-elevation lakes are typically oligotrophic and generally occupy poorly-buffered catchments characterized by sparsely or unvegetated talus, poorly developed soils, and exposed bedrock. Catchment vegetation is sparse, allowing inorganic nutrients to be released to surface waters, particularly during spring snowmelt (Williams et al. 2009).

The Teton Mountain Range is steep and rugged, with many peaks over 3,000 m asl and over 100 lakes formed in glacially scoured basins. Typically, deep lakes are selected for paleolimnological reconstruction, but many of the deep lakes of the Tetons are subject to avalanche debris on the frozen surface during winter. Inorganic debris is then deposited onto the soft sediments with the melting of ice-cover. Such debris not only makes sediment coring difficult, it compromises the integrity of the sediment record.

Shallow lakes are common in high-elevations in the Rocky Mountains. Shallow lakes, however, have not been considered explicitly with respect to atmospheric deposition of Nr. The physical and chemical properties of shallow lakes presumably dictate that their biota responds in an alternate manner to input of Nr than the biota of deeper high-elevation lakes. Indeed, shallow lakes of temperate zones are an archetype for alternate stable states, dependent upon nutrient loading (Scheffer and van Nes 2007, Cantonati and Lowe 2014). In low nutrient conditions, shallow lakes are highly transparent with abundant submerged macrophytes, while in high nutrient conditions, shallow lakes become turbid and macrophytes disappear. In addition to the characteristics of shallow lakes (e.g., reduced thermal stratification, exposure to wind mixing, resuspension of sediments), high-elevation shallow lakes possess unique features. For example, the water column and parts of the sediments may be frozen for a large part of the year. During the period of ice-cover, nutrient concentrations increase in the water column as a result of freeze concentration (Spaulding et al. 1993). High-elevation lakes receive greater ultraviolet radiation, which inhibits planktonic photosynthesis (Vinebrooke and Leavitt 1999), or favors particular species (Bothwell et al. 1993). While phytoplankton are inhibited by ultraviolet radiation, motile epipelagic species are able to migrate into surface sediments to avoid damaging radiation (Vinebrooke and Leavitt 1999). Furthermore, compared to deeper high-elevation lakes, shallow high-elevation lakes are subject to greater warming by light penetration (Strecker et al. 2004).

Diatoms have been used to define thresholds of environmental change in deep lakes (Fig. 2; Wolfe et al. 2001, 2003, Saros et al. 2003, Baron 2006, Arnett et al. 2012, Sheibley et al. 2014, Hundey et al. 2014). In particular, two planktonic diatom species, *Asterionella formosa* Hassall and *Fragilaria crotonensis* Kitton, have been documented as nitrophilous in lakes of the Rocky Mountains (Saros et al. 2010). Although these diatoms are common in mesotrophic and eutrophic lakes globally, their increased presence in oligotrophic lakes is interpreted as a response to subtle nutrient enrichment occurring in response to relatively low Nr inputs.

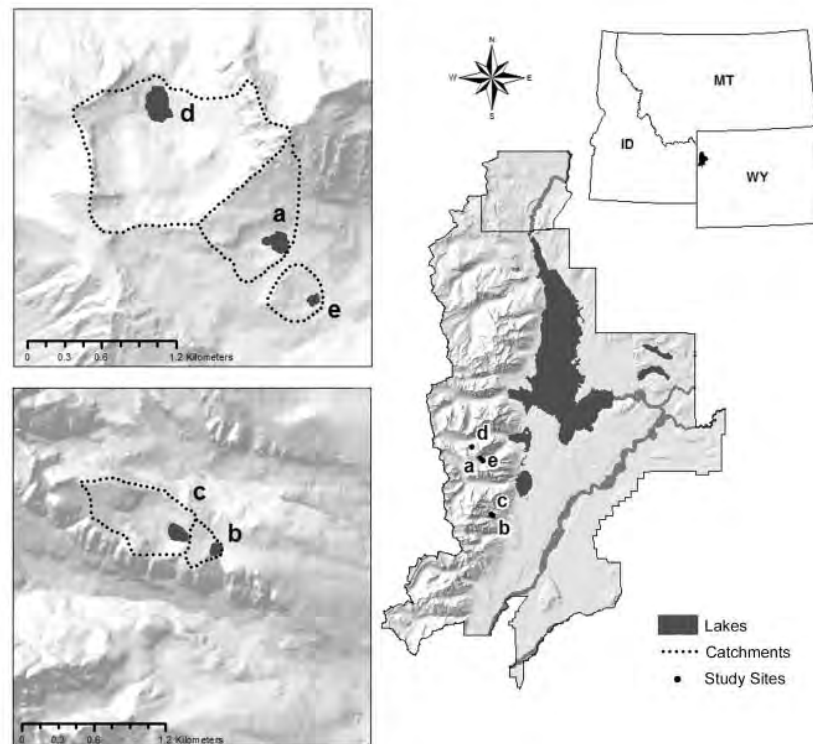


Figure 3. Map of Grand Teton National Park, Wyoming showing the major park water bodies five study lakes, a) Holly Lake, b) Surprise Lake, c) Amphitheater Lake, d) Grizzly Lake, and e) Whitebark Moraine Pond (unnamed on published maps), and their watersheds. Base map from U.S. Geological Survey digital data, NAD 1983, UTM Zone 12N.

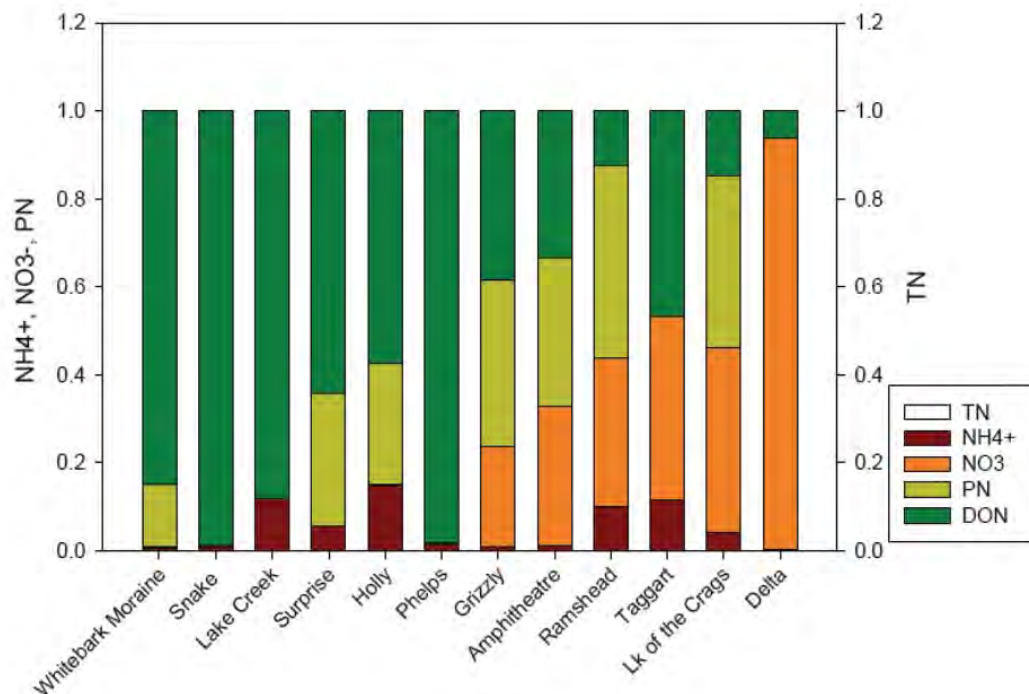


Figure 4. Plot of the form of nitrogen for lakes and streams in Grand Teton National Park, expressed as fraction of total N. Whitebark Moraine Pond is at one end of the spectrum, with most N as dissolved organic nitrogen (DON). In contrast, Delta Lake with its inflow from the Teton Glacier, has both the highest percentage of N as NO_3^- .

Diatoms have enabled the establishment of critical loads in aquatic ecosystems, defined as the threshold Nr deposition rate below which there is no discernible ecological effect (Porter and Johnson 2007). This approach is particularly informative for evaluating and meeting management targets (Pardo et al. 2011). In high-elevation regions of western North America, diatom-based estimates of the Nr critical load are of the order of 1.5 kg N ha⁻¹ yr⁻¹ as wet deposition (Baron 2006, Saros et al. 2010), much lower than temperate ecosystems at lower altitudes (Nanus et al. 2012). The response of diatoms in shallow lakes to Nr has not been investigated, but a reasonable expectation is for the critical load for biotic response in shallow lakes to be greater than in deep lakes.

Grand Teton National Park is proximal to several major Nr point sources, including the Snake River Valley of Idaho and northern Utah, where ammonia (NH₃) emissions from agriculture are sufficient to be detectable using infrared remote sensing (Fig. 3; Clarisse et al. 2009). Other sources include oil and gas extraction industries to the east and south of the park. Mean annual Nr deposition rates spanning the water years 1984-2012 ranged 0.8-1.4 kg N ha⁻¹ yr⁻¹, and all sites witness an increase in wet-deposition Nr deposition on the order of 0.02 kg N ha⁻¹ yr⁻¹. Wet plus dry Nr deposition on the east side of the Teton

Range (elevation 1978 m asl), was estimated at 2.5 kg N ha⁻¹ for the 2011 water year (Benedict et al. 2013). Deposition of Nr increases with elevation and elevation watersheds offer little uptake of dissolved inorganic N. As a result, high-elevation lakes are subject to the maximum impact of anthropogenic Nr (Seastedt et al. 2004). Therefore, the loads might be expected to be near 2.5 kg N ha⁻¹ in the many shallow, high-elevation lakes of the Tetons. In previous studies, lakes in the Tetons were ranked based on sensitivity to acidification due to atmospheric deposition, with thirty six percent of lakes predicted to be vulnerable (Nanus et al. 2005, 2009). This recent study was an assessment of the lake-sediment based evidence for regional Nr deposition, its chronology, and the nature of algal community responses in five shallow, high-elevation lakes of the Tetons (Fig. 4).

The Teton lakes showed assemblage-wide shifts in diatom assemblage, as evidenced by: 1) significant assemblage changes centered on ~1960, 2) pre-1960 assemblages differed significantly from post-1960 assemblages, 3) pre-1960 diatom assemblages fluctuated randomly, whereas post-1960 assemblages showed directional change, 4) changes in δ¹⁵N signatures were correlated with diatom community composition in Holly, Amphitheater, Grizzly and Whitebark Moraine lakes (Fig. 5).

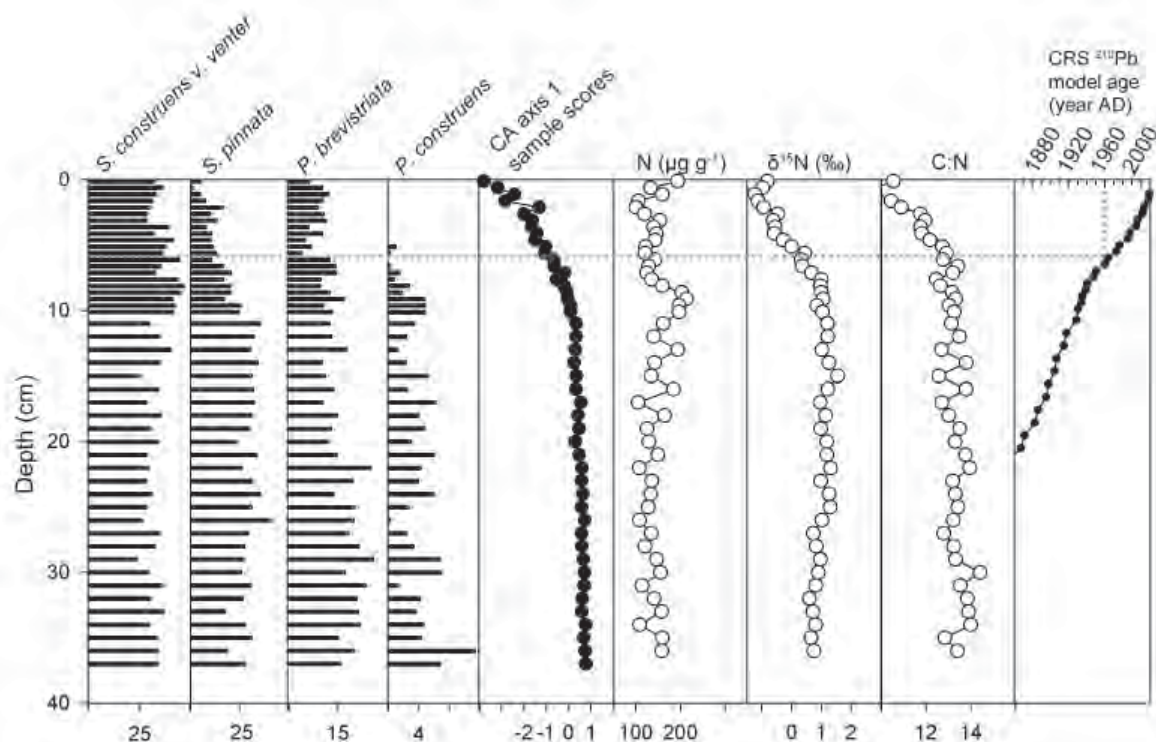


Figure 5. Sediment core fossil diatom stratigraphies and geochemistry from Whitebark Moraine Pond. Vertical bar of fossil diatom taxa found in sediment cores with greatest change in species composition. Sediment profiles of first correspondence axis (CA1), unconstrained ordination of species relative abundance, N (μg g⁻¹), δ¹⁵N, molar ratio of carbon to nitrogen (C:N) and CRS age model. Unconstrained CCA explained 36% of the variance ($p < 0.015$) with an eigenvalue of 0.155 for CA1. The year 1960 is marked with a dotted line.



Figure 6. Preparing to sample Whitebark Moraine Pond, a shallow high-elevation lake with greatest potential for warming by absorbance of heat by the lake sediments, particularly during the summer months.

Multiple physical factors create bias toward the dominance of benthic primary production in shallow high-elevation lakes. Incident light is available to diatoms growing in littoral zones (benthic areas above the light compensation depth) because of the high water transparency. Dissolved and particulate organic matter is greater in the sediments than in the water column, so that cells in close contact with sediments are less likely to be nutrient limited than planktonic cells. Furthermore, plankton may be at a distinct disadvantage, especially when dissolved organic carbon concentrations are low and minimally absorb damaging ultraviolet radiation. Ultraviolet radiation inhibits growth (Vinebrooke and Leavitt 1999), creating more transparent waters and favoring benthic diatoms that can escape ultraviolet radiation by migrating within the surface sediments.

Despite the fact that benthic algae are less sensitive to nutrient inputs, results indicate biotic response of shallow lakes to deposition of atmospheric N_r as registered by N isotopic depletion. The sediments show depletion of $\delta^{15}\text{N}$ by a mean of 2.2 ‰ across all lakes, and may reflect a combination of 1) changing atmospheric acidity, 2) diagenesis and 3) accelerated N_r deposition across both urban and remote regions of the northern hemisphere (Hobbs et al. 2010, Holtgrieve et al. 2011, Benedict et al. 2013, Wolfe et al. 2013). First, although high-elevation Teton lakes are vulnerable to acidification by N_r introduced through atmospheric deposition, neither the water

chemistry nor diatom species shifts are indicative of acidification. Based on detailed examination, diagenesis did not influence the timing or direction of the isotopic signal in the lakes. Finally, $\delta^{15}\text{N}$ signatures were most correlated with diatom community composition, with statistically significant relationships in Holly, Amphitheater, Grizzly and Whitebark Moraine lakes. Grizzly Lake's sediments, much older than 1850, begin to show a trend of linear depletion of $\delta^{15}\text{N}$ near 1850.

The effect of climatic warming on these lakes cannot be discounted, especially because diatom response to warming has been documented, particularly across the arctic (Douglas et al. 1994, Smol et al. 2005). Warming is likely to be greater in shallow lakes than in deeper lakes, especially during the brief ice-free summer season. A trend in rising temperatures, decline in precipitation, and increase in drought frequency have been documented in Wyoming (Mote et al. 2005).

A combination of warming and N deposition could affect benthic diatoms through altered trophic level interactions (Thompson et al. 2008), habitat disturbance and altered water transparency. Of all the study lakes, Whitebark Moraine Pond experienced the greatest relative change in diatom species assemblage and the shift began prior to other lakes. Whitebark Moraine Pond is small lake (1 ha) and the shallowest (3.7 m) of the study lakes (Fig. 6). It has the greatest potential for warming by absorbance

of heat by the lake sediments, particularly during the summer months. Given the outlook for greater warming, it is likely that the lakes will experience more ice-free days and warmer summer water temperatures. Synergy between warming temperatures and increased Nr deposition would be expected to accelerate primary production, favoring the accelerated C fixation and lower C:N, further altering benthic diatom species composition.

Shallow high-elevation lakes of the Tetons contain large littoral zones, which are typically areas of high productivity and biodiversity (Cantonati and Lowe 2014). Benthic diatoms in the littoral zone tend to be limited by light, rather than nutrients (Vadeboncoeur et al. 2001), which is likely the reason for a muted or indirect response to the nutrient status of the water column. Therefore, among lakes vulnerable to atmospheric deposition of Nr, shallow lakes are the least likely sites to experience biotic changes. Yet, benthic diatom assemblages are altered in the study lakes near 1960, in association with depletion of $\delta^{15}\text{N}$. It is also possible, however, that the combined effect of Nr deposition and warming accelerates the response of species shifts in benthic diatoms in shallow lakes. This study did not address the potential synergy of Nr deposition and warming, yet the combined effects may provide part of the explanation for the unexpected response by benthic diatoms. While uncertainties remain about the potential synergy of Nr deposition and warming, this study adds shallow lakes to the growing list of impacted high-elevation localities in western North America.

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What Can Mountain Lakes Tell Us About Climate Impacts?

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Rose, K. C., C. E. Williamson, C. E. H. Kissman, and J. E. Saros. 2015. Does allochthony in lakes change across an elevation gradient? *Ecology*:213–224.

Rapidly rising temperatures and changing precipitation patterns make mountain regions highly sensitive to climate changes. It has therefore been argued that mountain regions serve as indicators or sentinels of climate change, and we should look to these regions to understand the scope and magnitude of future ecological conditions more broadly (Huber et al. 2005, Price et al. 2013). However, we can't measure everything. If we want to understand synoptic ecological change in mountain regions, where should we look and what should we measure?

As the lowest point in the local landscape, lakes and other inland water bodies receive inputs from the surrounding terrestrial landscape through the rivers, streams, and groundwater that feed them. In this way, lakes integrate terrestrial environmental change, providing a single measurement location to understand the scope of change across an entire watershed (Williamson et al. 2009, Rose et al. 2009). Furthermore, lakes, and especially mountain lakes, provide valuable services to society. Many mountain lakes receive substantial quantities of snowfall meltwater input, and serve as drinking water supplies to many communities. Mountain lakes also serve as hiking destinations and recreational fisheries, supporting local economies in many regions.

How is climate change impacting mountain lakes, and what future changes might we expect to see in coming decades? And what do changes in lakes indicate about processes occurring in the watersheds that surround lakes? One of the most important mechanisms by which lakes are connected to the watersheds that surround them is via the flux of organic carbon. Inputs of terrestrial organic carbon, termed allochthonous inputs, reduce water clarity and the penetration of harmful ultraviolet radiation, regulate lake heat balance, subsidize aquatic food webs, and control lake carbon cycling (Cole et al. 2007, Jones et al. 2012). Aquatic food webs are often dependent on terrestrial carbon, and in many lakes, trout are made of trees (Sayre 2008). The balance between allochthonous inputs and internal lake production is termed the degree of allochthony.

Unfortunately, until recently little has been known about allochthonous inputs or the degree of allochthony in mountain lakes. In a recent publication (Rose et al. 2015), we found that allochthony decreased with increasing elevation in 30 lakes in the US Rocky Mountains, but not always in a straightforward manner (Fig. 1). Predictably, lakes above treeline had significantly lower terrestrial inputs of organic carbon than lower elevation sub-alpine and montane lakes. However, there was a sharp transition at treeline. While lower elevation montane lakes depended more on terrestrial carbon inputs, they were also more variable in their allochthony. The sources of this variability are unknown, but likely depend on factors such as lake productivity.

Given this new knowledge about allochthony in mountain lakes, what can we predict about how mountain lakes are changing? And can we use this knowledge to infer broader, regional climate change impacts? Mountain lake allochthony provides information about the amount of terrestrial carbon fixation and flux from land to water, which in turn is influenced by climate conditions. As the treeline increases in elevation in many regions (Harsch et al. 2009), there will be fewer and fewer alpine lakes, and lake allochthony will likely increase. Warming temperatures will increase growing season length. But precipitation plays a role in controlling the flux of terrestrial carbon from the landscape, and lakes in regions of warming temperatures but decreasing precipitation may see reduced allochthony or increased event-driven pulses of terrestrial inputs.

Measuring changes in terrestrial carbon inputs to lakes—lake allochthony—provides the ability to characterize climate changes across much broader spatial scales. But disentangling specific climate drivers such as temperature and precipitation remains a challenge, as both impact allochthony. Regardless, changes in terrestrial carbon inputs to mountain lakes are likely, which in turn will impact water quality and the services these ecosystems provide to society. Therefore, it is imperative we understand the magnitude and direction of future changes in lake allochthony and the effects of changing allochthony on lake ecosystems.

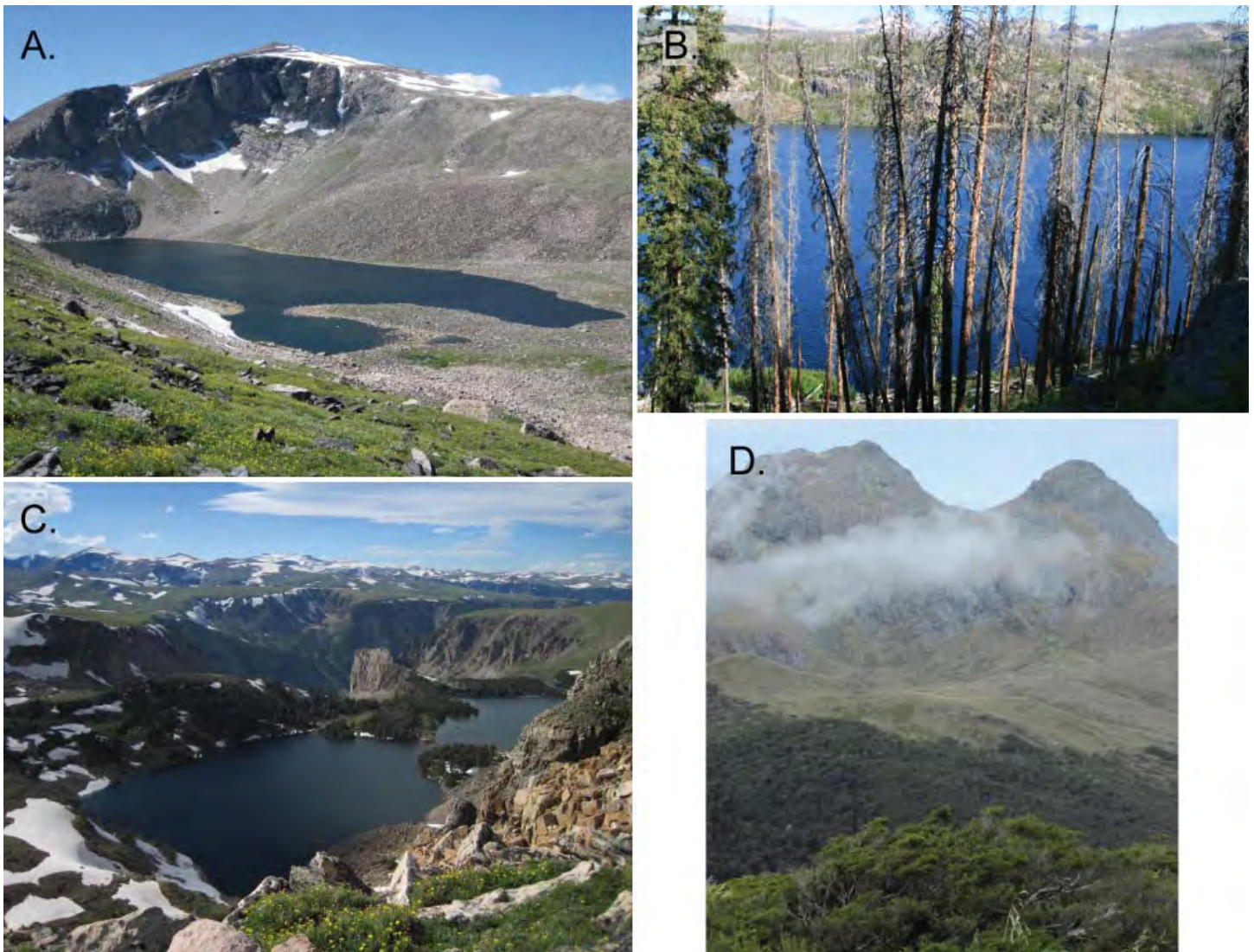


Figure 1. Terrestrial organic matter inputs to high elevation alpine lakes (study site Sliderock Lake, A) are much lower than to lower elevation montane lakes such as Kersey Lake (B), and sub-alpine lakes like Twin Lake (C) are in between. The location of treeline (D) appears to be a major factor determining terrestrial inputs to mountain lakes.

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Effects of Glacier Meltwater on the Algal Sedimentary Record of an Alpine Lake in the Central U.S. Rocky Mountains

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Slemmons K.E., J.E. Saros, J.R. Stone, S. McGowan, C.T. Hess and D. Cahl. 2015. Effects of glacier meltwater on the algal sedimentary record of an alpine lake in the central U.S. Rocky Mountains throughout the late Holocene. *Journal of Paleolimnology* 53:385-399, doi: 10.1007/s10933-015-9829-3.

One of the most visible signs of landscape change in alpine environments is the loss of glaciers. Worldwide, glaciers have been melting at rapid rates (Granshaw and Fountain 2006, Meier et al. 2007, Cannone et al. 2008). For example, Glacier National Park has experienced a 67% decrease in glacial cover within the last 150 years with glaciers expected to be absent from the namesake park by 2020 (Hall and Fagre 2003). Increased glacial melting causes an increase in glacier runoff to lakes and has a significant influence over the chemical, physical and biological nature of those lakes. For example, lakes in the Rocky Mountains that are glacier-fed have nitrate concentrations up to 200 times greater than counterpart snow-fed lakes (Saros et al. 2010), have higher rates of productivity, have different availability of nutrients, and have a lower species richness of primary producers (Slemmons and Saros 2012). As a result, glacier-fed lakes are often biologically and physically different from those that are snow-fed. To understand how the reduction and eventual disappearance of glaciers might influence a lake ecosystem in the future, it is imperative to understand how lakes have changed historically as glaciers expanded and contracted. A key question for paleolimnological interpretation is how these various effects from glaciers are integrated to influence past lake communities and affect the accuracy of inferences we can make from paleolimnological records.

In order to address the question of how glaciers influence lakes through time, we extracted lake sediment cores during the summer of 2010 from two lakes in the Beartooth Mountains to examine how algal communities have changed over the last 3,000 years (Fig. 1). Specifically, we examined algal pigments and sediment geochemistry in Jasper Lake, fed by a remnant glacier (area 0.1 km²) and Albino Lake, fed by snowmelt only (Fig. 2). In addition, we assessed diatom community change since these primary producers are often excellent indicators of environmental change. While these two lakes are separated hydrologically, they

are in close proximity and share similarities in many physical and chemical characteristics (Saros et al. 2010, Slemmons and Saros 2012) and provide an ideal model to compare the influence of glacial meltwater on lakes over time.

The two study lakes are similar in area and maximum depth, have similar water transparencies and total phosphorus concentrations (Jasper = 9 µg L⁻¹, Albino = 10 µg L⁻¹). A key difference between the two lakes is their nitrate concentrations, with 125 µg NO₃-N L⁻¹ in Jasper compared to 2 µg NO₃-N L⁻¹ in Albino. Subsequently, average water column chlorophyll concentrations are three times higher in Jasper Lake (4.2 µg L⁻¹) than in Albino Lake (1.4 µg L⁻¹). Sedimentation rates differ dramatically between Jasper and Albino Lakes largely given the glacial meltwater input into Jasper Lake.

The fossil algal records in glacier-fed Jasper Lake showed greater change through the 3,000 years, particularly since the Medieval Climate Anomaly (MCA; 750–1150 years BP; Carrara 1989) when compared to those of nearby snow-fed Albino Lake, which showed relatively little change (Figs. 3, 4). Jasper showed significant shifts in the dominant species throughout the core. Shortly before the MCA, the relative abundances of planktic species, *Discostella stelligera* and *Asterionella formosa*, began to increase. During the Little Ice Age (LIA) they sharply increased; *Fragilaria crotonensis* also increased and *Tetracyclus glans* showed a maximum peak, while *Aulacoseira* species declined notably. During the 20th century, *A. formosa*, *F. crotonensis*, and *D. stelligera* dominated the diatom assemblages. *Discostella stelligera* was a relatively abundant taxon in both lake records (Fig. 3). While this species can indicate other environmental conditions beyond nitrogen enrichment, the increase of *A. formosa* and *F. crotonensis*, two reliable N indicators, in conjunction with the increase in *D. stelligera* in Jasper Lake suggests that *D. stelligera* may also have responded to elevated nitrogen, with this enrichment enhanced in the 20th century with accelerated glacial melting. These two species are indicators of nitrogen enrichment in other alpine lakes of the Rocky Mountains, and have increased in snow-fed lakes in this region during the 20th century owing to enhanced atmospheric nitrogen deposition (Saros et al. 2005). This same pattern of 20th century change is apparent in the Albino Lake diatom record, with an



Figure 1. A) Field crew observing a glacier-fed lake, B) Courtney Wigdahl-Perry and Jasmine Saros extruding lake sediment from Jasper, C) Krista Slemmons, Courtney Perry-Wigdahl and Dom Winski extracting lake sediment core from Albino Lake, Beartooth Mountains, USA.

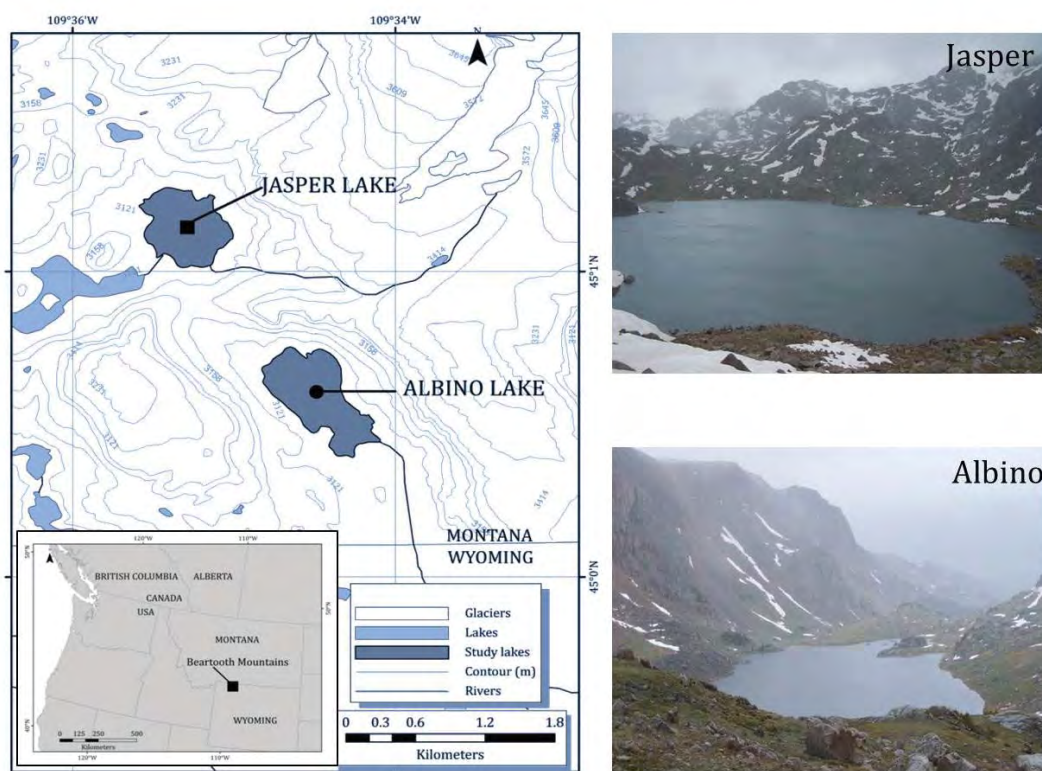


Figure 2. Location of study lakes, Jasper (square, glacier-fed) and Albino (circle; snow-fed) situated in the Beartooth Mountains of the central Rocky Mountains, USA.

increase in the relative abundance of *A. formosa* only over the last century. However, the increase in relative abundances of *A. formosa* and *F. crotonensis* much earlier in the diatom record in Jasper suggests that glacial meltwater had become a source of nitrogen enrichment to the lake. The continuing increases in relative abundances of these two species during the LIA and into the 20th century indicate that nitrogen enrichment grew stronger over time.

Diatom assemblage turnover (indicated by the DCA axis 1 scores) in Albino was highly variable throughout the core but demonstrated no directional change. Comparatively, Jasper assemblage turnover was relatively stable until near the middle of the MCA (~800 yrs BP), at which point turnover increased. Likewise, diatom species richness in Jasper Lake (raw richness values range = 23 – 47; mean = 36) was relatively constant up

until the LIA, at which point it shifted downward, followed by an additional downward shift during the 20th century (Fig. 4A). The decline in diatom species richness in Jasper Lake at the start of the LIA is also consistent with nitrogen enrichment. Historically, many snow-fed lakes in this region of the Rocky Mountains were nitrogen limited (Morris and Lewis 1989) and today show nitrogen and phosphorus co-limitation. In contrast, glacier-fed lakes in the central Rocky Mountains, including Jasper Lake, are phosphorus-limited (Slemmons and Saros 2012) owing to high nitrate concentrations that are delivered via glacier meltwater. Today, glacier-fed lakes in the central Rocky Mountains, including Jasper Lake, have lower species richness than snow-fed lakes in the area (Slemmons and Saros 2012). Species richness decline has been linked to nitrogen enrichment and subsequent decline in the number of nutrients limiting algal growth (Interlandi and Kilham 2001). We attribute the differences

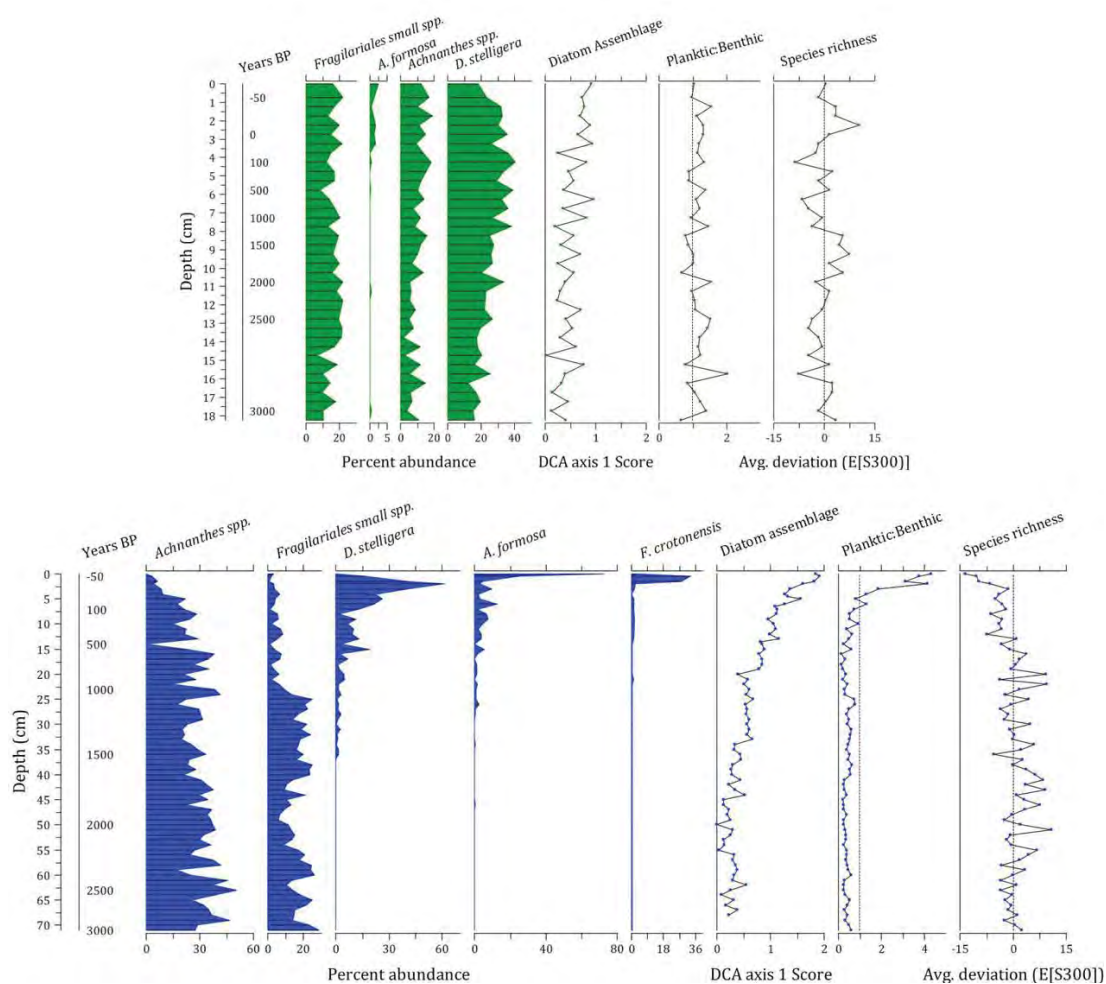


Figure 3. Diatom stratigraphy of Jasper Lake (glacier-fed; blue) and Albino Lake (snow-fed; green) showing the relative frequencies of key diatom species, planktic to benthic ratio of diatoms, detrended correspondence analysis (DCA) axis 1 scores of the entire diatom assemblages and species richness.

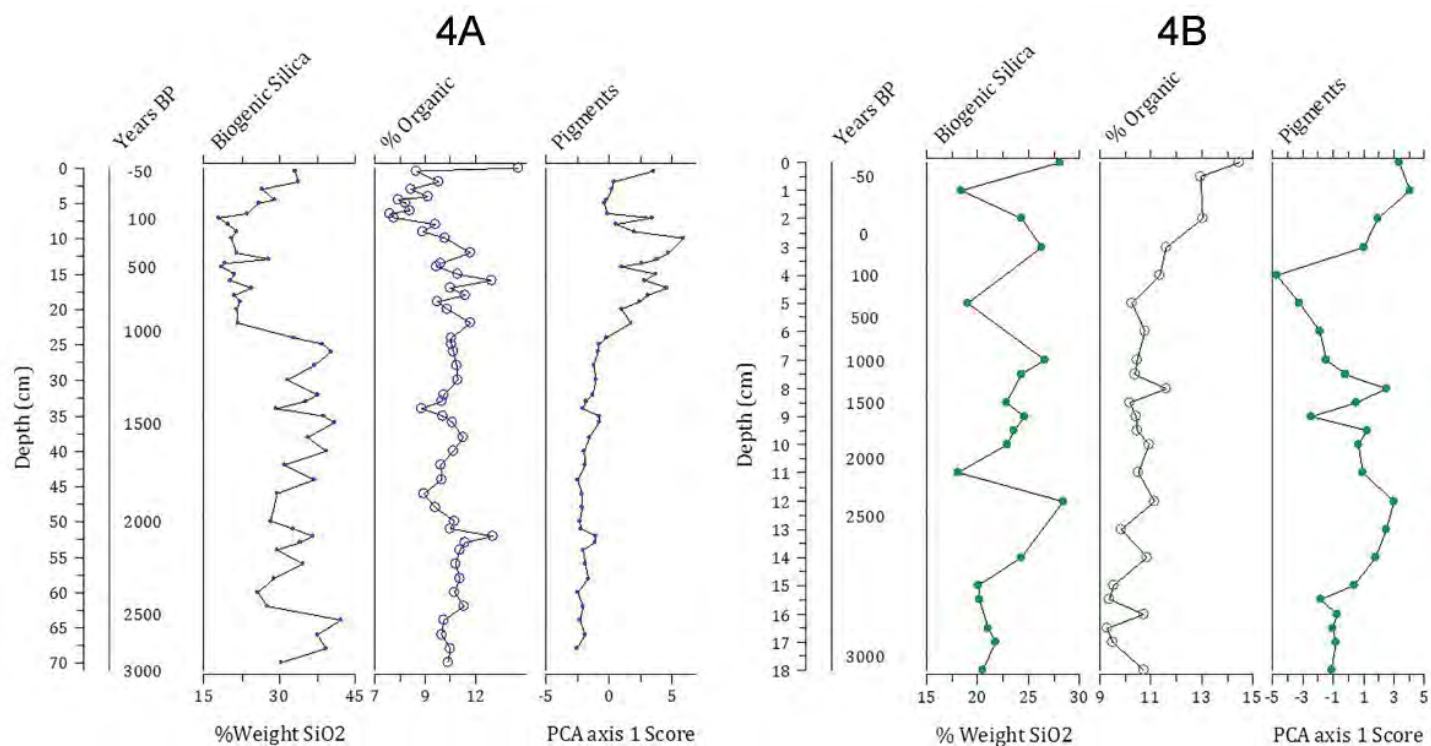


Figure 4. Comparison of select data for the two study lakes: 4A, Jasper (glacier-fed; blue) and 4B, Albino Lake (snow-fed; green) including biogenic silica based on percent weight of SiO_2 , percent organic analysis and principal components analysis on the entire pigment assemblage.

in the glacier-fed and snow-fed lakes in our study primarily to nitrogen enrichment from glacier meltwater starting just prior to the MCA when glacial meltwater influx to Jasper Lake would have increased with warming climate. Our results indicate that this glacier-fed lake has experienced nitrogen enrichment for over 1000 years as the mass balance of glaciers has varied. This underscores the importance of considering the effects of glaciers over time as they may skew the interpretations gleaned from paleolimnological indicators. This is particularly true when evidence of alpine glaciers is gone, further reinforcing the need for documentation of glacier size, presence and recession in a watershed. With the recent focus on nitrogen deposition issues in the Rocky Mountains (Baron et al. 2009, Saros et al. 2011), the confounding effects of nitrogen rich meltwater on lakes, in addition to atmospheric deposition serving as an additional source of nitrogen delivery to glacier-fed lakes, may alter the response observed in the fossil record, warranting that glacier-fed lakes remain outside of these types of studies focused on deposition changes over the 20th century.

Overall we found that, in the central Rocky Mountains, glacial meltwater is a powerful driver of algal community change and that nitrogen delivery is the most likely driver of that change.

This study highlights the importance of glaciers as a landscape feature that affects algal communities in lakes. It also sheds light on the importance of integrating glaciers as a driver of ecosystem processes for accurate paleolimnological interpretations particularly when alpine glaciers have disappeared.

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Glacial Meltwater Characteristics Depend on Glacier Type and Location

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Fegel T.S., Baron J.S., Fountain A.G., Johnson G.F., Hall E.K. 2016. The differing biogeochemical and microbial signatures of glaciers and rock glaciers. *JGR-Biogeosciences* DOI:10.1002/2015JG003236.

Glaciers and rock glaciers (which consist of coarse rock fragments bound together and lubricated by ice) sit at the interface of atmospheric and terrestrial environments (Slemmons et al. 2013). They integrate atmospherically deposited chemicals and weathering products, process reactive compounds through biotic and abiotic pathways, and then release the altered solutes to alpine headwaters. Across the American West alpine glaciers and rock glaciers are shrinking due to rising air temperatures. The resulting changes in volume, timing, and chemistry of meltwater discharged by these features appear to be having significant effects on the adjacent alpine headwater ecosystems they feed. Whereas both glaciers and rock glaciers are sources of seasonal meltwater, sediment, and solutes to headwater ecosystems (Baron et al. 2009, Saros et al. 2010, Singer et al. 2012, Thies et al. 2007), the differences between meltwater characteristics of each glacier type are poorly documented.

We asked whether the meltwater differed between glaciers and rock glaciers by comparing physical, chemical, and microbial characteristics of 25 alpine glaciers and 24 rock glaciers found in the Cascades, Sierra Nevada, and Rocky Mountains (Fig. 1). Sediment and surface water samples were collected in late summer 2012-2014 from 25 alpine glaciers and 24 rock glaciers. Weathering products, nutrients, the complexity of dissolved organic matter (determined with fluorescence), and bacterial richness and diversity from stream sediments (using 16S rDNA assays) were compared between glaciers and rock glaciers, and also between mountain ranges.

Our results suggest that glacier type dictates the concentration of weathering products released, the complexity of organic matter exported via meltwaters, and influences microbial diversity, while geographic region dictates the rock type that is weathered (and thus kind of weathering products released), the rate and intensity of weathering, the compounds that are atmospherically deposited, and possibly microbial diversity. The result is that some characteristics [e.g. temperature, weathering products, complexity

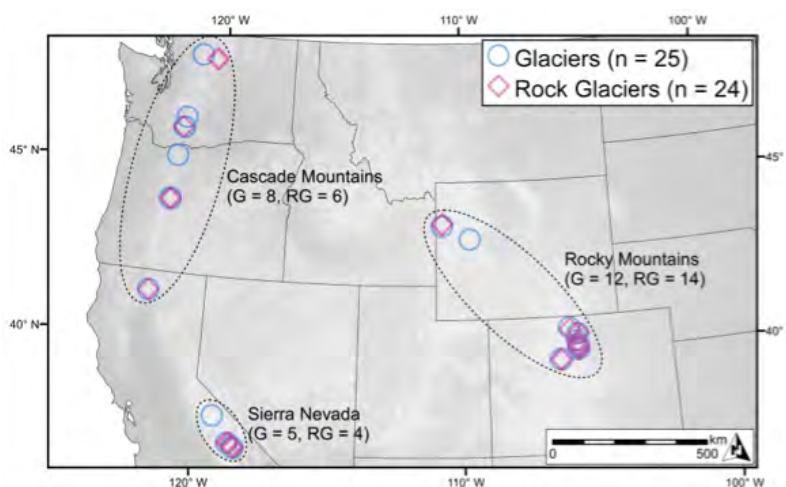


Figure 1. Glacier and rock glacier distribution map. Locations of contiguous U.S. glaciers and perennial ice features drawn from the Randolph Glacier Inventory and rock glaciers drawn from the Fountain Rock Glacier Inventory. Approximately 1500 glacial and perennial ice features are identified, yet >90% of them are clustered in just four states. Conversely, over 10,000 rock glaciers are identified and distributed across a broader geographic range.

of dissolved organic matter (DOM)] appear to be driven primarily by glacier type (i.e. rock or ice glacier) while other characteristics (e.g. NH_4^+ , NO_3^- , microbial processing of DOM) appear to be more influenced by geographic characteristics.

Water samples from glaciers and rock glaciers differed significantly in physical and chemical characteristics. Rock glacier meltwaters had higher temperatures, pH, and conductivity than glacier meltwaters (Fig. 2a-c). Rock glacier meltwaters were also enriched in a range of weathering products including SiO_2 , Ca^{2+} , K^+ , Mg^{2+} , and Sr^{2+} , but depleted in Fe^{3+} and Mn^{2+} relative to glaciers. Nitrate concentrations and total dissolved N were significantly higher in meltwater from rock glaciers than glaciers. Ammonium concentrations were more enriched in glacier

meltwaters than rock glacier meltwaters (Fig. 2d-f). There was no significant difference in DOC concentrations between glacier and rock glacier meltwaters but clear differences in composition of fluorescing dissolved organic matter between glacier types (data not shown). The DOM in meltwaters from rock glaciers displayed more complex, humic-like carbon than DOM in meltwaters from glaciers, even though DOM from both glacier meltwater types was of microbial rather than terrestrial plant origin. Glacial and rock glacial meltwaters in the Rocky Mountains had NO_3^- and NH_4^+ , and Total Dissolved N concentrations nearly twice as high in both glacier types from the other mountain ranges (Fig. 2d,e,f). Atmospheric N deposition is greatly elevated in the Colorado Front Range compared with other western mountains (Fenn et al. 2003).

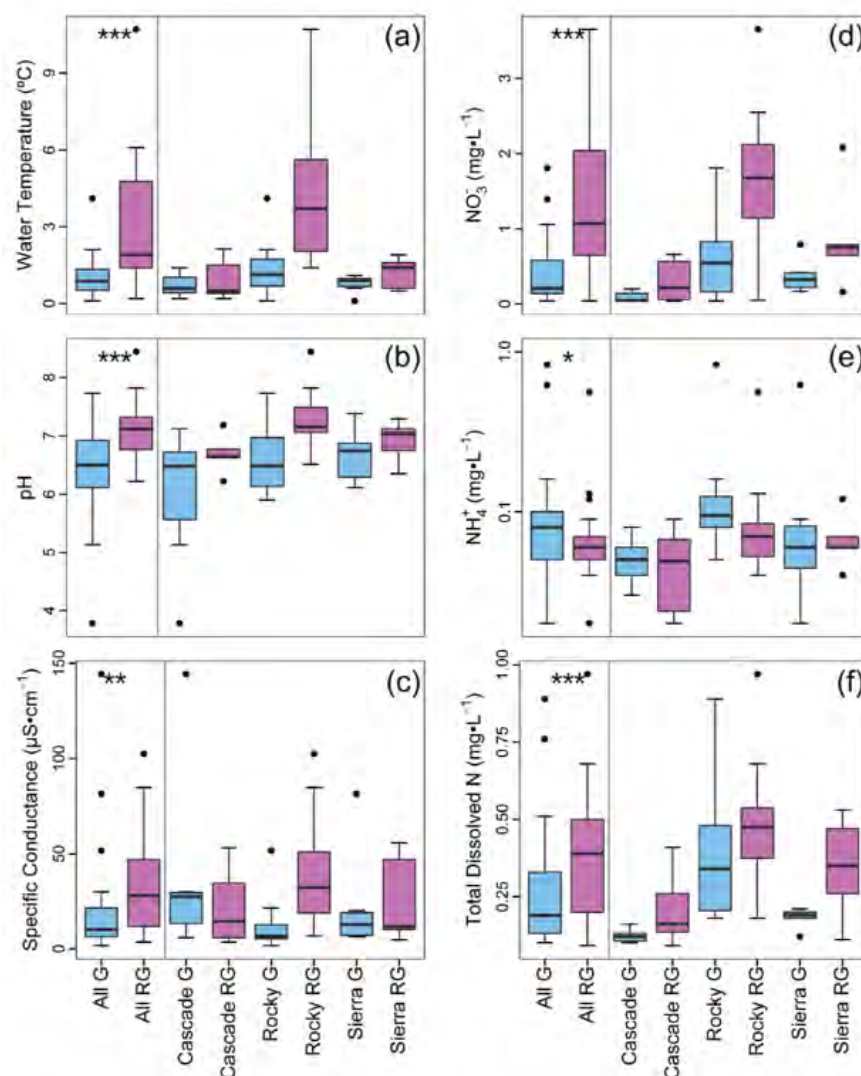


Figure 2. Physical and chemical measurements for glaciers and rock glaciers by mountain range. Glaciers are colored blue; rock glaciers are colored pink. Boxes represent upper and lower quartiles, whiskers indicate range of measurement, points indicate outliers, and bold bars indicate sample mean. * Indicates significance at $p < 0.05$, ** at $p < 0.01$, and *** at $p < 0.001$ using Welch-Satterthwaite T-Test for nonparametric sample sets.

The microbial community diversity was highest in the Rocky Mountains and lowest in the Sierra Nevada, although the lower richness from the Sierra Nevada could have been due to the smaller sample size (Fig. 3a). Ribosomal DNA sequencing revealed greater microbial diversity and also richness in rock glacier meltwater than glacier meltwaters (Fig. 3b). Whereas there was a considerable number of shared operational taxonomic units between glacial stream sediment types, there was also a large number of operational taxonomic units that were unique to each glacial stream sediment type with variability between sites as large as variability between glacier and rock glacier stream sediments. The Cascades samples shared over 50% of their operational taxonomic units with the Rockies (Fig. 3c).

The DOM values we observed for glaciers ($0.74 \pm 0.49 \text{ mg C L}^{-1}$) and rock glaciers ($0.82 \pm 0.59 \text{ mg C L}^{-1}$) were low. Differences in the structure of organic matter, revealed from the fluorescence indices, could cause differences in alpine ecosystem activity through preferential lability of compounds specific to a glacial type. Rock glaciers had higher humification, or complexity, of organic matter than glaciers. This suggests that rock glacial DOM is less labile than that of glaciers. We think this is possibly because: 1) there is likely quantitatively more (and more diverse) biological activity occurring within the pore spaces and stream sediments of the rock glacier, producing a broader range of more

complex and recalcitrant DOM compounds than glaciers; and 2) meltwaters of rock glaciers receive complex organic compounds leached from plants living on the rock glacier surface. Ice glaciers do not have plants growing on their surface, thus lack allochthonous input of complex DOM to their ice. These explanations are consistent with our analyses of the bacterial communities associated with each glacial type, as we saw higher microbial diversity and DOM complexity in rock glacier stream sediments compared to glacier stream sediments.

Rock glacier meltwaters may be representative of what future biogeochemical inputs will be in currently ice-glaciated watersheds. With increasing air temperatures, the elevated biogeochemical and microbial characteristics of rock glaciers compared to glaciers will likely dominate meltwaters that reach sensitive headwater ecosystems. Further, some glaciers are likely to become more rock glacier-like in the biogeochemistry of their meltwaters and increase the biogeochemical signal of rock glaciers on the alpine headwaters they feed. Our results suggest that both glacier type and range specific biogeochemical characteristics may provide bottom up controls on ecosystem function. Understanding which biogeochemical characteristics will be a function of glacier type and which will be driven by region allows for better implementation of management strategies to protect and adapt to these changing headwater ecosystems.

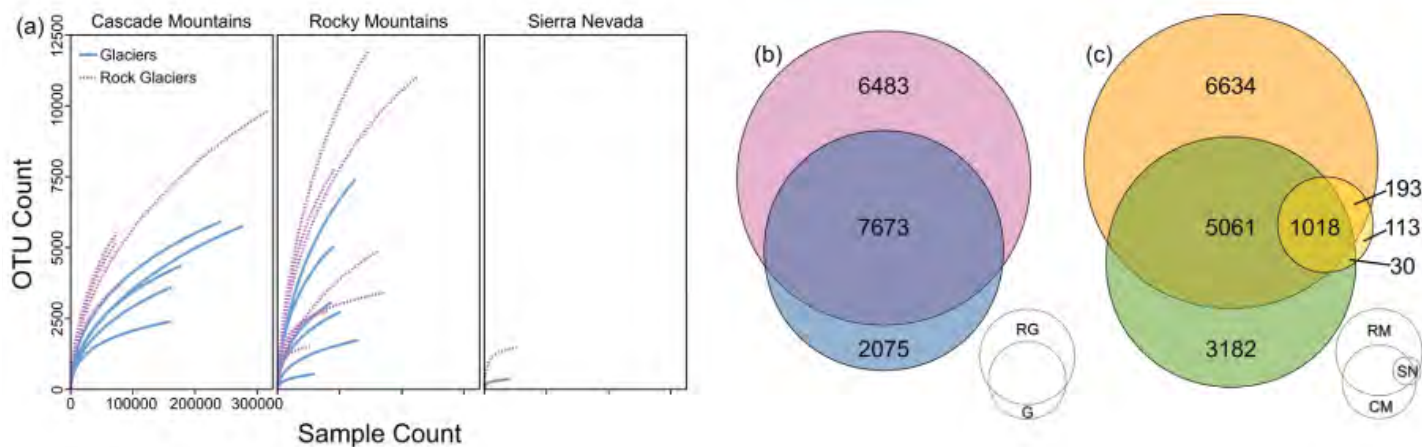


Figure 3. a) Rarefaction curves as an estimate of α -diversity for microbial communities sampled at the base of glaciers and rock glaciers in each of the surveyed mountain ranges. For each range, individual rock glaciers had higher microbial α -diversity than ice glaciers. Rock glaciers also had greater overall microbial richness (overall number of operational taxonomic units, or OTUs) at the measured sampling depth of each sample. Venn diagrams showing overlap in membership between microbial communities sampled from b) glaciers and rock glaciers (labeled G and RG), and c) between mountain ranges (Cascade Mountains = CM, Rocky Mountains = RM, and Sierra Nevada = SN). All numbers are representative of OTUs that are novel to their respective feature or area, or are common between overlapping spheres. Rock glaciers had a greater number of unique OTUs, however there was a large number of cosmopolitan OTUs between glacier types. The Rockies had the greatest number of OTUs, and shared the most OTUs with the Cascades. The Sierra Nevada had the fewest OTUs, and the majority was shared between all three mountain ranges.

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Delta Lake, Grand Teton National Park, Rocky Mountains, WY. Photo: Megan Otu

Catchment Characteristics and Landscape Position Regulate Dissolved Organic Matter in Lakes throughout the Sierra Nevada

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Sadro, S., C.E. Nelson, and J.M. Melack. 2012. The influence of lake landscape position and catchment characteristics on the biogeochemistry of lake chains in the Sierra Nevada (California). Ecosystems 15:363-186. DOI 10.1007/s10021-011-9515-x.

Dissolved organic matter (DOM) controls fundamental aspects of lake ecosystems (Williamson et al. 1999). It's often the largest pool of carbon in lakes, and because colored dissolved organic matter absorbs solar radiation, it regulates the amount of light available throughout the water column and structures thermal dynamics in lakes (Fee et al. 1996). As a result, a wide range of ecosystem processes are affected by DOM, including ecosystem rates of primary production and respiration, biogeochemical reaction rates, physical lake dynamics such as stratification and mixing, dissolved oxygen concentrations, the feeding behavior of organisms, and food web structure (Solomon et al. 2015). Importantly, it is both the concentration and composition of the DOM pool that affects these processes.

The DOM in lakes is composed of a mixture of compounds of varying molecular weights and structures that come from two primary sources. It originates as organic matter fixed within a lake by aquatic primary producers (autochthonous) or as terrestrial organic matter that is subsequently flushed into lakes or streams (allochthonous). Thus, both lake trophic status and rates of terrestrial loading determine DOM dynamics in lakes. The distinction between these two sources is important because autochthonous organic matter is thought to be more labile and bioavailable for microbes, while terrestrial DOM is more colored and comprised of larger organic molecules that are more resistant to biodegradation. Although the concentration of dissolved organic matter in lakes varies across the landscape, inputs to lakes have been changing systematically in some regions (Monteith et al. 2007, Roulet and Moore 2006). An understanding of the factors that regulate DOM dynamics in Sierra Nevada lakes is important for understanding how these systems may respond to changes in climate forcing.

As part of an effort to characterize the landscape factors that regulate the biogeochemistry of Sierran lakes, (Sadro et al. 2012) sampled epilimnetic waters from nearly 80 lakes from 14

catchments spanning longitudinal and elevational gradients of the Sierra Nevada (Fig. 1). Water samples were collected during the period of summer stratification and analyzed to determine the concentrations of dissolved organic carbon and nitrogen; and fluorescence analyses were done to characterize DOM composition. Lake productivity was assessed by measuring chlorophyll-a concentrations. Landscape characteristics were quantified through GIS analysis of USGS land cover and elevation data layers.

Sierra Nevada mountains of California

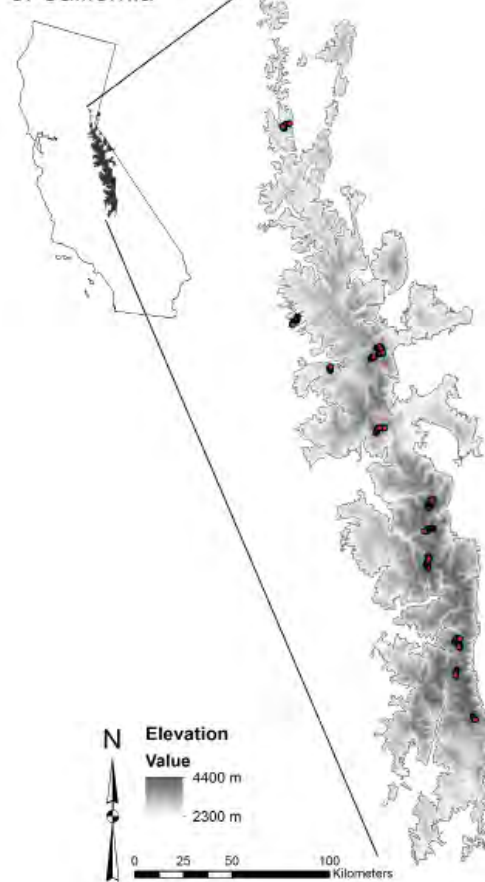


Figure 1. Map of California (inset) and the Sierra Nevada (outline is the 2300 m elevation contour). Red markers identify 76 lakes sampled from 14 catchments spanning the Sierra as part of this study.

What Regulates the Concentration of Dissolved Organic Matter in Sierran Lakes?

Dissolved organic matter concentrations in Sierran lakes are low, yet they vary by over an order of magnitude. DOC ranged from 11–317 $\mu\text{mol L}^{-1}$, DOP from less than 0.1–1 $\mu\text{mol L}^{-1}$, and DON from 4–18 $\mu\text{mol L}^{-1}$ among all the lakes we sampled. Such variation is driven largely by elevation and natural gradients in terrestrial inputs rather than lake productivity. For example, most Sierran lakes are oligotrophic, with chlorophyll-*a* concentrations that average less than 1 $\mu\text{g L}^{-1}$ and rarely climb above 3 $\mu\text{g L}^{-1}$. In contrast, the proportion of vegetation cover and extent of soil development vary dramatically with elevation, creating a large gradient in the source-pool of terrestrial organic matter available to wash into lakes.

Alpine habitats located above tree line are dominated by steep slopes with bare rock and loose scree. Where slopes are more gradual in alpine habitats, wet meadows and alpine tundra are present. Soil development and vegetation cover increase as you drop to lower elevations into the sub-alpine and montane zones. At these lower elevations slopes become less steep and both

shrub and forest cover increase. Over a distance of just a few kilometers it is possible to transition from a landscape nearly devoid of vegetation to one dominated by forest and shrub.

Such changes in habitat characteristics play an important role in structuring variation in DOM among lakes. Elevation, slope, and the proportion of rock or vegetation cover in catchments were all related to different measures of organic matter concentration (Fig. 2). Dissolved organic carbon (DOC) and total fluorescence (TF) both increased relatively consistently along these landscape gradients. Because terrestrial sources contribute to DOC pools (Gergel et al. 1999, Hood et al., 2005), DOC was expected to increase along downstream flow paths, especially in conjunction with increasing vegetation cover. Excluding three outlier catchments with abundant wet meadow or alpine tundra habitats (Fig. 2), shrub cover accounted for 42% and 56% of the variability in DOC and TF, respectively, an amount comparable to that explained by vegetation cover in other systems (Gergel et al. 1999, Martin and Soranno 2006). In contrast to the consistent change in DOC and TF with vegetation cover, the increase in dissolved organic nitrogen (DON) and phosphorus (DOP) was larger through the alpine zone than lower elevations, where shrub

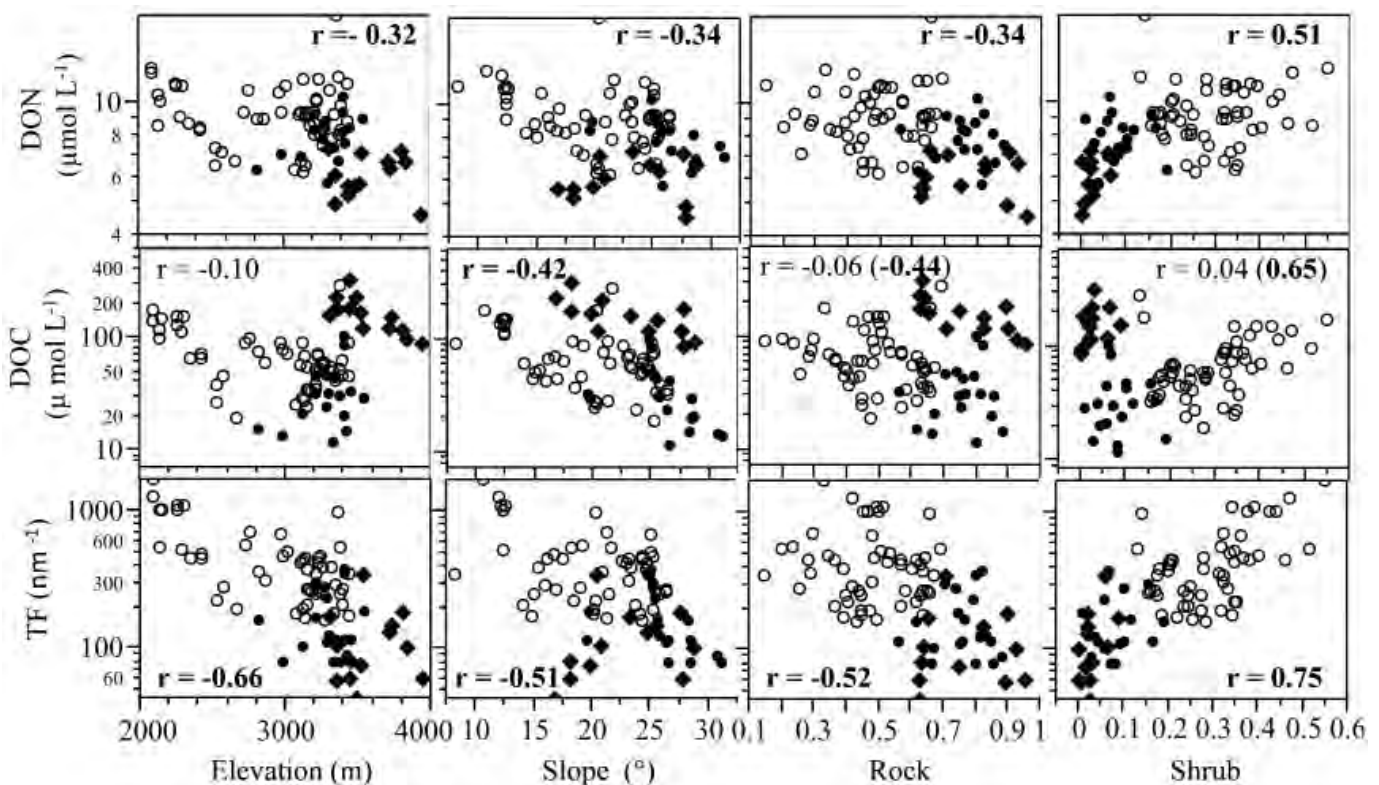


Figure 2. Landscape influences on dissolved organic matter: Dissolved organic carbon (DOC), dissolved organic nitrogen (DON), and total fluorescence (TF), a relative measure of the overall magnitude of dissolved organic matter. Not shown is dissolved organic phosphorus (DOP), which has the same pattern as DON. Black symbols correspond to lakes in the alpine zone (e.g., where vegetation cover is <20% and rock cover is >70%). Squares are lakes from two catchments dominated by alpine tundra. Values are Pearson correlation coefficients and bold are $p < 0.05$; values in parenthesis are correlation coefficients excluding outlier catchments.

cover was greater than ~25%. These differences in the behavior of DOC and DON or DOP concentrations along gradients in shrub cover suggest the composition of organic matter changes along landscape gradients, hinting at differences in the quality of organic matter among lakes.

How do Landscape Characteristics Affect the Composition of Dissolved Organic Matter in Sierran Lakes?

The stoichiometric composition of DOM is one of a number of ways to assess its quality and trace its source. For example, organic matter from terrestrial sources, which has higher cellulose and lignin content, typically has C:N ratios near 40. In contrast, C:N ratios in organic matter from aquatic sources are typically 5 – 10. Thus, increasing C:N or C:P ratios are indicative of less labile organic matter of terrestrial origin. Excluding the lakes in catchments dominated by alpine tundra, the C:N ratio of DOM increased linearly with shrub cover in the Sierra (Fig. 3A), suggesting DOM in lakes at lower elevations becomes increasingly dominated by terrestrial sources. The outlier lakes in tundra or wetland dominated catchments had the lowest quality DOM, with C:N ratios between 40 and 70.

The fluorescence characteristics of water can also be used to quantify relative allochthonous and autochthonous composition. The Fluorescence Index (McKnight et al. 2001) is a relative measure of terrestrial and aquatic sources of fulvic acid in DOM, with values near 1.2 reflecting allochthonous sources and 1.8 reflecting autochthonous sources. While there were only weak patterns in FI with landscape gradients in vegetation, classifying lakes according to their surrounding catchment characteristics demonstrated strong landscape effects on the composition of dissolved organic matter (Fig. 4). Lakes with the largest terrestrial signal in DOM (FI ~1.25) were located in catchments where wetlands or alpine tundra were abundant (i.e., the outlier lakes in Fig. 2 discussed above). Lakes in alpine catchments with little vegetation of any kind had the most autochthonous DOM (FI ~1.65). Falling between these end members and demonstrating an increasingly terrestrial signal in DOM composition with vegetation cover were lakes in subalpine catchments (FI~1.55) and shrub dominated habitats (FI~1.45).

Two other lines of evidence suggest DOM in Sierran lakes becomes increasingly allochthonous with increasing vegetation cover in catchments. First, the ratio between chlorophyll-a and TF, which reflects the balance between autochthonous and allochthonous source of DOM, decreases with increasing vegetation cover surrounding lakes (Fig. 3B). This indicates DOM dynamics in alpine lakes are governed by phytoplankton to a larger extent than at lower elevations, where increasingly dense

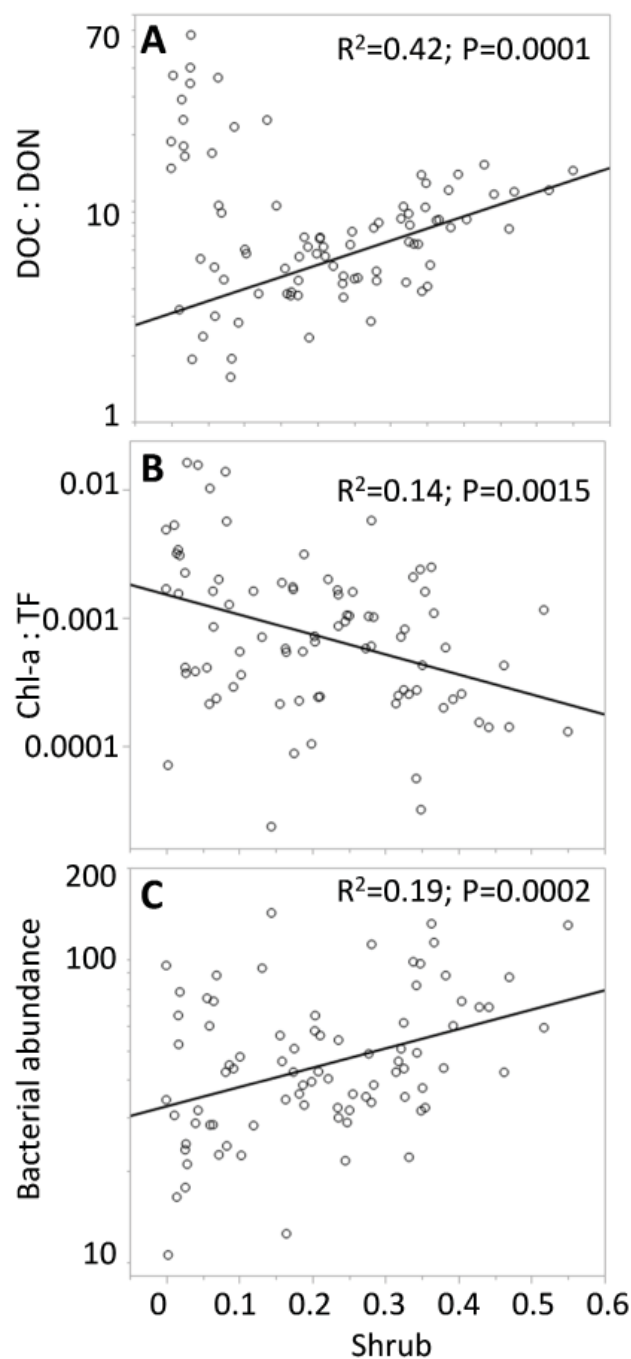


Figure 3. The terrestrial composition of DOM in Sierran lakes increases with increasing vegetation cover in the surrounding catchments, as illustrated through three separate indexes of allochthony along landscape gradients in proportion shrub cover: A) The ratio between chlorophyll-a and total fluorescence (TF) decreases with increasing shrub cover, reflecting a DOC pool increasingly dominated by terrestrial sources; B) Bacterial abundance (cells mL⁻¹ x10⁴) increases with increasing shrub cover, reflecting increasing heterotrophic biomass; and C) The DOC to DON and DOP ratios increase with increasing shrub cover, suggesting less labile material is contributed from catchment sources (DOC:DOP $R^2=0.19$; $P=0.0002$; outlier lakes from alpine tundra excluded from regression analysis).

vegetation causes a shift toward terrestrial sources of organic matter. Second, bacterioplankton abundance increases with decreasing elevation and increasing shrub cover (Fig. 3C), which suggests allochthonous carbon subsidies at lower elevations are supplementing heterotrophic microbial biomass.

Wetlands and the Effect of Small Scale Habitat Heterogeneity on DOM

Although many catchment characteristics change gradually with elevation, small scale habitat heterogeneity can confound our ability to predict DOM at larger spatial scales. For example, models that predict the concentration or composition of DOM in lakes were much more accurate within individual catchments, where up to 90% of variation was explained, than at among catchment spatial scales. Much of the unexplained variation in DOM along elevation gradients can be attributed to the presence of specific habitat types. In particular, wet meadow or tundra, which occurs across a broad elevation range, leach high concentrations of terrestrial DOM into lakes. Such spatial variation accounts for the behavior of the outlier lakes in our analysis (Fig. 2, black diamonds). Although meadow or tundra land cover classifications were not quantified as part of our study, they have been shown to be important contributors of DOC to aquatic systems at small spatial scales (Gergel et al.

1999, Williams et al. 2001). Accounting for these habitats will be critical for refining our ability to predict DOM in Sierran lakes, especially given their sensitivity to drought associated with climate change.

How Might Climate Change Alter DOM Dynamics in the Sierra Nevada?

There are multiple ways in which climate change may alter DOM loading in Sierran lakes. Warming temperatures are causing a shift in the distribution of plants, allowing an upward migration of vegetation to elevations that were historically denuded. With an increase in the frequency of prolonged periods of drought, less terrestrial DOM is flushed into lakes, with the potential to increase transparency (Williamson et al. 2016). Similarly, prolonged or repeated drought disrupts hydrologic connectivity in wetlands and reduces carbon fluxes into lakes. Conversely, a shift in the frequency of precipitation falling as rain rather than snow has the potential to mobilize larger amounts of terrestrial DOM from catchment soils, reducing transparency and altering ecosystem function (Sadro and Melack 2012). Such changes underscore the importance of understanding the factors that regulate the concentration and composition of dissolved organic matter in Sierran lakes.

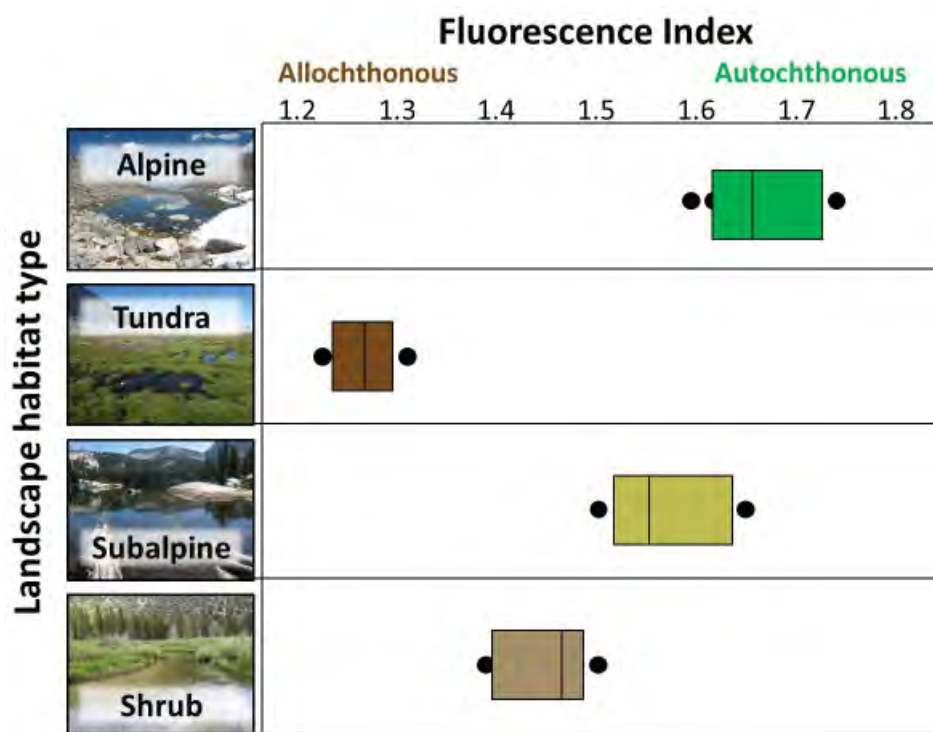


Figure 4. The composition of organic matter in Sierran lakes is strongly affected by the habitat characteristics of the surrounding catchment. The Fluorescence Index (FI) characterizes the relative contributions of autochthonous and allochthonous sources of fulvic acid to the DOM, and helps resolve differences between terrestrial and aquatic sources of dissolved organic carbon in lakes.

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Deep Trouble: The Dramatic Loss of Benthic Invertebrates at the Bottom of Lake Tahoe

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Caires, A. M., S. Chandra, B. L. Hayford, and M. E. Wittmann. 2013. Four decades of change: dramatic loss of zoobenthos in an oligotrophic lake exhibiting gradual eutrophication. *Freshwater Science* 32:692-705.

Two of the most common anthropogenic causes of ecosystem change in lakes are eutrophication (increased nutrient inputs resulting in algal growth and decreased clarity) and the introduction of invasive species (Sala et al. 2000, Lodge 2001, Schindler 2006, Smith et al. 2006). Such anthropogenic disturbances can affect organisms such as invertebrates and aquatic plants that occupy the benthos (bottom) of lakes. Lake Tahoe is a large, deep lake that has experienced eutrophication and an associated decline in clarity of almost 10 m in the past four decades (Goldman 1988, Jassby et al. 2003). Lake Tahoe has also seen the introduction of several non-native species, including mysid shrimp, crayfish, and Asian clams (Linn and Frantz 1965, Frantz and Cordone 1996, Wittmann et al. 2012). Lake Tahoe's assemblage of invertebrates living at the bottom of the lake is unique, and includes 10 endemic species, including stoneflies, blind shrimp (amphipods), flatworms, a seed shrimp (ostracod), and segmented worms (oligochaetes). We compared historical (1962-63) collections of benthic invertebrates in Lake Tahoe to our own (2008-09) collections of benthic invertebrates to determine if the distribution and density of these invertebrates have changed in response to recognized changes in the lake over the past four decades.

We attempted to replicate the spatial and vertical distribution of sample collection, as well as the sampling effort from the 1962-63 collections by Frantz and Cordone (1996). Benthic grab samples were collected in Lake Tahoe in 2008-09 from four transects from 1-450 m in depth (Fig. 1). All invertebrates visible to the naked eye were handpicked from each sample and were identified and enumerated. The presence or absence of aquatic plants in each sample was noted. We obtained previously-archived data from collections in 1962-63 to make direct comparisons of benthic invertebrate density, distribution, and aquatic plant presence between our surveys and those of Frantz and Cordone (1996). The collections from 1962-63 were made along transects at four locations from 1-501 m in depth.

Lakewide density of most benthic invertebrate taxa has declined since the 1960s (Table 1). Lakewide density of all benthic invertebrates combined decreased ~75%, and density of endemic invertebrate taxa decreased from 80 to >99.9% (Table 1). Declines were most striking between 50 and 110 m, where all native and endemic taxa except for pea clams (*Pisidium* spp.) declined significantly. Within this same depth interval (50 to 110 m), aquatic plant occurrence in samples was much lower in our 2008-09 collections than it was in the 1962-63 collections (Fig. 2). Aquatic plants were also found in deeper water in the 1960s than they were in our recent collections (Fig. 2). Peaks in density of most benthic invertebrate taxa collected in 1962-63 were within or near the zone of peak aquatic plant occurrence during that time period, with the exception of blind amphipods (*Stygobromus* spp.), whose densities peaked at depths deeper

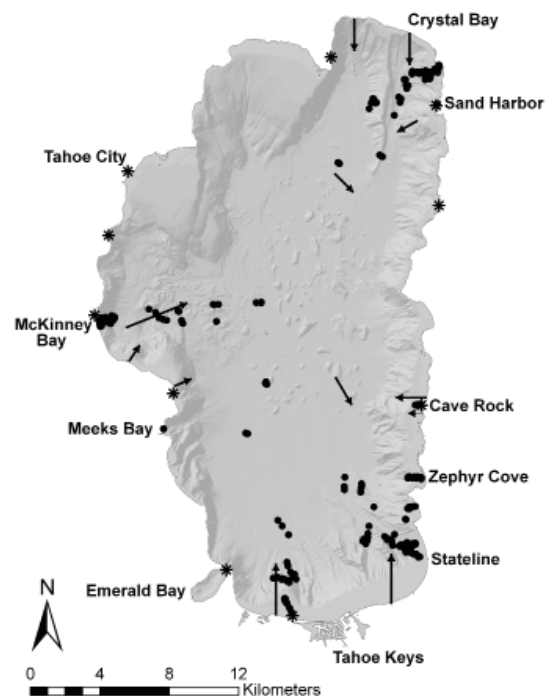


Figure 1. Map of Lake Tahoe with sampling sites indicated. Circles show benthic grabs taken in 2008-09 and arrows show transects from which benthic grabs were collected in 1962-63 (Frantz and Cordone 1996).

Taxon	1962-1963	2008-2009	% change
Density	(n = 389)	(n = 420)	
<i>Stygobromus</i> spp.	762.0 ± 179.5	0.1 ± 0.1	<-99.9
Turbellaria	164.3 ± 46.6	0.02 ± 0.02	<-99.9
<i>Candona tahoensis</i>	131.8 ± 57.2	21.9 ± 12.2	-83.4
<i>Capnia lacustra</i>	3.1 ± 1.7	0.2 ± 0.1	-93.5
Oligochaeta	938.8 ± 191.0	402.2 ± 79.4	-57.2
Gastropoda	6.2 ± 4.1	2.8 ± 1.9	-54.8
Chironomidae	68.1 ± 21.5	44.8 ± 11.0	-34.2
<i>Pisidium</i> spp.	3.3 ± 1.9	10.9 ± 2.9	230.3
All invertebrates	2134.9 ± 401.9	534.8 ± 103.5	-74.9

Table 1. Mean (± 1 SE) lakewide-weighted densities (no./m²) of benthic invertebrate taxa collected in historical and contemporary collections in Lake Tahoe. Percent change in density since the 1962-63 collections is given for each taxon. See Caires et al. (2013) for details about calculations of lakewide-weighted densities.

than most aquatic plant occurrence (Fig. 3A). Except for pea clams, benthic invertebrate densities from collections in 2008-09 were very low compared to densities in 1962-63 in the zone of historical peak aquatic plant occurrence, making this the zone in which the greatest invertebrate density declines were observed (Figs. 3A–H).

Our data suggest that the reductions in benthic invertebrate and aquatic plant communities in Lake Tahoe are closely tied. Benthic invertebrate associations with deepwater plant assemblages in Lake Tahoe have been documented previously (Frantz and Cordone 1996), and aquatic plants in lakes have long been known to support a greater abundance of aquatic invertebrates than sediments without aquatic plants (Krecker 1939, Dvořák and Best 1982, Brown et al. 1988, Newman 1991). Aquatic plants provide a surface for growth of algae, which can be an important food source for benthic invertebrates and plants also provide habitat and a refuge from predators. The macroalga, *Chara* spp., which was common in benthic samples from Lake Tahoe in the 1960s and was much less abundant in recent samples, is known for supporting especially large and speciose benthic invertebrate communities (Hanson 1990).

The large reduction in the density of blind amphipods (*Stygobromus* spp.) in Lake Tahoe does not appear directly tied to the reduction in aquatic plants, since historical populations of blind amphipods were found deeper than the occurrence of most aquatic plants. It is possible, however, that organic matter derived from aquatic plants in Lake Tahoe may have provided a food source for these deepwater blind amphipod populations if decomposing organic material was transported to deep areas of the lake. Lake Tahoe supported an extremely large population of blind amphipods between 60 and 500 m in the 1960s. Such a high density of benthic invertebrates is rare in the profundal zones of deep lakes, which are generally thought of as

depauperate (Goedkoop and Johnson 1996, Vadeboncoeur et al. 2003). The contribution of organic material from aquatic plant beds to profundal zones of deep lakes has not been examined, but such aquatic plant “food falls” have been documented in marine systems, in which populations of deepwater amphipods are attracted to the resulting organic material as a food source (Lawson et al. 1993, Vetter 1995, 1998).

The observed declines in the density and distribution of benthic invertebrates and deepwater plants in Lake Tahoe coincide with changes to the lake’s pelagic condition. Lake Tahoe’s decrease in clarity over the past four decades has been associated with a shift in the bottom of the euphotic zone (1% light penetration) from 80 to 57 m (Chandra et al. 2005). Progressive eutrophication since

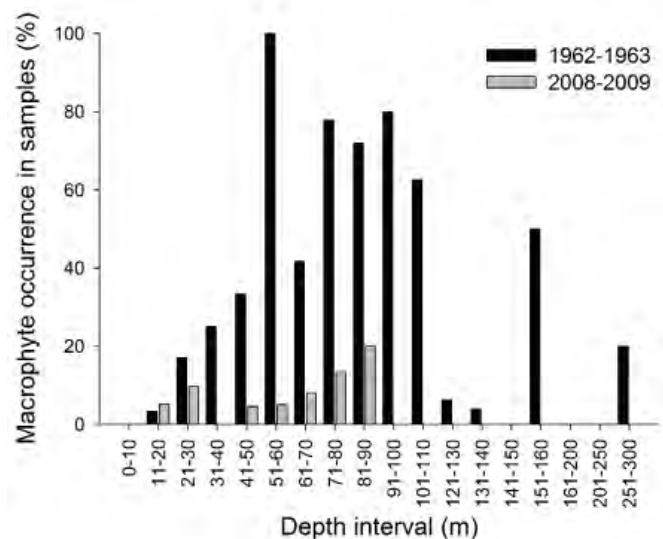


Figure 2. Percent occurrence of aquatic plants in historical and contemporary benthic samples collected from Lake Tahoe. Occurrence is defined as the presence of plant material in a sample.

the 1960s probably has caused increased shading to areas of the lake bottom that previously supported widespread plant and algal growth.

Nonnative species also could have contributed to the observed declines in benthic invertebrate density and aquatic plant occurrence in Lake Tahoe. In 1963-65, shortly after the 1962-63 benthic invertebrate survey, 333,000 mysid shrimp (*Mysis relicta*) were introduced to Lake Tahoe as a food source for lake trout (*Salvelinus namaycush*) (Linn and Frantz 1965, Frantz and Cordone 1996). Mysid shrimp in Lake Tahoe feed at night in the water column and return to the bottom of the lake during the

day to avoid fish predation, for a total daily vertical migration of up to 1000 m (Rybock 1978). *Mysis relicta* is omnivorous and consumes a variety of benthic and pelagic food items, including zooplankton, larval amphipods, and even small fish larvae (Parker 1980, Sealer and Binowski 1988, Johannsson et al. 2001, Bailey et al. 2006). It is possible that mysid shrimp have used native benthic invertebrates in Lake Tahoe as a food source, especially exposed blind amphipods (*Stygobromus* spp.) in profundal areas too deep for plant growth. Mysid shrimp were collected in benthic samples in 2008-09, and several shrimp were found in grabs that also contained the endemic stonefly *Capnia lacustra* and the blind amphipod *Stygobromus* spp.

Another nonnative invertebrate that could be affecting native benthic invertebrate and aquatic plant assemblages in Lake Tahoe is the signal crayfish (*Pacifastacus leniusculus*). Crayfish have been present in the lake since 1895, but crayfish catch per unit effort (CPUE) has nearly doubled since the 1960s (J. Umek, University of Nevada, Reno, unpublished data). Adult crayfish in Lake Tahoe target algae and aquatic plants for food, whereas juveniles consume mainly small benthic invertebrates (Flint 1975). Crayfish in Lake Tahoe migrate to >50 m in depth in the winter (J. Umek, University of Nevada, Reno, unpublished data). Thus, they potentially could affect deepwater plant assemblages and their associated fauna. The specific effects of nonnative species on benthic invertebrate and plant populations in Lake Tahoe are not well understood, but they probably have contributed to the declines observed in our study.

The long period between sampling events makes it difficult to determine whether the declines observed in our study are solely a function of changes that have occurred to the lake over the past four decades, or if the declines also reflect temporal variation in benthic invertebrate populations. However, the absence or extreme scarcity of several endemic taxa (*Phagocata tahoena*, *Dendrocoelopsis hymanae*, *Stygobromus lacicolus*, *Stygobromus tahoensis*, and *Capnia lacustra*) in our collections indicates that these taxa are at risk of extinction. Research is needed to examine seasonal variation in the abundance and distribution of endemic taxa, the association between endemic taxa and native aquatic plants, and mechanisms contributing to the observed declines in native plant and invertebrate communities in Lake Tahoe.

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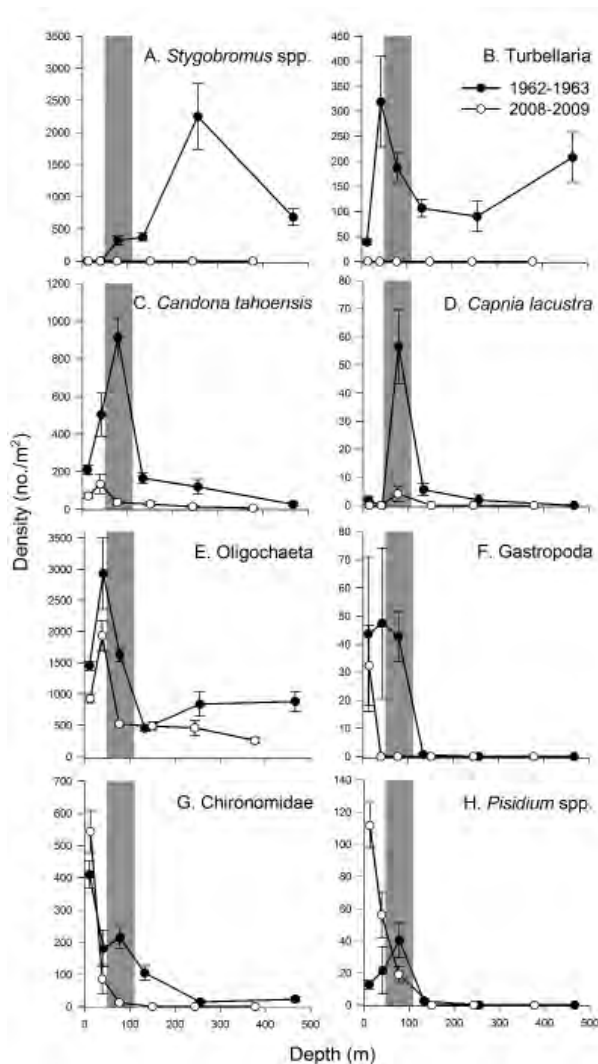


Figure 3. Mean (± 1 SE) density by depth for blind amphipods (*Stygobromus* spp., A), flatworms (*Turbellaria*, B), seed shrimp (*Candona tahoensis*, C), the deepwater stonefly (*Capnia lacustra*, D), segmented worms (*Oligochaeta*, E), snails (*Gastropoda*, F), non-biting midges (*Chironomidae*, G), and pea clams (*Pisidium* spp., H). The grey area from 50-110 m indicates the depth in which aquatic plant beds were concentrated in the 1960s.

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A Tale of Three Lakes: A Comparison of Biodiversity between Lake Tahoe and Crater Lake, USA, and Lake Hövsgöl, Mongolia

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Lake Tahoe is one of the largest lakes in the world. Large lakes, those lakes with depths greater than 100 m or surface areas greater than 248 km², comprise less than 0.0001% of the world's lakes (Herdendorf 1982, Downing et al. 2006). Despite this rarity, the world's largest and deepest lakes are valuable resources, serving as cultural icons such as Lake Tahoe and supporting a significant part of the world's freshwater biodiversity (Vadeboncoeur et al. 2011). A major goal of conservation is maintaining biodiversity, but biodiversity of freshwater invertebrates is often overlooked (Strayer 2015), particularly in large lakes (Vadeboncoeur et al. 2011). Human activities have impacted lake ecosystems, impairing biodiversity (Dodson et al. 2000) and necessitating assessment and monitoring of lake communities. Lake Tahoe's bottom or benthic invertebrate community has shown significant declines over the past four decades (Caires et al. 2013) and since the benthic habitat of large lakes supports at least 95% of all invertebrate species from large lakes (Vadeboncoeur et al. 2011), this decline in Lake Tahoe invertebrates likely affects biodiversity in the entire lake. Direct comparison of biodiversity is the basis of most biological monitoring for conservation research (Noss 1990), but biodiversity comparisons between insular ecosystems such as large, deep lakes are difficult, often due to great geographic distance between lakes.

Using a widespread group of environmentally sensitive, bottom-dwelling lake invertebrates may overcome difficulties in comparing biodiversity of large lakes, particularly lakes facing impacts from human activities. Thus, biodiversity of the common and widespread non-biting midges or Chironomidae was compared between Lake Tahoe, USA and two other large, deep lakes: Lake Hövsgöl, Mongolia and Crater Lake, USA. All three lakes are ecologically similar (e.g. deep and large, alpine to subalpine, north temperate lakes) and represent different management strategies along a conservation gradient (Fig. 1). Chironomidae are useful in comparison studies of this kind as they are sensitive to environmental change in lakes such as

increased nutrients or eutrophication, and are particularly useful in tracking changes in trophic status of lakes from conditions of low nutrients (oligotrophic) to high nutrients (eutrophic) (Sæther 1975, Sæther 1979). The specific objectives of this study were to: 1) determine the trophic status of the three lakes using chironomid-based lake typology; 2) test whether community structure was similar between the three lakes despite geographic distance; and 3) examine the variation of diversity between lakes and depth regions within each lake.

Three Large Lakes

Lake Tahoe is a subalpine, ultra-oligotrophic to oligotrophic, graben lake in the states of California and Nevada, western USA, where increasing cultural eutrophication is coupling the flow of energy between the pelagic environment and benthic habitat where invertebrates reside. Crater Lake is an alpine, ultra-oligotrophic, caldera lake in the state of Oregon, western USA. Lake Hövsgöl is a subalpine, ultra-oligotrophic to oligotrophic, graben, lake in the Hövsgöl province in the north central region of Mongolia (for a detailed description of the three lakes see Goldman 1981, Kalbe and Schacke 1996, Goldman 2000, Chandra et al. 2005, Goulden et al. 2006, Larson et al. 2007a). Morphometric characteristics vary between the three lakes (Hayford et al. 2015). Crater Lake is managed entirely by the United States Federal Government as part of the National Park System and is the most conserved of the three study lakes. It has experienced little to no cultural eutrophication. Lake Hövsgöl, located in south central Siberia, is managed by the Mongolian government as a National Park, which has allowed some natural resource use and development on the shores of the lake. It faces increasing eutrophication from grazing and tourism. Lake Tahoe has the greatest amount of development of the three lakes, and it has experienced gradual cultural eutrophication over the past four decades from extensive land use and urbanization in its watershed. A total of 199 benthic samples were collected: 122 along 10 transects in Lake Tahoe in 2008-2009; 55 along 9 transects in Lake Hövsgöl in 1995 and 1997; and, 22 along 3 transects in Crater Lake in 2009 (Fig. 2; Hayford et al. 2015). Chironomidae were separated from other invertebrates and non-living parts of the samples and identified to genus. Other

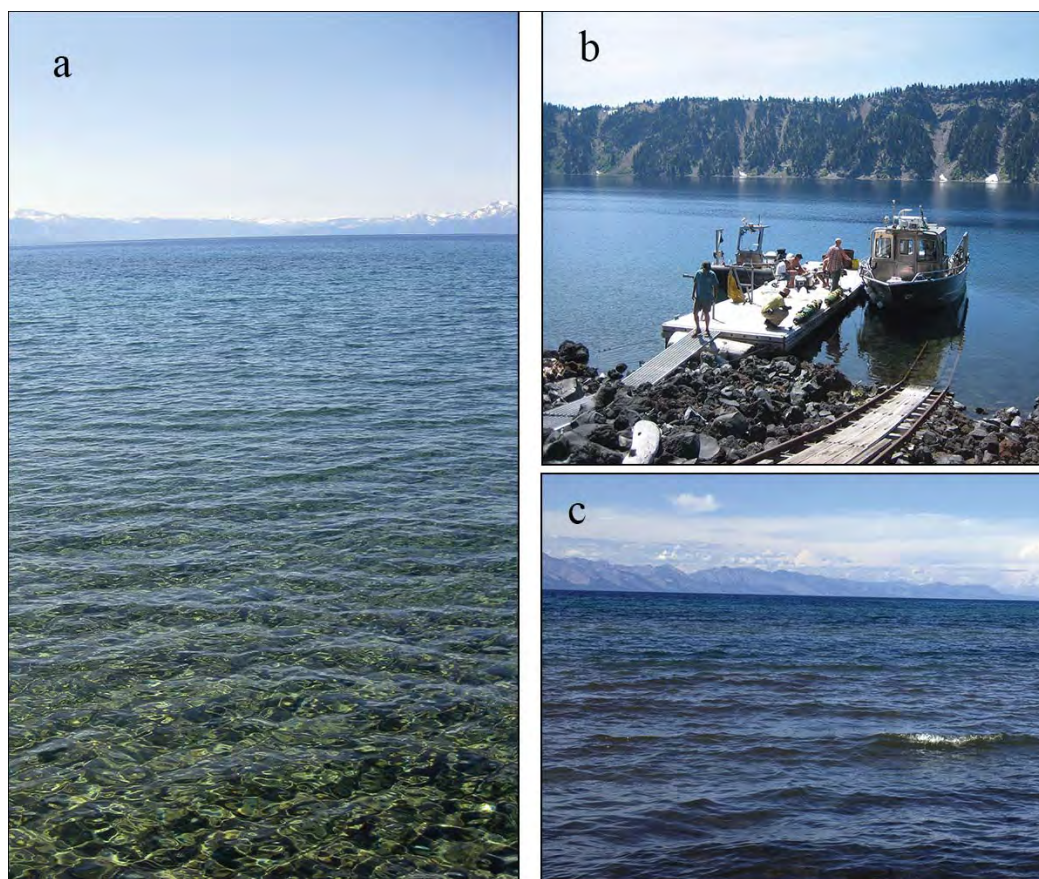


Figure 1. The three study lakes: (a) Lake Tahoe at King's Beach along the western shore in California; (b) Crater Lake, Oregon from the boat dock showing the research vessel and field crew; (c) Lake Hövsgöl, Mongolia, along the south eastern shore. Note the water clarity and surrounding mountains for each lake.

components such as substrate type were also identified from the samples (Hayford et al. 2015). Sampling did not involve endangered or protected species and permission was given for sampling the three lakes as described in Hayford et al. (2015).

Large lake ecosystems are complex and communities are structured in relation to their depth from the nearshore environment to the deepest reaches (Brinkhurst 1974). Comparisons between the three lakes were broken down into chironomid communities from two depth zones representing the nearshore and deep environments, as these two depth zones have very different benthic communities (Hayford and Ferrington 2006, Caires et al. 2013). Chironomid communities from soft substrates such as sand and silt were compared from the nearshore environment of the three lakes (defined as 3.5-25 m in depth) and the deep environment (defined as 30-60 m in depth) (Hayford et al. 2015). Lake typing based on chironomids (Sæther 1975, Sæther 1979) indicated trophic status of the deep

environment of the three lakes. An analysis of similarity was run to test whether community structure was similar between the three lakes despite geographic distance. Standard measures of diversity (Shannon-Wiener or H') were used to examine the variation of diversity between lakes and depth regions within each lake. See Hayford et al. (2015) for more details.

Lake Tahoe, Crater Lake and Lake Hövsgöl Differed in Trophic Class

Lake typology based on chironomids classified Lake Hövsgöl as ultra-oligotrophic, indicating very low nutrient concentrations and high clarity; Crater Lake as oligotrophic, indicating low nutrient concentrations and high clarity; and Lake Tahoe as oligotrophic to mesotrophic, indicating low to medium nutrient concentrations and moderate to high clarity. Chemical and optical clarity studies also show that Lake Hövsgöl and Crater Lake are ultra-oligotrophic to oligotrophic (Kalbe and Schacke 1996,

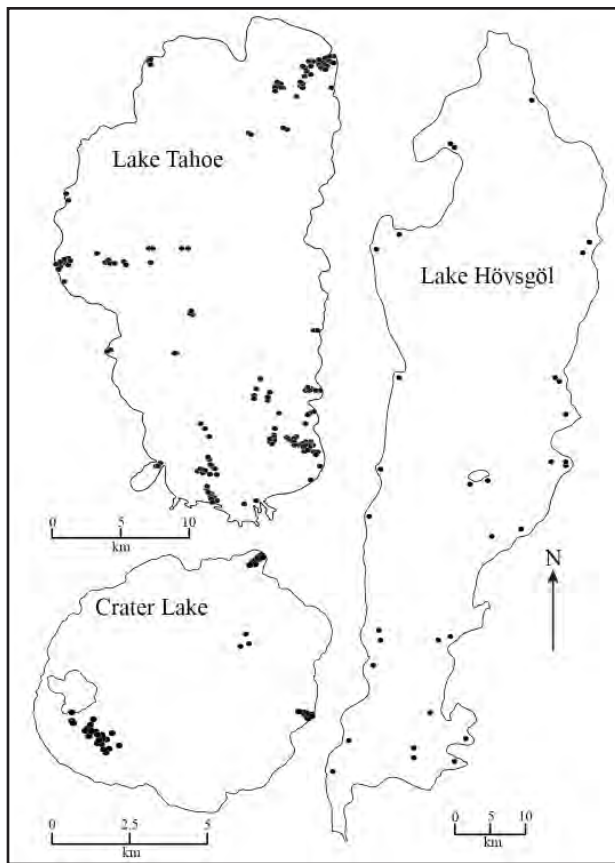


Figure 2. Map of Lake Tahoe, USA, Crater Lake, USA and Lake Hövsgöl, Mongolia. Solid circles indicate sampling locations in 2008 and 2009 for Lake Tahoe, 2009 for Crater Lake, and 1995-1997 for Lake Hövsgöl.

Goulden et al. 2006, Larson et al. 2007b). On the other hand, the lake typing of Lake Tahoe as oligotrophic/mesotrophic differs considerably from the traditional pelagic classification of the lake as ultra-oligotrophic to oligotrophic (Goldman 1981, Goldman 2000). The outcome of chironomid-based lake typology analysis of Lake Tahoe is supported by other studies showing impact to lake benthos by gradual eutrophication. Nutrient enrichment in Lake Tahoe has led to changes in energy flow between pelagic and benthic communities (Chandra et al. 2005), and significant declines in overall benthic taxa including major changes in chironomid communities (Caires et al. 2013). The differences we observed between benthic and pelagic measures of lake trophic condition based on benthic invertebrate community change may indicate a substantial shift in trophic state, while snapshot pelagic and nutrient indicators indicate only a gradual change. Thus, understanding changes to benthic environments may be a critical aspect of documenting functional changes in lakes that may not be otherwise signaled from traditional pelagic measurements.

Chironomid Communities Differed by Lake and Lake Zone

Large geographic distances and historical biogeographic differences should have produced very different chironomid communities between the three lakes (Fig. 3a), but the communities show some affinities (Fig. 3b). Analysis of similarity calculates the difference between communities as the overall amount of dissimilarity in pairwise comparisons

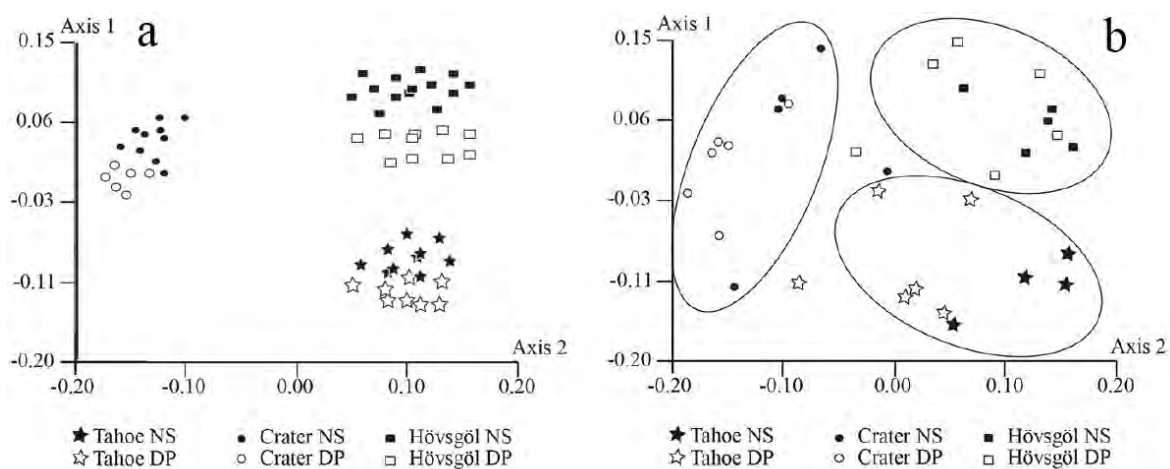


Figure 3. Predictions versus outcome of ordination based on non-metric multidimensional scaling (nMDS) analysis of chironomid communities from the three lakes and lake zones (black fill and NS = nearshore, no fill and DP= deep zone) in this study. (a) Prediction of how sites and depth zones may separate in an ordination given geographic distance of the lakes; (b) Outcome of nMDS with two axes chosen to best display the data (stress = 0.20).

Group pairwise comparison		ANOSIM	
Lake and habitat	Lake and Habitat	<i>R</i>	Significance
Lake Tahoe nearshore	Lake Tahoe deep	0.28	$p < 0.01$
Lake Tahoe nearshore	Crater Lake nearshore	0.50	$p < 0.01$
Lake Tahoe nearshore	Crater Lake deep	0.56	$p < 0.01$
Lake Tahoe nearshore	Lake Hövsgöl nearshore	0.30	$p < 0.01$
Lake Tahoe nearshore	Lake Hövsgöl deep	0.03	NS
Lake Tahoe deep	Crater Lake nearshore	0.17	$p < 0.01$
Lake Tahoe deep	Crater Lake deep	0.29	$p < 0.01$
Lake Tahoe deep	Lake Hövsgöl nearshore	0.47	$p < 0.01$
Lake Tahoe deep	Lake Hövsgöl deep	0.14	NS
Crater Lake nearshore	Crater Lake deep	0.32	$p < 0.01$
Crater Lake nearshore	Lake Hövsgöl nearshore	0.59	$p < 0.01$
Crater Lake nearshore	Lake Hövsgöl deep	0.89	$p < 0.01$
Crater Lake deep	Lake Hövsgöl nearshore	0.65	$p < 0.01$
Crater Lake deep	Lake Hövsgöl deep	0.92	$p < 0.01$
Lake Hövsgöl nearshore	Lake Hövsgöl deep	0.03	NS

Table 1. Pairwise comparisons of chironomid communities from the different habitats in Lake Tahoe, Crater Lake, and Lake Hövsgöl. Distance *R*-statistics and *p*-values given from ANOSIM. The closer *R* is to 1 the greater the distance or dissimilarity between two communities being compared.

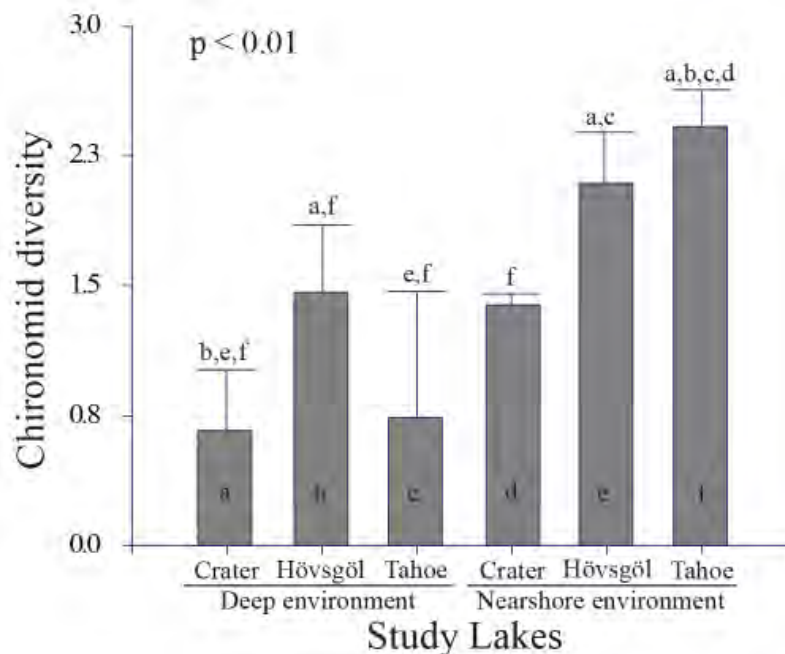


Figure 4. Variation in mean (± 1 SE) taxon diversity of chironomid communities in this study. The y axis represents Shannon-Wiener diversity (H'). The x axis represents lake zones and lakes. Letters that differ above and within the bars indicate a significant difference in mean diversity (H') ($p < 0.05$; one-way ANOVA, Tukey's test) for chironomid communities collected from the different lake regions and lakes.

with R values closer to 1 indicating the most different or dissimilar communities. Conversely, the closer R is to 0 the more similar two communities are. Surprisingly, most community dissimilarities were relatively low (Table 1). Dissimilarities were not significantly different between the chironomid communities in the Lake Tahoe deep and nearshore environments and the Lake Hövsgöl deep environment, indicating some similarity between these communities. The Lake Hövsgöl deep and nearshore zone communities were also somewhat similar. These results indicate that Lake Hövsgöl may potentially serve as a reference for changes in Lake Tahoe, particularly changes to Lake Tahoe's deep zones (e.g. Caires et al. 2013). The similar age, origin, and specifically the similar morphometry of Lake Hövsgöl and Lake Tahoe (Goldman 1981, Kalbe and Schacke 1996, Goldman 2000, Goulden et al. 2006) may explain the low degree of dissimilarity between chironomid communities. The utility of Lake Hövsgöl and Crater Lake as a reference lake for Lake Tahoe should be further explored.

Biodiversity Varied Between Lakes and Depth Zones

Mean Shannon-Wiener diversity of chironomid communities was 0.93 in Crater Lake, 1.43 in Lake Hövsgöl, and 1.67 in Lake Tahoe and varied significantly between Lake Hövsgöl and Crater Lake (One-way ANOVA, $p < 0.05$, $F = 5.05$). Mean diversity varied between the depth zones of the three lakes, with the highest diversity in Lake Tahoe's nearshore community and the lowest in the Crater Lake deep environment (one-way ANOVA, $p < 0.00$, $F = 12.30$, Fig. 4). In general, we observed the lowest nearshore chironomid diversity in Crater Lake, followed by Lake Hövsgöl, then by Lake Tahoe (Fig. 4), possibly indicating that nearshore chironomid diversity increased along a gradient of increasing shoreline development in the three lakes. The diversity of benthic invertebrates has been shown to increase with increased nutrients in mesocosm studies (Blumenshine et al. 1997), streams (Evans-White et al. 2009), and lakes (Dodson et al. 2000, Jeppesen et al. 2000), which could explain the differences in diversity among our study lakes. Greater habitat heterogeneity and surface area are factors that also support greater diversity (Dodson et al. 2000, Vadeboncoeur et al. 2011). This may help explain the lower chironomid diversity observed in Crater Lake. However, Lake Tahoe has less surface area and a smaller watershed than does Lake Hövsgöl, leading us to expect lower diversity in Lake Tahoe than Lake Hövsgöl according to lake surface area and heterogeneity. It is therefore more likely that the differences in chironomid diversity observed between Lakes Hövsgöl and Tahoe are a result of increased nutrient inputs along Lake Tahoe's shoreline.

Diversity of macroinvertebrates increases with nutrient loading, but typically declines past a nutrient threshold (Donohue et al. 2009, Evans-White et al. 2009). The higher diversity of Lake Tahoe's chironomid community in the nearshore zone may actually betoken impairment, particularly in an oligotrophic system that naturally supports relatively low diversity. Nearshore and deep zones exhibited markedly different patterns in diversity in our study lakes. Contrary to the patterns observed in the nearshore environment, diversity in the deep zones was highest in Lake Hövsgöl followed by Lake Tahoe, which had comparably low diversity relative to Crater Lake (Fig. 4). The low chironomid diversity in Lake Tahoe's deep environment, relative to the deep environment of Lake Hövsgöl in particular, corroborates observed density declines and changes to community structure in the Lake Tahoe basin over time (Caires et al. 2013). Significant declines in densities of Lake Tahoe's deep-environment benthic invertebrates over the past four decades may be attributed to changes to the lake environment, including gradual eutrophication, declines in the spatial extent of native aquatic plants, and the impact of non-native species (Caires et al. 2013).

Implications for Conservation

Collectively, three important outcomes of our research for conservation and management of lakes were clear: 1) these large lake benthic invertebrate communities are sensitive to trophic conditions and benthic monitoring should accompany pelagic measures of lake trophic state, 2) large lakes may serve as benthic community references for one another, even across large geographic distances, and 3) depth variation in benthic communities can be substantial and must be considered in monitoring programs and diversity comparisons. Given that benthic communities are often overlooked in lake management, we suggest that lake managers use early indicators of eutrophication, such as changes in benthic diversity and lake typology to monitor large lakes.

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Response of High Elevation Lakes to Recent Climate Change: The View from the Great Basin

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Porinchu, D.F., Reinemann, S.R., Mark, B., Box, J. and Rolland, N. 2010. Application of a midge-based inference model for air temperature reveals evidence of late-20th century warming in sub-alpine lakes in the central Great Basin, United States. Quaternary International 215:15-26.

Reinemann, S., Porinchu, D.F., and Mark, B.G. 2014. Regional climate change evidenced by recent shifts in chironomid community composition in sub-alpine and alpine lakes in the Great Basin of the United States. Arctic, Antarctic and Alpine Research 46:600-615.

With the recognition that high-elevation environments are both responsive and extremely sensitive to changes in temperature and precipitation, it is critical that we improve our understanding of how global climate change will affect freshwater resources and aquatic ecosystems in alpine environments. Multi-proxy analyses of sediment cores recovered from lakes in the Great Basin of the United States provide the opportunity to: (1) describe the past and present distribution of aquatic fauna in alpine lakes; (2) place recent ecological responses and aquatic community dynamics in a longer-term context; and (3) establish 'baseline' conditions against which the effects of projected global change in this region can be evaluated. Analysis of sub-fossil midge remains from seven high-resolution, lacustrine records, recovered from the Ruby Mountains, East Humboldt Mountains and the Snake Range in the central Great Basin, was undertaken to examine the timing and rates of 20th and early 21st century faunal turnover and improve our understanding of regional climate and aquatic ecosystem variability during recent decades.

The impacts of local, regional and global drivers of climate and environmental change are recorded in the sedimentary archive preserved in lakes (Smol and Douglas 2007). Analysis of these sediment archives can provide insight into the spatial and temporal patterns of recent climate change in the Great Basin of the United States and improve our understanding of the linkage between local conditions and regional and hemispheric climate forcing. Subfossil midge analysis has successfully been used to develop high-resolution (sub-decadal) reconstructions of 20th and 21st century temperature change throughout the

Intermountain West (Porinchu et al. 2007, Porinchu et al. 2010, Reinemann et al. 2014). These studies add to the growing body of evidence documenting the impacts of climate change on alpine and subalpine lake ecosystems in the Great Basin of the United States. This is especially important given that lakes in the Great Basin continue to be poorly monitored with limited faunal surveys and long-term instrumental climate data available.

The seven, small, glacially formed lakes described in this study have a mean elevation of 2980 m a.s.l. (see Table 1 for details, Fig. 1 for location). Sediment was recovered from the approximate center of each lake by a messenger-operated, modified Glew gravity corer. All cores preserved the flocculent

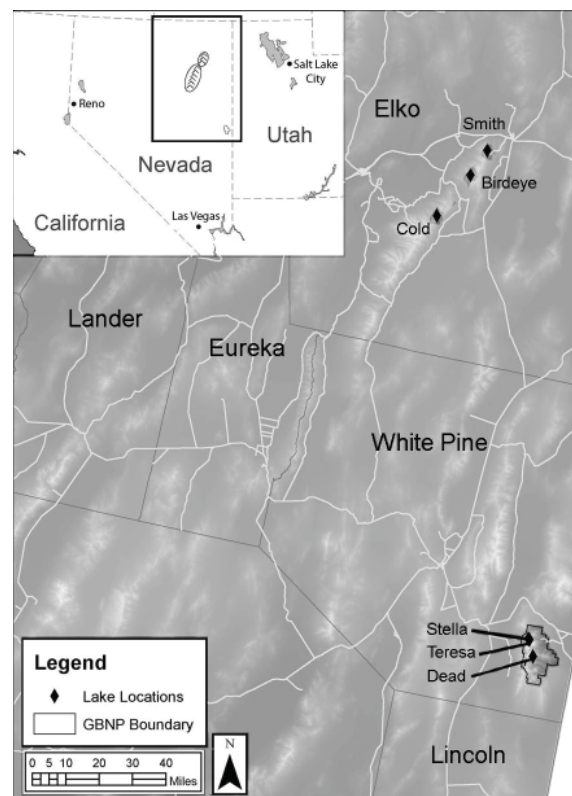


Figure 1. Location of study site lakes in the central Great Basin (inset). The seven lakes are located in the East Humboldt Range, the Ruby Mountains, and in Great Basin National Park (boundary plotted on map) in the Snake Range. Nevada counties and major lakes are labeled for reference (inset) (Reinemann et al. 2014).

Variables	Smith Lake	Birdeye Lake	Cold Lake	Stella Lake	Teresa Lake	Baker Lake	Dead Lake
Year Cored	2010	2010	2011	2011	2010	2007	2010
Elevation (m)	2780	2854	3015	3175	3135	3194	2916
Depth (m)	3.60	3.85	6.00	1.50	2.00	1.60	2.00
Lake Volume (m ³)	31,460	11,760	12,380	9,350	8,450	20,140	780
Surface Area (ha)	1.8	0.6	0.4	1.9	0.7	0.9	0.1
Catchment Area (ha)	63.9	15.2	40.5	17.0	107.9	51.7	5.2
Drainage Ratio (catchment:lake surface)	33.6	25.3	101.3	8.9	154.1	57.44	52.0
Catchment Aspect	NE	NE	N	NE	NE	E	E
Secchi Depth (m)	Unlimited	Unlimited	5.12	Unlimited	Unlimited	Unlimited	Unlimited
Measured SWT (°C)	15.09	17.05	10.07	13.77	*	14.20	*

Notes: SWT – surface water temperature. *Sensor malfunction

Table 1. Selected limnological and environmental measurements for the study sites.

surface sediment, evidenced by little to no disturbance of the surface-water interface. The uppermost sediment (0-10 cm) from each sediment core was extruded in the field at 0.25 cm increments, with coarser sampling resolution for depths below 10 cm. The sediment cores were dated using ²¹⁰Pb, and analyzed for sediment organic content (estimated by loss-on-ignition [LOI]) and subfossil midges. Midge and statistical analyses were based on standard procedures (Walker 2001), with a minimum of 45 head capsules identified/sample (Heiri et al. 2003). The timing and rate of faunal turnover, as a proxy of ecological change, was determined using detrended correspondence analysis (DCA). Application of a midge-based inference model for mean July air temperature (MJAT), based on 79 lakes and 54 midge taxa

(Porinchu et al. 2010), to the midge stratigraphies developed from these lakes enabled the development of quantitative reconstructions of MJAT spanning the 20th and early 21st centuries.

Well-dated subfossil midge stratigraphies were developed for the seven study sites. The midge stratigraphy developed for Smith Lake (SMT) is depicted in Figure 2. A total of 15 midge taxa were identified in Smith Lake (SMT). The midges assemblages clustered in three zones: SMT-I spans A.D. 1900 to A.D. 1959; SMT-II spans A.D. 1959 to A.D. 1990; and SMT-III spans A.D. 1990 to the present. Taxa that dominate the basal part of the core (*Chironomus* and *Psectrocladius semicirculatus/sordidellus*)

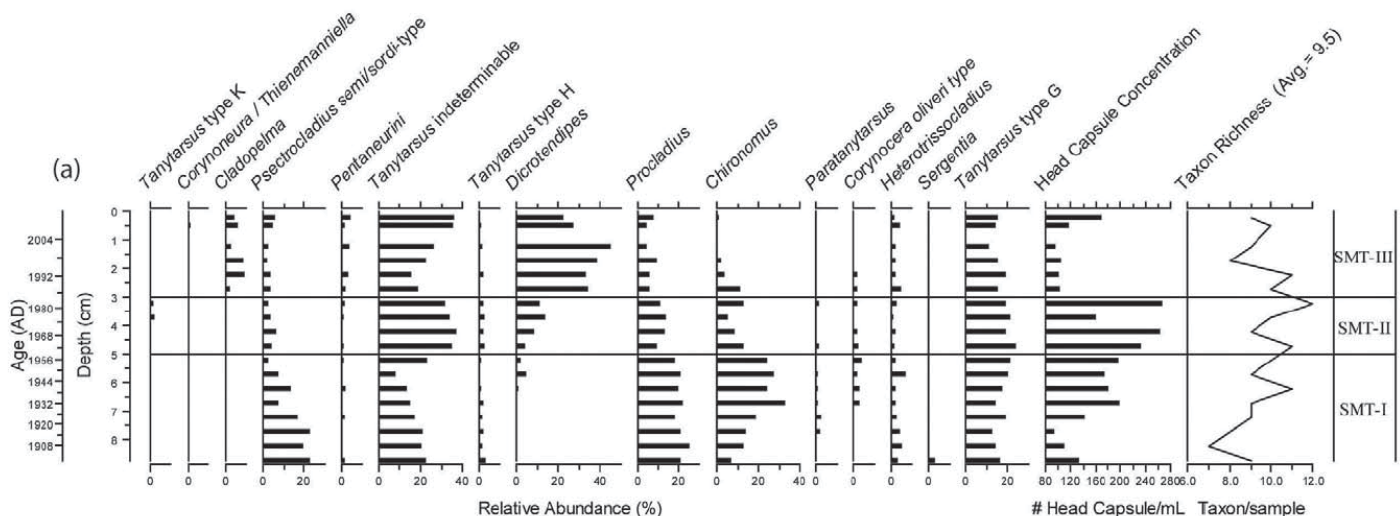


Figure 2. Chironomid stratigraphy for Smith Lake, NV. Taxa have been arranged according to their mean July air temperature (MJAT) optima based on the regional chironomid-based inference model (Porinchu et al. 2010), with decreasing optima temperature from left to right. Horizontal lines divide chronozones, as identified in the text. Abbreviations for chironomid taxa: *Psectrocladius semi/sordi-type* = *Psectrocladius semicirculatus/sordidellus* (Reinemann et al. 2014).

decrease to below 5% in the mid-20th century. Many taxa present at the base of the core are nearly extirpated and replaced by thermophilous taxa such as *Cladopelma* and *Dicrotendipes*, in recent decades, with *Dicrotendipes* reaching a relative abundance of over 40% in A.D. 2000. *Dicrotendipes* occurs in the littoral zone of mesotrophic to eutrophic lakes and is often associated with macrophytes (Brooks et al. 2007). This taxon is identified as thermophilic in most modern calibration sets, including the IMW training set (Haskett and Porinchu, 2014). *Dicrotendipes* was present in five of the seven lakes incorporated in this study. The abundance of *Dicrotendipes* has increased in all five lakes in the post-A.D. 1970 interval (Figure 3). Increases in the relative abundance of thermophilous midge taxa, such as *Dicrotendipes* and *Cladopelma*, are observed in high elevation lakes from the Sierra Nevada to the Colorado Front Range (Porinchu et al. 2007, Porinchu et al. 2010, Porinchu et al. unpublished). The DCA of the subfossil midge assemblages reveals that a large amount of compositional turnover characterizes the late 20th and early 21st centuries at all seven lakes (Figure 4). A striking feature is the unidirectional compositional change that occurs post-A.D. 1970. The shift in the midge community in the central Great Basin post-dates the shift in diatom flora observed to have occurred in the mid-20th century in high elevation lakes in the Uinta Mountains, UT (Hundey et al. 2014). Interestingly, the midge assemblages in Stella and Teresa lakes display very little turnover throughout much of the 20th century; however, notable turnover in the midge communities in these lakes is observed to occur post-A.D. 1990.

The increase in *Dicrotendipes*, which characterizes five of the study lakes in the post A.D.1970 interval, provides a distinct signal of dramatic ecological change in high elevation lakes in the IMW in recent decades. The timing of the shift in *Dicrotendipes* is consistent with the timing of turnover in the diatom flora of temperate lakes (i.e. 1970s) (Rühland et al. 2008, 2015). Elevated temperatures during the 20th century have been linked to shifts observed in aquatic ecosystems in alpine, arctic, and temperate sites in North America (Rühland et al. 2008). The length of the ice-free season, the timing of ice-melt, changes in the strength or duration of thermal stratification and enhanced or prolonged nutrient suspension have been identified as potential mechanism(s) influencing lake productivity and the ecology of high-elevation lakes (Karst-Riddoch et al. 2005, Porinchu et al. 2010, Hundey et al. 2014, Rühland et al. 2015). It is important to note that factors including habitat availability, nutrient loading, and lake level fluctuations can influence the structure and composition of aquatic communities. For example, nitrogen deposition to high-elevation lakes in the Rocky Mountains and elsewhere in the western United States, has been linked to changing limnic and biotic conditions in recent decades (Baron et al. 2000, Sickman et al. 2003, Wolfe et al. 2003, Moser et al. 2010, Saros et al. 2011, 2012, Hundey et al. 2014, Spaulding et al. 2015, Hundey et al. 2016). These recent studies clearly highlight how abiotic processes, e.g. water chemistry, lake depth and temperature; and biotic processes, e.g. trophic interactions, can influence aquatic community composition and structure.

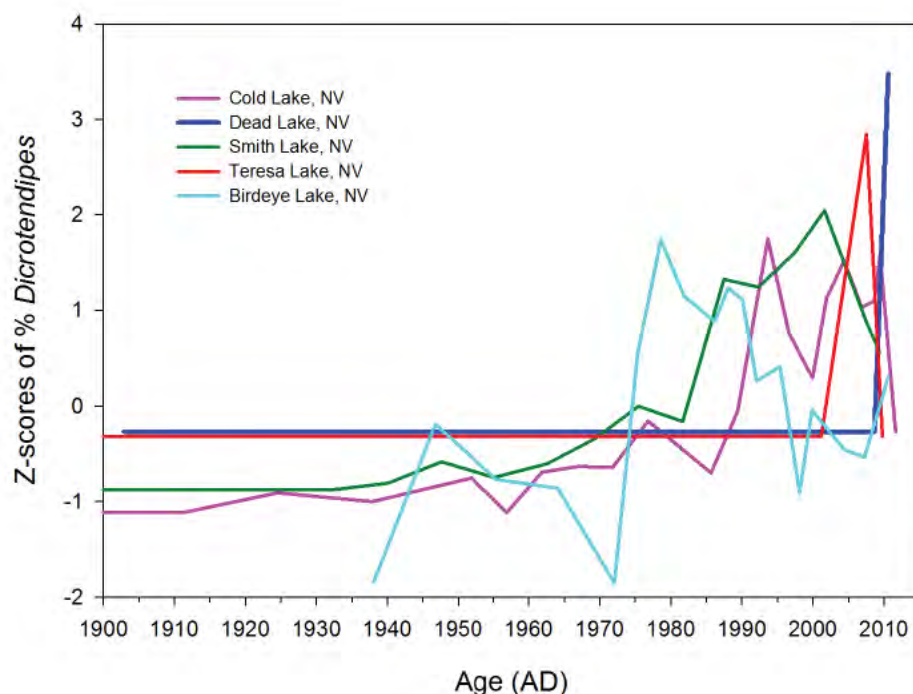


Figure 3. Timing of increased relative abundances (Z-scores) of *Dicrotendipes* in high elevation lakes in the Great Basin.

The relative role that these processes play varies spatially and temporally, with the effects of climate and environmental change becoming increasingly important over longer timescales (Anderson et al., 2008).

A plot of deviations of MJAT from the long-term average for all the lakes for the period A.D. 1895–2012 is depicted in Figure 5. The deviation of July air temperature from Nevada Climate Division #2 (NV#2), which encompasses the region, is also illustrated in Figure 5. For the early 20th century, the northeast portion of Nevada was characterized by average or below average chironomid-inferred temperature. Nevada Climate Division #2 with the exception of the 1930s also experiences an average or below average air temperature during the early 20th century. Starting around A.D. 1950 and extending to A.D. 1990, the lake and the climate division data exhibit similar temperature trends. Post–A.D. 1990, Cold Lake, Birdeye Lake, Smith Lake, and Nevada Climate Division #2 all experienced above average chironomid-inferred MJAT and air temperatures. The chironomid-based temperature reconstructions from Teresa and Dead Lakes do not correspond to the reconstructions for the other four lakes in this study or the climate data from Nevada Climate Division #2. The muted response of the chironomid community in Teresea and Dead lakes during the 20th century may reflect

low alpha diversity, resulting from the dominance of a limited number of midge taxa in each lake.

Examination of the biotic and geochemical properties of the lake sediment records, together with knowledge of the local catchment conditions and characteristics, provides insight into the timing and rate of change observed in high elevation aquatic ecosystems and the relative importance of temperature in influencing midge community composition during the 20th and early 21st centuries. The rate of faunal turnover during recent decades exceeds anything observed during the previous ~120 years. Application of a robust midge-based inference model for MJAT to the midge stratigraphies from these lakes indicates that aquatic communities in sub-alpine and alpine lakes in the Great Basin have been influenced by elevated air temperatures during recent decades. This study further supports earlier research from western United States and other regions, mainly Europe, documenting recent changes in midge communities in high elevation lakes (Battarbee et al. 2002, Solovieva et al. 2005, Porinchu et al. 2007, 2010). The results of this research provide insight into the spatial and temporal patterns of recent climate change in the Great Basin of the United States and improve our understanding of the linkage between local conditions and regional and hemispheric climate forcing.

Timing of Subfossil Midge Turnover

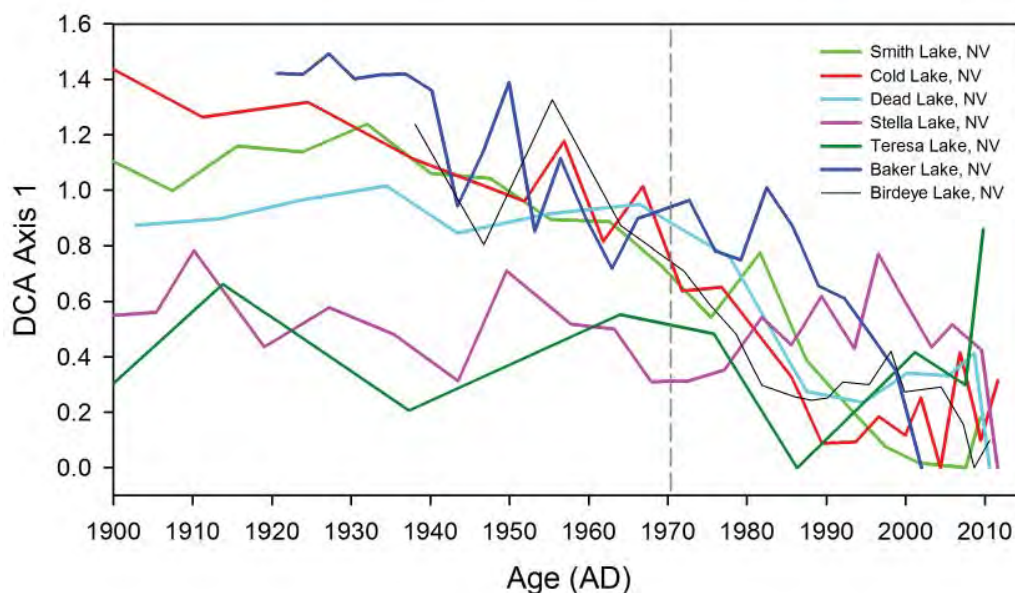


Figure 4. Detrended correspondence analysis (DCA) Axis 1 plotted against age for Smith, Birdeye, Teresa, Dead, Cold, Baker and Stella lakes.

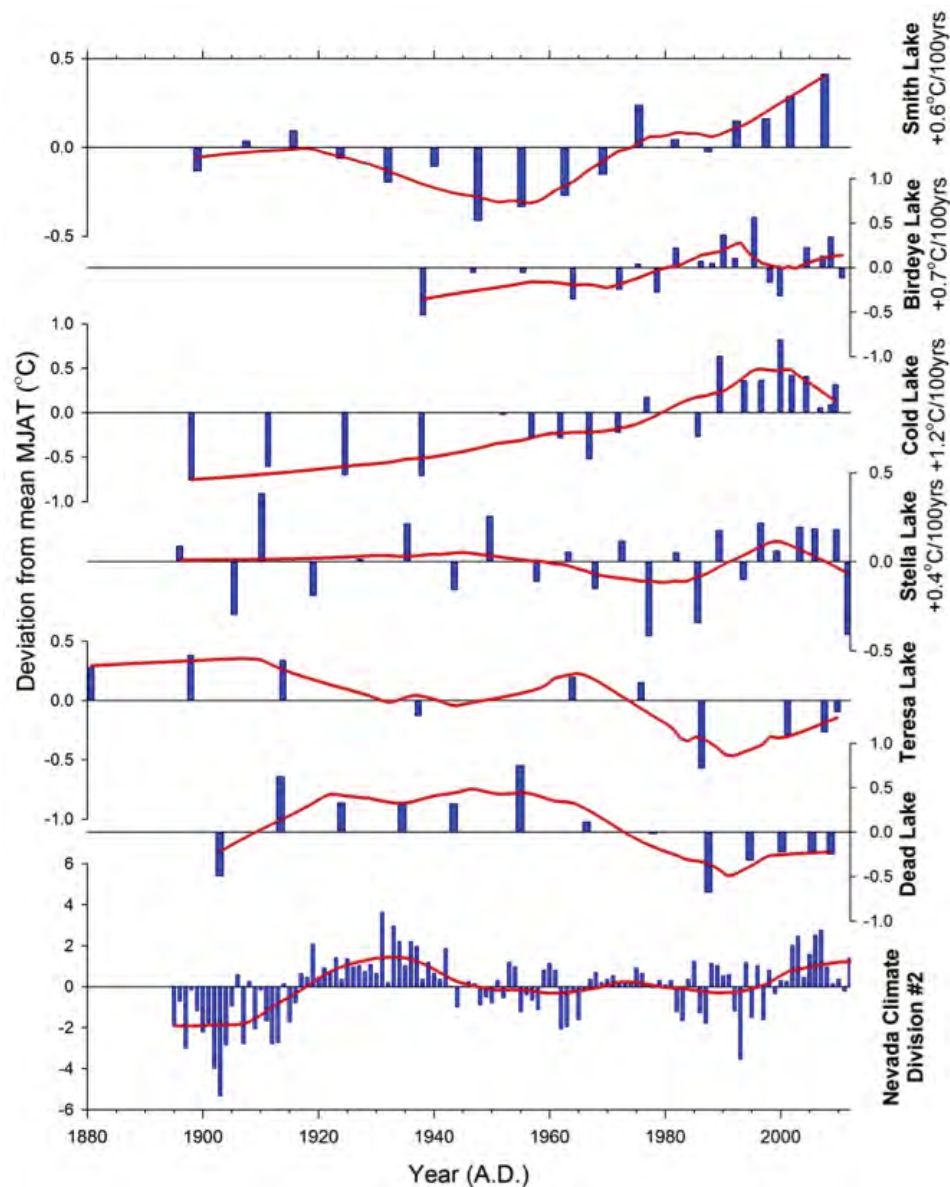


Figure 5. Deviations of the chironomid-based MJAT from the long-term mean of each lake ordered based on the lakes' location (Fig.1) from north (Smith Lake) to south (Dead Lake). Deviations of air temperature over the period from AD 1895 to 2012 for Nevada Climate Division #2, which encompasses all the lake sites. Thick line represents a LOWESS smoother (span = 0.4). (Reinemann et al. 2014). Baker Lake not plotted (see Porinchu et al. 2010).

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Uinta Mountains and Lakes: Sensitive Indicators of Climate Change

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Louderback, L.A., Rhode, D., Madsen, D.B., and Metcalfe, M. 2015. Rapid vegetation shifts in the Uinta Mountains (Utah and Wyoming, USA) during the Late Pleistocene and Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* 438:327-343.

The Uinta Mountains straddle an important transition between major climate regimes, and can thus indicate major climatic change with vegetation shifts. Two pollen cores from montane Uinta sites on the Utah-Wyoming border (Marsh Lake Bog and Camp Bog, respectively) were used to analyze vegetation shifts from the latest Pleistocene through the Holocene (Louderback et al. 2015) (Fig. 1). The records correspond with those from adjacent portions of the Rocky Mountains, all demonstrating a major shift from alpine steppe to open spruce parkland at ~11,700-11,200 cal yr BP (Fig. 2). Although this is seen in other pollen records, the mechanistic explanation varies from warmer temperatures and/or greater effective moisture.

A second major shift to lodgepole pine forest began at ~8,400 cal yr BP at Marsh Lake Bog (Fig. 2). The rise in pine began at about the same time at Camp Bog, but pine dominance took nearly 2,000 years longer (Fig. 3). Pine dominance increased even more at Camp Bog after ~3,400 cal yr BP. The development of lodgepole pine forest may have been a direct response of this dominant species to warmer conditions and/or the result of

subtle changes in the competitive hierarchy of tree species near a sensitive ecotone. Marsh Lake Bog and Camp Bog lie at the ecotone between spruce and lodgepole pine, so even a minor climatic change may not result in a shift in forest composition like that recorded in these pollen records (Fig. 4). Slightly warmer winters (1-2 °C), or slightly less annual precipitation, or some combination of these variables, would have been enough to tip the competitive balance in favor of lodgepole pine.

The difference in the rate and full expression of lodgepole forest development (taking nearly 2,000 years longer at Camp Bog) was probably due to a set of complex and local factors, such as cold air drainage and landscape position. An analysis of SNOTEL records from 1987 to 2014 at a high elevation site similar to Marsh Lake Bog (Steel Creek Park, 3109 m) and a lower elevation site similar to Camp Bog (Hewinta, 2901 m) revealed a consistent depression of 1.6 °C at the latter, presumably due to cold air drainage (Fig. 5). We argue that a consistent depression of 1.6 °C due to the landscape position of Camp Bog would, if sustained over long periods of time, account at least in part for the delayed arrival and subsequent development of this forest type.

Lodgepole pine forest persisted throughout the late Holocene and appears to be the long-term regional 'climax' forest, rather than a seral stage. Fire does not appear to have triggered the



Figure 1. View of Marsh Lake Bog coring locality looking east (left) and of Camp Bog coring locality looking south (right).

middle Holocene shift from spruce-dominated to lodgepole pine-dominated forests in this area, but may have contributed to its long-term persistence to the present day (Fig. 6).

The complexities of the Uinta Mountains are emphasized by forest ecologists: "...there is a lack of understanding with regard to the discontinuity of [vegetation] zones..." and only after "the basic ecological processes are understood, [can] the effects of environmental change on the future forests of the Uinta Mountains...be projected more accurately" (Shaw and Long,

2007:626). Our study has shown that those projections must take into account variations in landscape position that ultimately result in microclimatic patchiness, microrefugia and, therefore, very different vegetation histories between adjacent stands.

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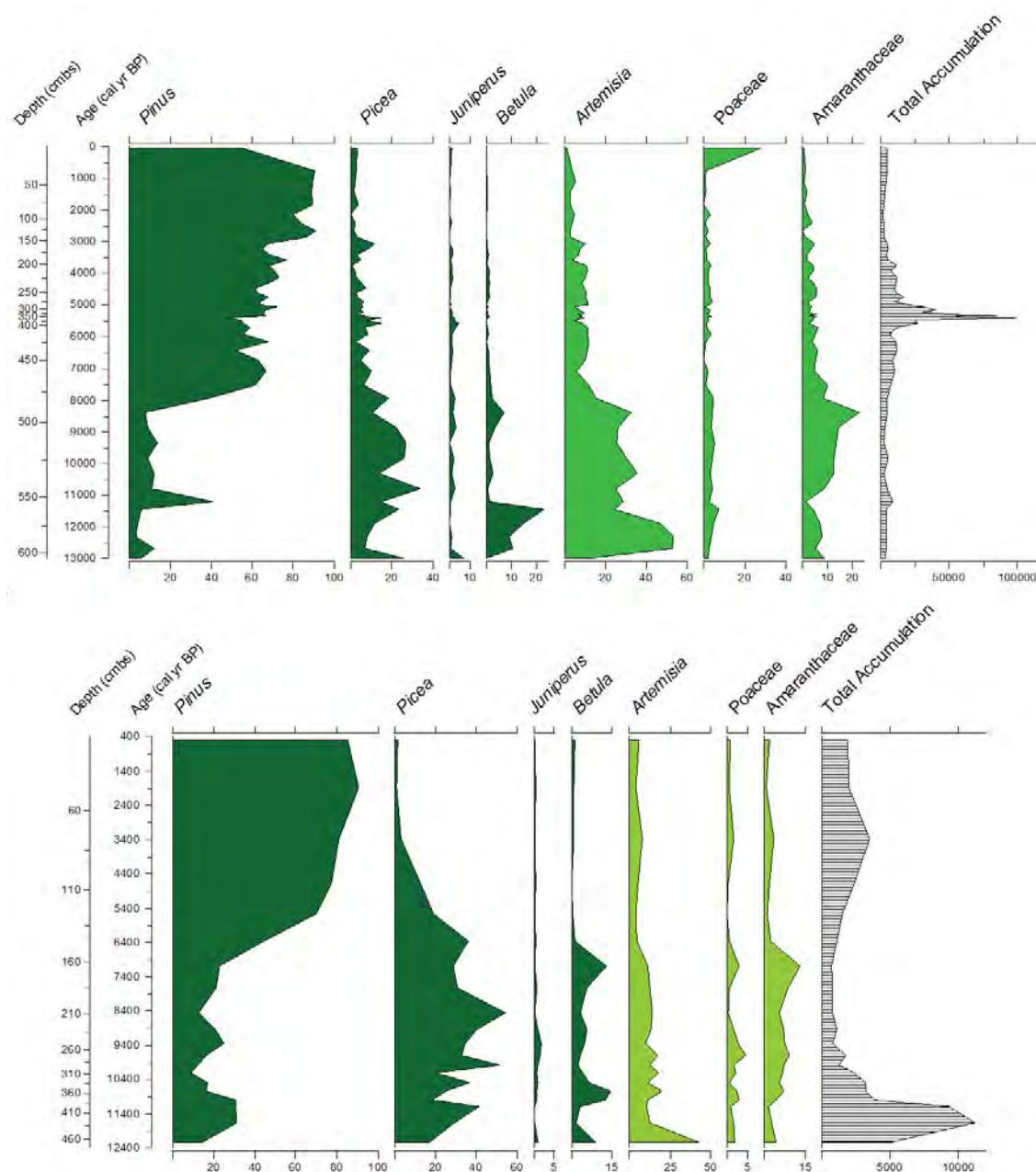


Figure 2. Terrestrial plant pollen taxa (percent of total) from the Marsh Lake (top) and Camp Bog (bottom) cores. Taxa that contributed minor amounts, indeterminate grains and unknown taxa are not shown. Total terrestrial pollen accumulation values (log grains/cm²/year) are in the far right column. Age (cal yr BP) is produced from age model in Louderback et al. (2015).

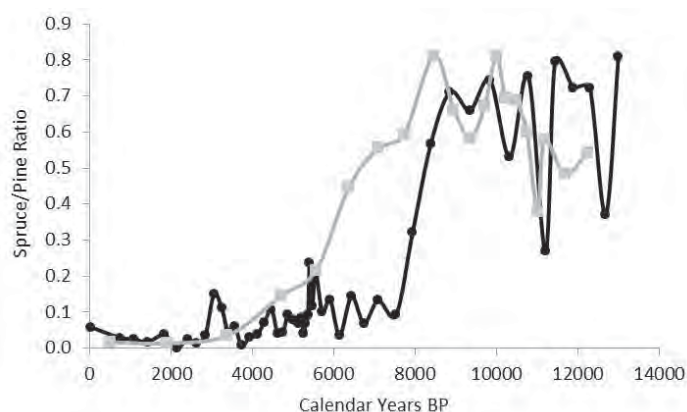


Figure 3. Spruce/pine ratios from Marsh Lake Bog (black line) and Camp Bog (gray line) showing the difference in rates of development of lodgepole pine forest.

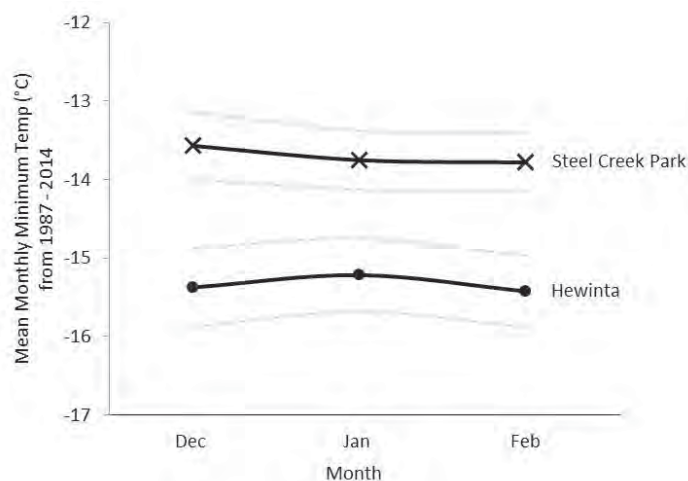


Figure 5. Mean monthly minimum temperatures (°C) for December, January and February 1987 – 2014 at the Steel Creek Park (3109 m) and Hewinta (2901 m) SNOTEL sites. Confidence intervals (95%) are indicated by gray dashed lines. Comparisons between sites of the same month were all significantly different (t-test, single tail, $P < 0.001$).

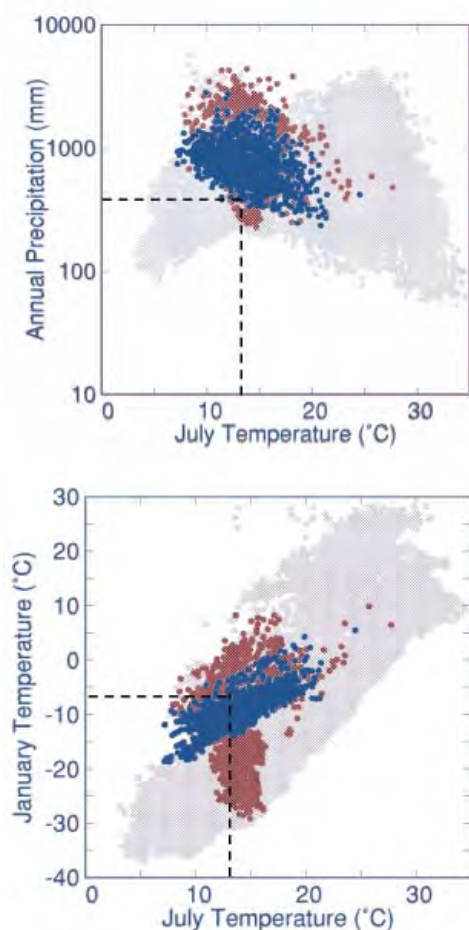


Figure 4. Climate envelopes (mean annual precipitation and mean January and July temperatures) for the presence of lodgepole pine (red dots) and Engelmann spruce (dark blue dots) in North America. Gray dots represent climate stations where the species are absent. Images are modified from Thompson et al. (1999). The dashed lines represent SNOTEL data from the Hewinta Site at 2900 m (Annual ppt: 670 mm, July temp: 13 °C, Jan temp: -7 °C).

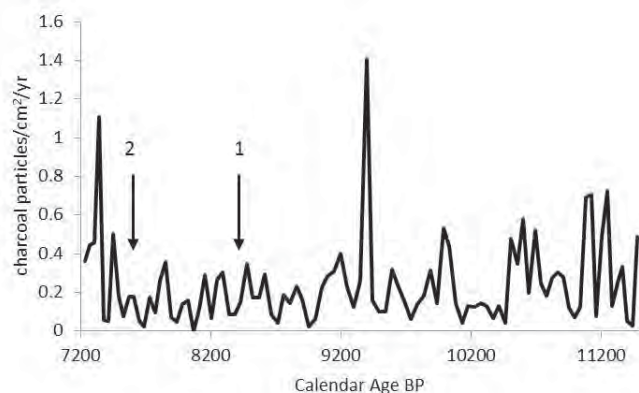


Figure 6. Charcoal abundance at Marsh Lake Bog between 465-560 cmbs and its relationship to 1) the development of lodgepole pine forest (8,400 cal yr BP) and 2) the dominance of lodgepole pine forest (7,600 cal yr BP).

FOLIO

Photos by Steve Sadro



Chickenfoot Lake, John Muir Wilderness.



Lower Desolation Lake, Humphries Basin, John Muir Wilderness.



Dragon Peak reflected in Ray Lake, Sequoia and Kings Canyon National Parks.



Bullfrog Lake and Kearsarge Pinnacles, Sequoia and Kings Canyon National Parks.

ARTICLES

Leaf to Landscape: Understanding and Mapping Forest Vulnerability to Hotter Droughts

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(This article first appeared in the Winter 2016 issue of the U.S. Geological Survey's *Climate Matters* newsletter [https://www2.usgs.gov/climate_landuse/clu_rd/pdfs/newsletterV4Winter2016.pdf], and has been slightly modified.)

“Hotter droughts” (also called “global-change-type droughts” or “hot droughts”) are an emerging but poorly-understood climate-change threat to forests worldwide. We are using California’s recent hotter drought (2012-2015) as a preview of the future, gaining the information needed to help forest managers adapt to a warming world.

Background and Need

Most people are used to thinking of droughts as periods of low water supply (precipitation), but often overlook the other side of the equation: atmospheric water demand (the drying power of the atmosphere). For example, if we look only at precipitation records, California’s recent drought would rank as severe but not necessarily unprecedented; comparable periods of low precipitation occurred during the 1920s and 1930s. However, compared to the 1920s and 1930s, temperatures during the 2012-

2015 drought were substantially warmer, which increased the atmosphere’s evaporative demand for water and easily made this the most severe drought in California’s 120-year instrumental record, and perhaps much longer. Additionally, water supplies for California’s cities, agriculture, industry, and forests all depend on the accumulation of a thick mountain snowpack each winter, which then melts and slowly releases water during the otherwise dry summer months. But the higher temperatures of the recent drought meant that virtually no snow accumulated during the winter, and the little bit that did accumulate melted far earlier than usual in the spring.

The effects of California’s drought on forests, particularly in the Sierra Nevada mountain range, have been extreme. U.S. Forest Service experts estimated that, by the summer of 2015, tens of millions of trees had died, most of them in lower-elevation forests (Fig. 1). Virtually no species has been spared, with substantially



Figure 1. California’s hotter drought has already killed millions of trees, particularly in low-elevation forests. Photo: N. Stephenson, USGS.

elevated mortality recorded in pines, firs, incense cedars, and oaks. A glaring exception has been the iconic giant sequoias; only a handful of sequoias have died, and those that died usually already had fire scar damage at their bases, which likely reduced their ability to transport water to their crowns. But even though the vast majority of sequoias have survived the drought, many of them experienced unprecedented foliage die-back (Fig. 2). By systematically shedding their older leaves, sequoias have conserved water by reducing the leaf area that is exposed to the drying power of the atmosphere.

If Earth continues to warm as projected, forests will experience hotter droughts that are both more frequent and more severe. Fortunately, managers are not helpless in the face of such changes; they can increase forest resistance to (ability to survive) hotter droughts. For example, forests can be thinned – usually by prescribed fire or mechanical thinning that selectively removes smaller trees – to reduce competition for water among the remaining trees. But the task is so vast that forest managers

must perform triage, deciding where on the landscape their limited funds will be best applied. They thus need reliable forest vulnerability maps to help them strategically target their treatments, and to help them plan appropriate responses to future forest die-offs in highly vulnerable areas that they are not able to treat.

The Leaf to Landscape Project

Using California's hotter drought as a potential preview of the future, we have worked with stakeholders to catalyze the Leaf to Landscape project. Leaf to Landscape has two broad, complementary goals. First, it aims to provide empirically-derived maps of forest vulnerability to hotter droughts for large parts of California, letting the trees themselves reveal which parts of the landscape are most and least vulnerable. Second, it aims to improve our basic mechanistic understanding of forest vulnerability to hotter droughts, providing the grist for models with applications well beyond California.

To reach these ends, Leaf to Landscape has three main components, designed to be integrated across scales – from tree leaves to entire forests. The first is tree physiology during drought, spanning about 10 dominant species. Individual trees are climbed by professional climbers, and small branches are cut from high in their crowns (Fig. 3). Back on the ground, one or more small branches are immediately inserted in a pressure chamber to quantify the degree of drought stress experienced by each tree (Fig. 4). The remaining branch samples are then transported to a laboratory where leaf water content and other chemical markers – which together can provide insight into a tree's level of drought stress – are quantified.

These measurements of drought physiology are strategically co-located with the second component of Leaf to Landscape: tree population monitoring. One of the backbones of this monitoring is a network of 30 permanent forest plots, which has been used to annually track the health and fate of each of some 30,000 trees for up to 34 years (Fig. 5). These data provide an invaluable long-term baseline of forest health, dynamics, and agents of tree mortality during “normal” forest conditions. Continued monitoring throughout the drought provides key information on the timing and proximate causes of tree mortality. Adding to these data, foliage dieback in giant sequoias is now monitored annually.

Both of the preceding components – tree drought physiology and population monitoring – provide essential calibration and validation for the third component: remote sensing (Fig. 6). Remote sensing allows us to map forest drought responses over broad landscapes. High-resolution LiDAR is used to create a detailed three-dimensional map of tree crowns for millions of



Figure 2. Giant sequoias have fared better than other tree species, but in many cases have shown unprecedented foliage dieback in response to the drought. Photo: N. Stephenson, USGS.

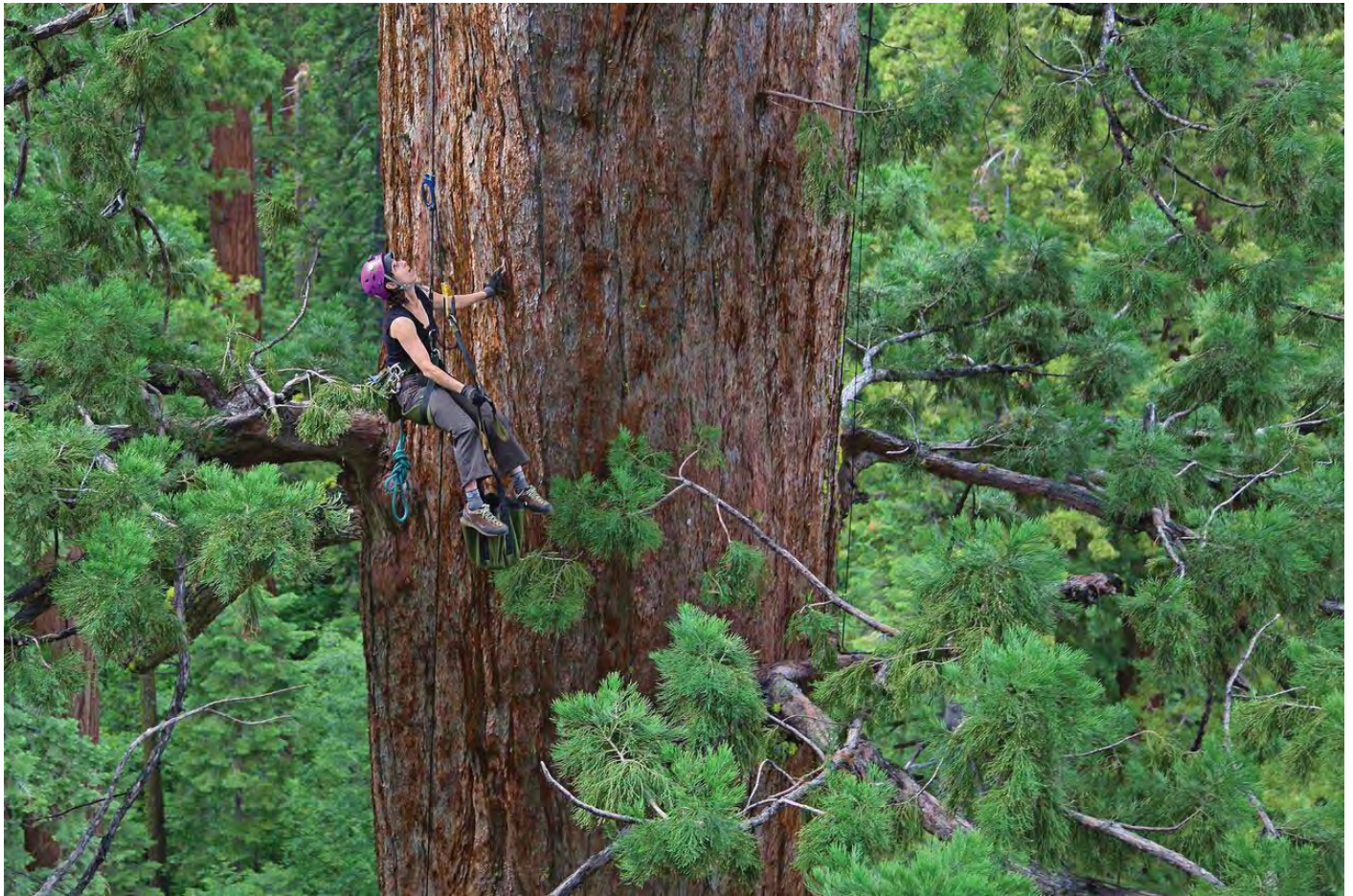


Figure 3. A University of California, Berkeley scientist climbs a giant sequoia to sample branches from high in its crown. Photo: A. Ambrose, UC Berkeley.

trees. The spectral reflectance each tree crown is also recorded, allowing identification to species and measuring whole-crown water content (Fig. 7) and chemical signatures (such as nitrogen and non-structural carbohydrates) that may be related to tree health and drought stress.

The Leaf to Landscape project has successfully completed all three of these data collection components during its first full year. Reflecting the interdisciplinary nature of the work, funding and in-kind contributions came from The U.S. Geological Survey, the National Park Service, the U.S. Forest Service, Stanford University/Carnegie Institute of Science, and the University of California, Berkeley.

Data analyses are underway, but early results from giant sequoias may give hints of findings to come. Remote sensing reveals substantial spatial variation in sequoias' whole-crown water contents (Fig. 7). In contrast, direct ground-based measurements show very little spatial variation in sequoias' leaf water content



Figure 4. A pressure chamber is used to record how much pressure is required to squeeze water out of a small sequoia branch – a measure of the drought stress experienced by the sequoia. Photo: A. Ambrose, UC Berkeley.



Figure 5. U.S. Geological Survey biologists assess the health of a sugar pine, one of tens of thousands of individual trees whose fates have been tracked annually throughout the drought. Photo: USGS.



Figure 6. An aircraft captures high-resolution LiDAR and hyperspectral images of forests during the drought. Photo: G. Asner, Carnegie Institute of Science.

or drought stress. The apparent paradox might be explained by spatial variation in whole-crown leaf area; that is, sequoias might maintain favorable water status by adjusting their total leaf area. Low leaf area could reflect responses to acute drought (i.e., sequoias abruptly reduce their leaf area by shedding older foliage, as in Fig. 2) and/or long-term adjustments to sites with chronically low water supplies (i.e., sequoias never develop a large total leaf area). Much work remains to be done, but, at least for sequoias, total crown water content during the current drought might prove to be an indicator of site vulnerability to hotter droughts of the future.

Future Directions

Fortunately, during the winter of 2015-2016 California has been getting some limited relief from its crippling drought. But even if the current moisture is followed by several more wet years, thus signaling the end of the drought, the Leaf to Landscape project's efforts to understand forest vulnerability to hotter

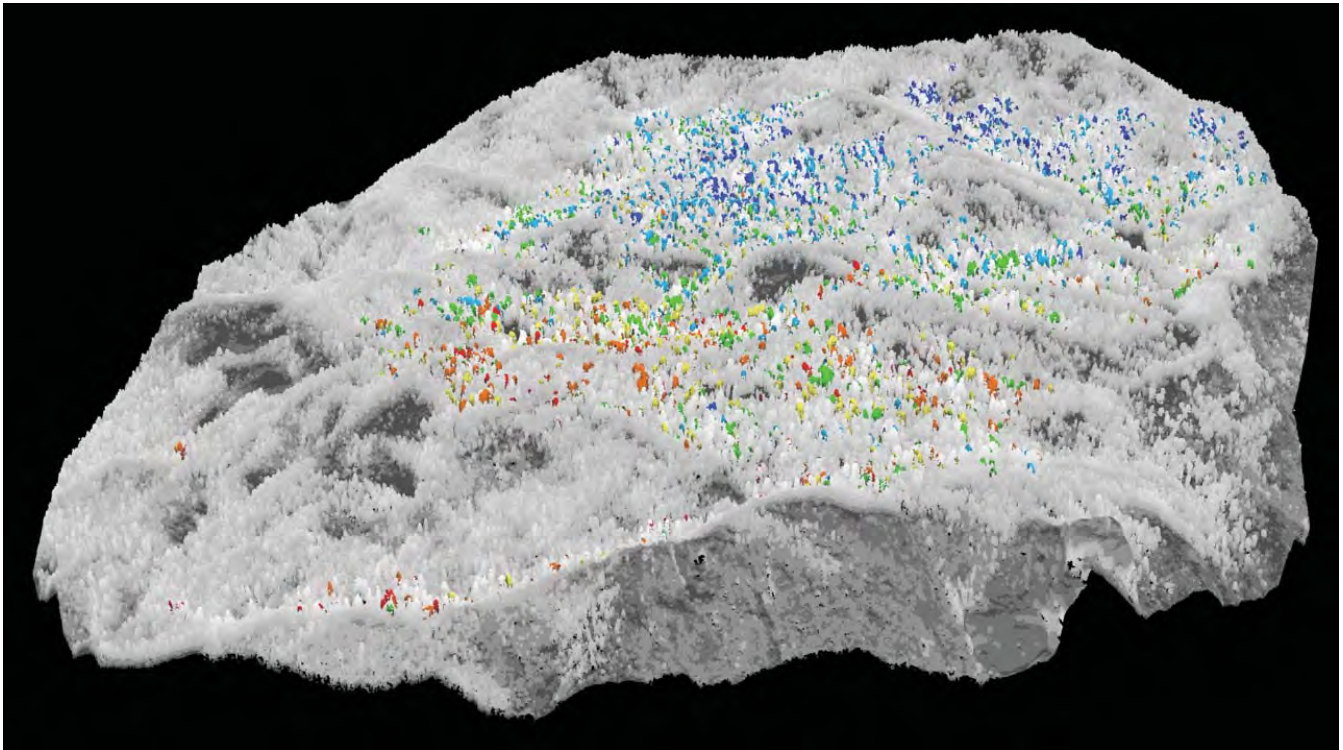


Figure 7. Remote imagery reveals a pronounced spatial gradient in the whole-crown water content of individual giant sequoias during the drought. Warmer colors indicate lower water content. Photo: G. Asner, Carnegie Institute of Science.

droughts will continue, especially to document and understand lagged drought effects and forest recovery. For example, anecdotal accounts suggest that tree mortality remains elevated for one or more years following drought. Leaf to Landscape will quantify the magnitude and duration of lagged tree mortality, and will determine the agents contributing to it (such as insects and pathogens). The project will also document the rate and magnitude of tree crown recovery – leaf area, water content, and chemistry – and interpret its relationship to tree growth and mortality.

We also hope to complete maps of forest vulnerability for some large sections of California, passing the information to land managers and helping with interpretation. The Leaf to Landscape project promises to improve our basic understanding of an emerging climate change phenomenon, with broad implications and applications.

Further Reading

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INTERVIEW

Dave Porinchu is widely respected as a thought leader in paleolimnology and climate relations of mountain lakes. As such, I sought his insights on the value and importance of lake research to the special lakes' feature in this issue of Mountain Views. Dave continues his pioneering research that leverages chironomid-based reconstructions of late Pleistocene, Holocene, and modern climate. His work takes him from the Great Basin to Siberia, where his interests in high-elevation dynamics over space and time are well served. Dave currently is Associate Professor in the Department of Geography, University of Georgia, Athens; his PhD (2002, UCLA) and MS (1997, University of New Brunswick, Fredericton University of New Brunswick, Fredericton) focused on chironomid-inferred and paleolimnological analyses of mountain lakes. Dave has authored numerous papers, including many with seminal impact. I especially thank Dave for contributing a Brevia article to this issue, in which he and co-author Scott Reinemann highlight key messages from their recent publication on lakes in the Great Basin. —Editor

DAVE PORINCHU



Connie: Can you give a brief profile of your current research, some of the questions that keep you up at night, and the disciplines that you invoke while chasing the answers?

Dave: I am actively working, along with my graduate students, on documenting recent and long-term patterns of climate and environmental change in Central America and the Intermountain West (IMW) of the United States. I largely focus on using proxies (biological, physical and geochemical) extracted from sediment cores recovered from lakes located in alpine and sub-alpine settings to derive qualitative and quantitative inferences of past climate variability. My research foci and the approaches I utilize are greatly informed by the outstanding research being conducted by colleagues working at the nexus of paleolimnology, paleoecology, climatology and ecology. I have become increasingly interested in using stable isotopes of C and N in bulk lake sediment and stable isotopes of O extracted from subfossil chironomid remains to address how high elevation aquatic ecosystems are responding to elevated air temperature and hydroclimate variability in recent decades. Currently, I am particularly interested in characterizing how the retreat of

small alpine glaciers, in response to altered temperature and precipitation regimes, will impact thermally sensitive aquatic invertebrates and aquatic communities.

Connie: What are a few of the key insights you are proud to have documented in your career so far?

Dave: Some of my early work on midge biogeography identified the importance of latitudinal treeline in Eurasia in serving as a biogeographic boundary for the distribution of chironomids, delineating cold-water taxa such as *Abiskomyia* and *Parakiefferiella nigra*, in tundra lakes from temperate taxa such as *Zalutschia zalutschicola* and *Microtendipes*, in lakes south of treeline. I've documented that the temporal pattern of warming, inferred from the multi-proxy analysis of lake sediment cores, is broadly consistent in the central Canadian Arctic, suggesting a regionally synchronous response to climate forcing in this region during the late Holocene. Lastly, application of robust midge-based inference models for air and water temperature has enabled me to document that the warming experienced by high elevation lakes in the Intermountain West during the late 20th and early 21st centuries is unprecedented in the context of the last ~ 150 years.

Connie: In that your work is highly interdisciplinary, what role(s) do mountain lakes play in your research?

Dave: You are correct that my research has a strong interdisciplinary component. In recent years I have closely collaborated with a broad spectrum of researchers, including geographers, geologists, biogeographers, climate modelers, and ecologists. Mountain lakes are critical to my research, mostly because I love spending time near them (and sometimes immersed in them). Until relatively recently, little was known about the relationship between midges and the contemporaneous environment in the mountains of North America. Refining our knowledge of chironomid ecology and biogeography in alpine



Wheeler Peak Trailhead, Great Basin National Park, NV (August 2013) with colleagues from Oregon State University.

settings, one of the primary focuses of my on-going research, will improve our ability to provide meaningful qualitative and quantitative interpretations of environmental conditions in these sensitive regions.

Connie: Tell us more about chironomids. Are there abundant chironomids in all mountain lakes? Why are they useful as proxies, and what kinds of information do they tell you? How does information from chironomid records relate to other proxies such as pollen or diatoms?

Dave: Chironomids, also known as non-biting midges, are one of the most ubiquitous and abundant insects found in freshwater ecosystems. Chironomids are well suited for paleolimnological studies because the larvae possess chitinous head capsules, which are well-preserved in lake sediment, are easily recovered and identified. Chironomids are very sensitive to temperature (air and water), making them a very useful and important proxy for documenting thermal conditions and climate variability in the recent past. In addition, chironomids have been successfully used to track eutrophication and fluctuations in lake level and salinity. Studies that incorporate multiple proxies, e.g. diatoms, pollen, chironomids, stable isotopes, can provide great insight into past environmental and climate change, although competing interpretations may result. The Snowmastodon Project is an example of a study that I've been involved with which has used the multiproxy approach with great success (see the special issue on the Snowmastodon Project in *Quaternary Research*, 2014).

Connie: I know you teach courses at the UG on biogeography and geomorphology, among others. What aspects of teaching do you like the most, and what do you aspire for your students as a teacher?

Dave: At UGA I typically teach a large introductory class on *Physical Geography*, an upper-level class on *Global Climate Change* and a graduate seminar on *Geographic Thought*. I feel that one of the key strengths of a geographer is the ability to view the world around us holistically. We understand that most, if not all, phenomena, found in the biophysical and cultural landscapes that surround us, are linked through space and time. I would like to pass on to students the ability to analyze and synthesize disparate pieces of information, varying at multiple spatial and temporal scales, to develop a coherent worldview that enables them to more clearly understand cause and effect, as well as structure and agency.

Connie: Do you have any big work goals or challenges that you are working toward in, say, the next five years?

Dave: Over the next few years I would like to: 1) more explicitly work on disentangling the relative influence of various interacting anthropogenic stresses on aquatic ecosystems and in doing so hope to further add to our understanding of lake ecology, structure and function; and 2) characterize how the rapid, on-going reduction in the volume of alpine glaciers will impact alpine aquatic ecosystems in the IMW in coming decades.

Connie: Do you like to swim in the lakes where you work? Dive?

Dave: Unfortunately, I don't take advantage of the opportunity to become one with mountain lakes enough. When I do find myself in a lake it's usually because I'm trying to recover equipment!



Installing temperature data loggers in Baker Lake, Great Basin National Park, NV.

VOICES IN THE WIND

In this section, I query members of the CIRMOUNT community for their perspective on a topic of interest. Discussions about the Anthropocene, and whether it should merit formal recognition, are increasing, and I posed the following question to several colleagues. —Editor

Q: The International Stratigraphic Commission (ICS) is considering formal designation of the Anthropocene, a new time interval when the "global environment, at some level, is shaped by humankind rather than vice versa". For the ICS, this would require a globally recognized and stratigraphically determined time interval, with an as-yet uncertain start date. Some scientists support this approach, while others feel it is overly formal and geologically based, and prefer to retain the term for informal reference. Thinking regionally, from the perspective of mountain region(s) in which you work, would you consider the idea of a stratigraphically defined Anthropocene to be relevant, or do you prefer informal use? In either case, when do you think that the Anthropocene started in your mountain region and why? For reference, see: Edwards, L.E. 2016. What is the Anthropocene? EOS 97: 6-7.

Cathy Whitlock, Montana Institute on Ecosystems and Department of Earth Sciences, Montana State University, Bozeman, MT

Defining a new geologic epoch that demarcates the emergence of humans as a global force rests on the loftiest of goals: championing awareness of the need for planetary sustainability. The difficulty in defining the Anthropocene, as distinct from the Holocene, lies in the details, and the devil in this case is agreeing upon a geologic reference location that preserves a distinctive boundary to mark its beginning. Such a type section is required by the rules of the International Union of Geological Sciences (IUGS) for establishing a new geologic time interval. A number of markers have been proposed to define a new Anthropocene epoch: ~50,000 years ago with beginning of megafaunal extinctions; ~10,000 years ago with the first evidence of agriculture in the Near East; the middle Holocene (~ 5000 years ago) with the spread of Neolithic agriculture; and 1610 AD, the so-called Orbis spike when decreased atmospheric CO₂ is attributed to forest expansion after Columbus. Others would assign the inception of the Anthropocene to the period when the coal-fired steam engine was first deployed in early 1800s, to the first above-ground nuclear testing in 1945, or to the global deposition of fly ash in 1950. I note that a recent, informal poll taken at the American Geophysical Union (Dec 2015) showed no agreement among scientists on when the Anthropocene should begin or even if formal recognition was warranted.



The human signature in mountainous regions around the world could easily be placed at many of these inception points, but the boundaries would be asynchronous or hardly visible in the stratigraphic record for most. In the mountains of the northwestern U.S. and Patagonia where I work, pre-European populations were largely small mobile groups of hunters and gatherers, and paleo-ecological evidence of their presence is spatially limited and temporally varied. The first distinctive imprint of people occurs in the mid-late 19th century, with Euro-American settlement, and this signature becomes stronger in the 20th century with logging, burning, mining, and agriculture. Evidence of these activities can be found in pollen, charcoal, lithological, and geochemical records preserved in lake sediments. Perhaps with time, the boundary of the Anthropocene will be easier to identify in the geologic record, because the time-transgressive markers of human activity will become compressed and thus more distinctive with their burial and compaction in sedimentary archives. In the meantime, it is worth adhering to IUGS rules, and so far, a global stratigraphic boundary is not yet clear enough to identify a type section for a new Anthropocene epoch.

Wally Woolfenden, USDA Forest Service, Mountain Heritage Enterprise Team (retired), Swall Meadows, CA

It is, of course, important to acknowledge the environmental and climatic effects of human preeminence as a geological force by defining a period of time when that has been occurring. Whether or not the Anthropocene will be formally designated a geological



unit within the Geological Time Scale its informal use has become very popular and widespread. It seems odd, however, that a conventional scientific term for an epoch is so used. Formal or informal, it is essential that the Anthropocene, to be useful, have a beginning. If it is adopted by the International Commission of Stratigraphy, I favor a designated time boundary (Global Standard Stratigraphic Age) rather than the more difficult identification of a fixed reference point in a stratigraphic section (Global Stratigraphic Section and Point). Out of the several suggested time boundaries my preference is the beginning of agriculture and animal domestication, which occurred about 12,000 years ago in the Middle East and not long after in Southwest Asia (archaeologists keep extending the origins). This resulted in the transformation of the landscape that eventually affected climate by way of augmenting carbon dioxide and methane in the atmosphere (Ruddiman 2003). So, one thing leads to another: where did the Holocene go? Well, the Holocene is just an interglacial, the latest of a long series in the Pleistocene Epoch and its loss won't cause much heartburn. The new Anthropocene Epoch is much more significant.

After the beginning of the Anthropocene human modification of the environment spread throughout the world and began at different times in various regions. The question here involves mountains. The mountain region I have worked in is the southern Sierra Nevada range and the White/Inyo ranges to the east, in California. It is usually assumed that these montane ecosystems, primarily at lower elevations, were altered during historic settlement by European and Asian Americans who mined, logged, farmed and grazed the land. These mountains, however, had been occupied for millennia by prehistoric indigenous societies. Knowledge has been accumulating that these earlier people had already altered the mountain regions and created in large part a cultural landscape that had been believed to be natural. This is true of much of California (e.g. Anderson 2005). Indigenous land management practices promoted desired plant communities, modified the structure of others, and enhanced the diversity of many habitats for desired plant and animal resources. The use of frequent burning in Sierra Nevada forests and pine/oak woodlands cleared underbrush for new growth, maintained open fuel and vegetation structure, and favored grass for its seeds over shrubs. This practice prevented large, crowning fires. Pinyon groves in the White/Inyo Mountains were also burned, pruned, weeded, cleared of duff, and terminal branches pinched off to increase cone development. Meadows, having important plant resources, were also maintained by burning and removing tree and shrub seedlings that would otherwise encroach on the meadows. Other management techniques such as selective harvesting, transplanting, and dispersal by broadcasting seeds may have modified the genetic structure of plants. It is difficult to assign a beginning date for prehistoric habitat modification since

it was an evolutionary and learning process over a long period of time and the resolution of archaeological and paleo-ecological data is inadequate to discriminate cultural from natural changes. An estimate can be proposed from archaeological data that indicates intensive settlement at least three thousand years ago.

Anderson, M. K. 2005. *Tending the Wild*. Berkeley, University of California Press.

Ruddiman, W. F. 2003. The Anthropogenic greenhouse era began thousands of years ago. *Climatic Change* 61: 261–293

Claudia Drexler, Mountain Research Initiative, Bern, Switzerland

I live in the Gürbetal, at the foot of the Gantrisch mountain range in Switzerland. I am looking across the valley and over to the mountains in order to find the traces of the epoch during which humanity has begun to have a significant impact on the environment.



There are human traces all over these steep mountains! Herdsmen and farmers have forged this landscape over thousands of years. It started after the ice ages when humans found open meadows on the slopes of the mountains while the valleys were covered in impenetrable forest. Cattle have been domesticated in the Alps for 7,000 years! At the Morgetenpass, which I can glimpse when I look over to the left, farmers found arrow points from the Bronze ages when they built a new house, and the pass itself was used by the Romans as part of the connection from Upper Italy northwards. This ancient impact of our ancestors on the mountain environment has laid the foundation for how mountains are part of our everyday life now - for skiing, hiking, experiencing nature and culture. In this case the Anthropocene would have started just after the last ice age...

I can also try not to look at the mountains behind me, but out onto the plain, called "Moos", which is beautiful for early morning running and watching shooting stars. It was one of the plains that had closed forest after the last ice age. In the 19th century the correction of the Gürbe River allowed more intensive agricultural production where before the swampy land was only good enough for cattle and some cabbage... In this case the Anthropocene would have started in the mid-19th century.

Of course the big shots of science asking the questions, „What is the Anthropocene?“ and „Are We in It?“ neither mean the slopes of the Gantrisch nor the Gürbetal. But living here these are human traces on the environment that are here for everyone

to see, while global climate change and its effects like the 2015 hailstorm that hit the village, or lilac that is about to flower as I write this text, are only minor irritations.

Humans have changed their environment since the beginning of settledness. The point is that there are more of us now, and that we have more powerful technologies. For me it is obvious that on a planet with *Anthropos* there has to be an *Anthropocene*. If stratigraphers criticize the idea, saying clear-cut evidence for a new epoch simply isn't there, this shows that hard-core natural science is not able to match the speed of current realities and will always come late.

Erik Beever, U.S. Geological Survey, Northern Rocky Mtn. Science Center, Bozeman, MT

This compelling question requires thinking on many levels, in my view. Most fundamentally, I think that the Edwards (2016) article makes a key point that bears remembering...namely, that of the imprecision of the stratigraphic record. The finest-resolution temporal distinction that I've been aware of was on the order of centuries, and very rarely multiple decades. Going further back in time, this precision degrades to millennia and eventually, to millions of years for the oldest material. The key implication for this is that although there may be decades to centuries to millennia when various types of anthropogenic signals show up in the stratigraphic record, such distinction may not be detectable, at points in the future. Given this potentially allowable source of imprecision, then I think that, if indeed defined stratigraphically, it is preferable to allow the start date to vary, by place or region. Human presence apparently arrived to different mountain chains at different centuries and millennia, and arguably passed the tipping point of greater influence at different decades. Consequently, a more-informal definition that can be tailored to the specifics of each individual research question will be more informative, across the many mountains of western North America in which I work. Among the options in Fig. 1 of Edwards 2016, I lean towards those with greater "splitting", because these allow for the testing of more hypotheses than if one were to lump numerous time periods together...although it is possible to lump later (e.g., if no difference is found between adjacent time periods, for a given response variable), it is not as simple to split, once lumped. Analogously, I lean towards the *Anthropocene* being assigned the rank of an "age" within the *Holocene* epoch.



Although I imagine that it would depend on the specific measure being investigated, another complicating factor is that deposition and preservation of materials varies dramatically, across the mountain ranges of western N. America. Even in the same state of Oregon, I suspect that there is at least an order of magnitude of difference in how rapidly something degrades in the Cascades of northern Oregon, as compared to in the significantly more-arid Steens Mountains.

Depending on the threshold of humans' "shaping" of mountain ecosystems that is required, the *Anthropocene* started somewhere between the 19th century and the mid-1970s. Although there are clearly localized examples of clear human effects, regionally, the *Anthropocene* is more commonly detected once mechanized industrialization arrived. Across the Sierra Nevada of California and the hydrographic Great Basin, one can still detect legacies of the very-heavy livestock stocking rates used pervasively during 1890-1920. In terms of the most-consistent signal of anthropogenic influence, less-direct consequences of contemporary climate change hit a point of inflection in the mid-1970s.

J. Madeleine Nash, Independent science journalist, San Francisco, CA

Anthropocene has an undeniable ring to it, so perfectly does it capture the time in which we are living -- a time when human beings, now more than 7 billion strong, are forcing profound geochemical and geophysical change. As a journalist I've always liked the term. And yet I rarely use it.



Photo credit: T. Nash

Why? When I write about the *Holocene*, I can describe it as the scientific term for the epoch that started 11,800 years ago, as the earth exited the last Ice Age. But I can't so easily define the *Anthropocene*, which currently has a grab bag of possible dates for its onset.

Which date to choose? 1964, when radioactive fallout peaked prior to implementation of the nuclear test ban? 1610, when the decimation of native populations in the New World allowed forests to regrow, triggering a noticeable dip in releases of CO₂? What about 1800, the proximate start of the Industrial Revolution? Or 5,000 BCE, when farming became widespread enough to begin affecting atmospheric concentrations of greenhouse gases?

To all of these I say, *Meh*.

There are couple of other options that I find more palatable.

The first is to make Anthropocene a legitimate substitution for Holocene. (The Holocene, after all, began only slightly before the Neolithic Revolution and the start of human civilization.) The Anthropocene would thus acquire what it currently lacks—a fast-hold in the ladder of time.

The second option is more radical. Why not arbitrarily declare the year 2000 the beginning of the Anthropocene? It's a round number. It coincides with the start of a new millennium. It allows the Holocene a nice long run. And it creates no messy problems when dealing with the existing body of scientific literature.

Of course, the year 2000 lacks a golden spike in the geologic record. In fact, it doesn't even have a silver or copper spike. What recommends it is a purely qualitative imperative. By the year 2000, I would argue, it had become abundantly clear that we aren't living in the good old Holocene any more. By then, like Dorothy in the *Wizard of Oz*, we realized that we'd left Kansas far, far behind.

David Charlet, Department of Biology, College of Southern Nevada, Las Vegas, NV

The idea that the global environment is being shaped by humans rather than the environment shaping humans is the pinnacle of hubris. My mountains slough off humus and humans with equal ease. The hubris is thinking that we control the environment. I do not mean to diminish the distress I feel when our actions appear to destroy the ecosystems in my region, but I do not think these impacts yet are sufficient to constitute the status of a geologic Epoch, Period, Era or Eon, and thus proclaim ourselves the principal influence of a new geologic episode at any scale. Such proclamations are hubris.

The Holocene Epoch is thought by some to have begun about 12,000 years ago, with the retreat of continental ice and release from the grips of the "Ice Age" (meaning the Pleistocene Epoch). Both the Holocene and Pleistocene belong to the Quaternary Period of the Cenozoic Era. I began my doctoral work to learn more about how the starkly evident signs on my mountains and valleys were made and how they shaped the life that is here,



problems that have plagued me my entire adult life. As I was learning the classic geologic precession of epochs, a simple and direct essay by geologist Stephen J. Gould (1991) was published: "Abolish the Recent." Gould argued that we should abandon the idea of a Holocene Epoch since we have not yet left the Pleistocene persuaded me immediately, and I have found nothing to dissuade me since.

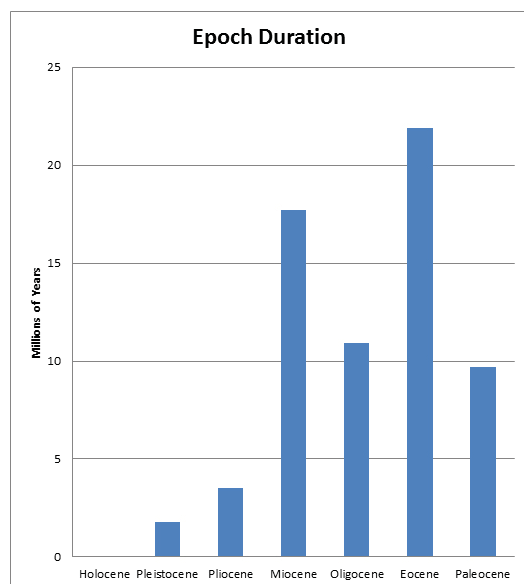
Perspective in art is the craft of creating the illusion that the 2-dimensional surface of a canvas represents a 3-dimensional space, where objects closest to the point of observation are the largest in the painting, with objects becoming progressively smaller as they appear to be further in the distance. I believe we fall prey to the same illusion but in reverse when it comes to contemplating geologic time. All time in the immediate past appears enormous, while Epochs in the distant past, regardless of size or duration, are miniaturized. Indeed, the 12,000 years of the Holocene are trivial when compared to the 2.5-3 million years of the Pleistocene. The Pliocene, with duration of about 3.5 million years is comparable. Further distant Epochs are the Miocene, Oligocene, Eocene, and Paleocene, which lasted about 18, 11, 22, and 10 million years respectively.

"Anthropo-" is not apropos because as it is used it means human. But projected large-scale geologic changes due to humans are not innate properties of humans, only a particular kind of human influence. The impact of the first people in my area was trivial and yet remarkable that they persisted here from the end of the "Ice Age," or the whole of the "Holocene." The invasive forms that came later had a very different attitude, and 100 years of their presence completely overshadows the prior 12,000 years of continuous occupation by humans. The early outposts of the pioneers in my region were established in 1851 in northern and 1855 in southern Nevada by the Church of Latter Day Saints. They struggled, had little impact, and were withdrawn in 1857. In my area, The Anthropocene, if I must accept it, began in 1859 with the discovery of gold at Gold Hill, Nevada.

At this point, I am not comfortable with Anthropocene at any geologic "level." Are we to "abolish the Recent" only to embrace the Anthropocene? Whether or not there is an Anthropocene is our test. If we find a way to cross the threshold that unhinges the glacial-interglacial episodes, whether by our inducing out-of-control warming or by producing a nuclear winter, then I would say that we have entered the Anthropocene and failed the test. It seems clear that unless we learn lessons quickly, mainly concerning how we do not control our environment, we will be the victims of nature's tendency to equilibrate. We already know well enough what the world is like during glacial maxima and minima, and we cannot live like this in those either of those times. We are painting ourselves into a box canyon from

which there can be no escape. I would not be teaching young people about the environment if I thought this was a foregone conclusion.

Gould, S.J. 1991. Abolish the Recent. *Natural History* 100(5): 16–21.



Anne Kelly, USGS Canyonlands Research Station, Moab UT

The Anthropocene is a useful concept, however or whether it ends up being formalized. On the Colorado Plateau, the dawn of the Anthropocene could be most usefully defined at two time periods, albeit the magnitudes of change during each period are vastly different. The first is the time at which early North Americans began hunting megafauna and/or farming enough to substantially alter local hydrology, ecosystem structure, surface albedo, or other regional-scale processes. The second is the time at which industrialization began to alter the Plateau, including large-scale livestock grazing, farming, dams, railroad-building, mining, and atmospheric CO₂ increase, among many others. Defining the Anthropocene as beginning in the mid-19th century would probably be useful to most land management questions on the Colorado Plateau.



Photo credit: J. Grande

Paul Sheppard, Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ

Personally, I don't see the need or justification for adopting Anthropocene in the geological time scale, at least not at the epoch level, or even the age level. It's not that humans haven't left, or aren't leaving, a mark on Earth, as we certainly have and continue to do so. Given that units of the existing geological time scale are bracketed in part by events such as mass extinctions and/or climate changes, both of which are occurring now in part due to humans, it would seem that an Anthropocene something would be in order. But, viewing humanity modestly, it seems that little evidence of us will persist in the geological record after we're gone (Alan Weisman, *The World Without Us*, 2007), so I'm not convinced that inhabitants of Earth in the distant future would discern our impacts as equal to, say, the Permian or Cretaceous Extinctions, or the Pleistocene-Holocene climate change.



As for mountains in which I work, the mid-elevation ponderosa pine forests of the Sky Islands of the American Southwest have been hugely affected by humans by the alteration of fire regimes. Ponderosa pine forests used to burn frequently in fires of low severity that slowly crept across the ground surface, consuming needles and other debris as well as small trees, but not often killing many large trees and melting soils. Now, seemingly every summer a few fires grow out of hand and burn vast swaths of forests, killing whole stands of trees, including old trees that had been living for hundreds of years, and creating moonscapes. This is regrettable for us humans here and now, as for decades after such fires we lose the myriad goods and services that healthy ecosystems provide. But I don't see even this change in mountain ecology as easily discernible in environmental records long after humans are gone. Fire prone ecosystems will re-equilibrate quickly after the lights go out, and our influence on forest disturbance will probably be viewable as only a blip, if at all.

That's it: If Anthropocene were adopted into the geological time scale, I would propose this temporal resolution: The Anthropocene Blip.

Kathleen Matthews, USDA Forest Service, Pacific Southwest Research Station, Albany, CA

I believe that a stratigraphically defined Anthropocene is quite relevant especially for the high mountain aquatic ecosystems of the Sierra Nevada. Since the 1800s, humans have dramatically altered these Wilderness systems by widespread grazing (first sheep then cattle) and exotic trout stocking into fishless lakes and streams. Mountain meadows on the Kern Plateau have been significantly changed and degraded by sheep and cattle grazing starting in the 1800s. These meadows composed primarily of decomposed granite now show the classic signs of overgrazing: incised channels, collapsed banks, moving stream channels, lowered water table, drying meadows overtaken by sagebrush, and warming stream temperatures. These dramatic changes started when European settlers began their widespread grazing activities in the Sierra Nevada; grazing has resulted in meadow drying and a dramatic change from moist herbaceous willow and sedge dominated streambanks to drier sagebrush dominated



landscapes. These widespread changes in meadow ecosystems have had deleterious impacts on native species such as the California golden trout and willow flycatcher.

Exotic trout were first brought by mules into streams and lakes of the high elevation Sierra Nevada in 5 gallon milk cans and after World War 2 were dropped by California state fisheries agency airplanes in widespread stocking across the Sierra Nevada. These exotic trout have dramatically changed the aquatic biota of fishless lakes: amphibians, invertebrates, and even garter snakes that rely on amphibian prey have declined in abundance and distribution across the Sierra Nevada. Fish managers considered these lakes “barren” because they did not contain catchable trout so they embarked on a widespread campaign to provide fishing opportunities with no studies to determine the consequences. This major disturbance to the native biota unfortunately had many unintended consequences and resulted in the federal listing of amphibians and the major change in zooplankton and other invertebrates.

The Anthropocene began in the early 1800s in high elevation ecosystems in the Sierra Nevada and continue to this day. It should be designated and defined as a specific subdivision in the continuum of time.

FIRST PERSON



Panorama of the Great Western Divide from the 2015 snow survey. Photo: Analisa Skeen.

Pray for Rain: Tokopah Basin Snow Survey, 2016

Analisa Skeen

*Sequoia and Kings Canyon National Parks
Three Rivers, California*

We are greeted by a holler. The light from our headlamps bounces against the trees and the stone walls of the hut. It's my dad who has yelled out to us. He stands at the front door illuminated by the cabin light and the half-moon that hangs on the horizon.

"Go ahead, Adam," I say, "Blaze onward." Adam hikes past me, picking up speed.

The track is frozen and my skis slide easy on the snow. Sweat beads at my temples, my neck, my upper lip. I shift the weight of my pack.

When I reach the hut Dad slaps me on the back. "How was the ski up?"

"Real nice," I say. Adam nods in agreement.

We started hiking this afternoon in the fog but broke out of it soon enough. By the time I had put on my skis and Adam, his snowshoes, we had climbed out of the seeping grey and into a clear, blue sky. We made it to the top of the hump just in time to catch the alpenglow light up the high ridges of this basin. The Tokopah stretched before us: up, toward the highest peaks of the Sierra Nevada, and down, beneath the fog, to the low hills of the San Joaquin Valley.

I have stood on that ridge, have made this slow climb to the Pear Lake Hut, in every season. The curves and sharp lines of this basin are familiar to me even in the dim moonlight. My dad

works for the University of California conducting research in the Tokopah watershed and has been doing so since before I was born. We are here, trudging through snow on fat skis, for the same reason we have come before: to conduct the annual snow survey, grab a few lake samples, dig a few pits, and spend some time a few thousand feet closer to the sky.

When we stomp into the hut, we are welcomed by a slew of wide smiles and sunburned cheeks. Adam and I have arrived a day later than the rest of the crew, hiking up after school and work.

"We've got burritos!" Steve says from the stove. "Analisa, there's a can of olives here for you." He smiles at me; he knows I don't like olives.

There are seven of us crammed into the cabin. Jim, the principal investigator and a professor at UC Riverside, fiddles with equipment at one end of the long table in the center of the room. Stephen and Jake, both UCR graduate students, discuss the amount of snow they dug out of the pit (10,000 pounds apparently; 8,000 of which they had to throw back in). Steve, a recently-appointed professor at UC Davis, flips tortillas, and, representing UC Santa Barbara, Adam has found a seat and scarfs down one of Steve's burritos.

Tired from the heavy climb, it doesn't take long for us to find our beds. I wriggle deep into my sleeping bag. Jim turns off the light. I am out.

By 9:00am the next morning, we have slapped on our skis and divided up the day's work. We split into three teams: one for the snow pit, and two for surveying snow depths. Steve and I have been assigned a transect that climbs along the southern edge of the basin and wraps around to the back of the Tablelands.

It is a hard pull to the top of the ridge behind the hut. The sky is empty; the wind, restless, and the snow gleams in the sun—blue, smooth, polished. Last year, my dusty boots scraped against granite as I hiked up this ridge. Mountain heather struggled through fractured slabs, the river cascaded, unhindered by snow or ice, to the valley, and wiry grass pushed through dry soil. It was the driest year on record.

The Sierra Nevada, so named for their serrated edges and snow-capped peaks, stretch some 400 miles down the state of California. All along their length dams and reservoirs, hydroelectric plants, flumes and canals, are employed to capture the water that is preserved by the Sierra's snowpack. This formidable mountain range is the source for 60% of California's working water. The snow I am pushing my skis across provides water for 25 million people, 15% of the state's overall electrical power, 7% of its available groundwater, and over 50% of the water used to irrigate the 3 million acres of cultivated land in the Central Valley, the most productive agricultural region in the world.

The University of California has been conducting snow surveys in this basin for over thirty years. Jim and Dad have been present for most of them. At night, they regale us with tales of snow pits twelve meters deep, of elaborately constructed staircases and multi-level shoveling operations.

"We used to take fifteen probes out to survey," they say, gesturing to the meter-long poles with which we measure snow depths. "And we'd use them too." These days, we don't take more than seven probes out.

Steve and I ascend, two hundred paces at a time, towards the southern edge of the basin. The wind blows steady and cold across the still-frozen snow. The sun rises in the sky, its light tuning from white to yellow. I am working hard, my chest filled with the slightly-nauseated breath of empty air, my muscles acutely aware of each movement.

"This is good," I say. Steve stops and widens his stance, jamming and twisting the probe into the snow until it hits the earth. I pull out the GPS and open a new data point.

"313," Steve calls out. I enter it. Not bad, three meters and a little bit. He moves to the second point and down the probe goes again. I watch the GPS, waiting for the satellites to get a handle on our position.



I am skiing above the tablelands on the edge of the Tokopah watershed. Photo: Steve Sadro.



My dad, Kevin Skeen, skiing from Emerald Lake to Pear Lake, with a view back toward California's Central Valley. Photo: Steve Sadro.

"251," he calls. He moves farther up the hillside. The satellites are still thinking.

My dad and I did this transect last year and didn't even bother to put snowshoes on. Most of our points didn't break the two-meter mark. Many of them were simply zero. It is a relief to have a heavier snowpack.

"Woah," Steve says. "415!"

"Nice!" It is the deepest point of the day.

As we continue along the edge of the basin Steve and I talk about the papers he is working on. We discuss our mutual disdain for slimy lunch meat. We talk about bread-baking and bike-riding and teaching, about summer backpacking trips, dogs. It is a normal day and the data we collect seem almost inconsequential. I don't really think about what it means, or where it will go. It is just a string of numbers.

It is well after noon when we break out of the Tokopah. Before us, the world drops off. The Great Western Divide appears suddenly before us. Miles and miles of jagged granite fall thousands of feet to the Kaweah River valley. It is breathtaking.

From where we stand, I can follow the river all the way to the flatlands of the Central Valley. It is here, I know, that Highway 99

runs like a fat vein down the center of the state. I drove to Fresno just a few weeks ago and watched row upon row of boxy orange trees and tangled grape vines flash by my window. There, raised on a chain-link fence, a banner: *Pray for rain*; an old red barn, painted with the phrase, *Build dams, not trains*; a teenager with a t-shirt that read *When in drought, dam it*.

The Tokopah watershed project, and projects like it, has collected years of snowpack, runoff, and water chemistry data. Data that finds itself, in our changing climate, relevant not only to the scientific community, but also to the citizens of California and beyond; to the teenager that wears a t-shirt that reads 'when in drought, dam it'; to the farmer that believes the water crisis is a crisis of inadequate storage and not a crisis of an inadequate resource; to the dinner tables, at home and abroad, that feast on California oranges and olives and peaches.

I do not know what a string of numbers can do to help a state in the crux of a water crisis. What I do know, is that the snow we measure today will melt and flow ever-downward—over granite, through the sharp ravines of the foothills, into a wild, frothed river—until it settles on the smooth surface of Lake Kaweah, where it will hit the hard wall of a dam. And when the Valley is parched and dusty, the water will be released into canals of concrete and will pour into orchards and holding tanks. It will



My skis and skins, looking back down the Tokopah Basin toward Pear Lake. Photo: Steve Sadro.



The crew skiing over Topaz Lake after a long day. Photo: Steve Sadro.

quench the need of a thirsty orange tree, or cool the brow of a sweltering field-hand. And before long, I will walk into a grocery store, or stop to buy strawberries on the side of the road, and that snow will find itself, in one form or another, in my hands.

It is late in the day when we meet up with the rest of the crew. We stand at the back of the basin and peel off our skins. The skis feel slick and loose without the thick fur on the bottoms. The snow has melted to a slush. It is slow and wet—perfect spring skiing.

We hoot and holler with wide smiles, cutting easy turns down the valley. When we reach the last ridge before the hut, the sun drops into the horizon and the light is warm. Tired, hollow, ecstatic, we tear down the hillside.

Somehow, this is the story the data tells. Somehow, this string of numbers connects the snow I ski on to the cracked earth and summer sun, to the soil that works its way into the farmer's palms, to the city-slick businessman that scurries past a bursting fountain, to the family somewhere in the Midwest that slices up an orange. I do not know how a string of numbers can say so much. But they do.

At the bottom, Steve grins at me. "I'll drop my pack if you want to go up again." I am reluctant, my body empty, but Steve is already taking his pack off and putting his skins back on.

I smile. "Let's do this," I say. And we begin again, to climb upward.



Steve Sadro, collecting lake samples at Emerald Lake. Photo: Kevin Skeen.



Fog rising in the valley. The Watchtower is the impressive rock face. Photo: Steve Sadro.

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Analisa Skeen is a recent graduate of Montana State University. Currently, she works for Sequoia & Kings Canyon National Parks and will do so until she begins graduate school next fall. She will be studying rhetoric and composition at Michigan State University.

FIELD NOTES

This section of Mountain Views Chronicle spotlights where we—mountain scientists, resource managers, and other professionals—work. Feel free to submit Field Notes about your favorite mountain region. —Editor



Figure 1. White Mountains burns. 2004 fires burned hundreds of thousands of acres in this part of Alaska.

The Other White Mountains: A Window into the Boreal Future

Jeremy Littell

*DOI Alaska Climate Science Center
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“The field”. “Fieldwork”. Those phrases have magic in them, of more than one kind. The modern kind is we put that phrase in email autoresponders and it seems to absolve diverse failures. Apparently, others have patience for something that is becoming increasingly rare – time for fieldwork, time to go get the data from the big “out there”. But there’s another kind, the kind that implies some nostalgia for a time when more than a few scientists did everything, including writing their papers, in “the field”. Some immersed themselves for years in the processes they were studying “out there”. Not many of us do that for any meaningful length of time anymore.

This trip, on the way to “out there”, and as if to remind me of the opportunity before me, the weatherband announced a useful fact - that the “sun.....will not set”. For the five days either side of summer solstice, this part of Alaska has continual sunlight. Arctic plants and birds make use of the short season, and so can I; when the sun doesn’t set, there is one fewer limitation on what it is possible to do in a day.

I have the good fortune to conduct science that depends on data from places with comparatively little human influence other than changing climate. Before I implied purpose by calling it “the field”, I sought solace in places that have become, at least to me, “the field.” Over the last many years, that has gradually changed, and now I come to this place and others like it to settle questions with observation, to make measurements. Maybe truer to the complexity actually unfolding here, I also come hoping to sharpen my questions to the point they can be addressed with observation at all. But that means I have traded solace for a kind of urgency because “the field” is changing fast, and the time to collect measurements is in ever shorter supply. I have replaced contemplation of wild places in wild places with the need to traverse those wild places fast enough to get sufficient data. Pursuit of that task in this place rewards simplicity and going as light and fast as possible. The equipment for this looks like an odd mix of mountain endurance sport, rural hardware store, and science fair electronics experiments.

I'm on a bluff above the treeline ecotone, among ptarmigan leks and scattered krummholz, about 100 km northwest of Fairbanks and about the same distance south of the Arctic Circle. To the west, south, and east, the view unfolds for tens of kilometers of the rolling foothills of the White Mountains (Fig. 1), with peaks reaching 1500 m to the north behind me. These are not the White Mountains famed for high wind in New Hampshire, nor those famed for ancient bristlecone pines in Inyo County, California. These White Mountains are short by those standards, but have a different superlative – they are part of a larger geography between the Alaska Range to the south and the Brooks Range to the north that, in some summers, rivals the entire lower 48 states for area burned by wildfire. In part that is because Fairbanks gets less annual precipitation than Tucson, AZ and is warming at twice the global average. Recently, we also have snowdrought; fire season begins during our dry, bright spring rather than in the transition between spring and our wet late summer.

Over a decade ago, these foothills were an expanse of spruce (*Picea glauca* in the uplands, *P. mariana* over permafrost, and depending on whom you believe, their hybrids where nothing limits the possibility), all of it diffusing into textbook treelines, three kinds of tundra, and snow peaks. From here, I can also glimpse the future. In this small part of an immense fire-prone geography, wave upon wave upon wave of silver and charred

stems stand anchored in a sea of green dwarf birch and pink fireweed, the result of early 2000s fires and smaller recent re-burns. The view is on the order of 100,000 hectares of burned spruce, and that's just the part I can see with binoculars. Out there, behind the mountains, and in other unseen valleys, there are islands of living spruce amid fire runs of varying severity. How will this landscape change in the next decade? The next century?

That's the reason I am here. From both paleoecological data and modern observation, it is clear that increases in fire frequency and possibly severity favor deciduous broadleaved trees rather than the spruce we think of as characteristic of this landscape. After fire, reestablishment of spruce, surface moss and lichen, and permafrost is contingent on a fire-free period of many decades. Warming likely decreases that interval on average, and also increases the likelihood that permafrost can become locally discontinuous after disturbance, allowing infiltration and fundamentally changing site hydrology. Whether a major transition from spruce to aspen or birch occurs is probably dependent on fire severity, microclimate, and soil texture.

Just below, at a precise point among the bryophytes and lichen, is a tiny sensor I placed about 13 months ago (Fig. 2). Following coded instructions, it woke hourly all year to monitor



Figure 2. Sensor near treeline. Surface temperature sensors allow estimation of snowpack duration. Paired with air temperature, soil temperature, and other measurements deployed in a network, variation in watershed responses can be measured.



Figure 3. Late winter in the burn. April snowpack coincides with the return of long days to the Arctic.

temperature, recorded the measurement, and returned to its stasis. It is one of a cohort of over a hundred, each with identical instructions, each with nearly 10,000 hours of information about how cold it was (or this year, wasn't), whether there was snow cover (Fig. 3), and, if not, how bright it was there on the carpet of spongy tundra, or among the burned spruce (Fig. 4), dwarf birch and tussock (Fig. 5). It knows nothing of the evolving questions that keep me occupied between plots, how critical it is to keep waking up and recording, nor any relief that the local brown bear has not found it for another year. It is part of a network designed to record air, surface, soil temperature, and snowpack, effectively

the pulse of the watershed, but has little else to say, especially regarding my wish to have this wild place serve the dual purpose of wilderness and laboratory. I have to admit, though, that their precision and reliability considerably exceed my own. After messing around finding equipment and trying to get started early while it's still cool, I am only a quarter way through a figure-eight loop that will take 14 hours to complete, pulling last year's sensors and replacing them with those for the coming year. A day's work for me in "the field" for 10,000 hours of manifold replicated surface climate.



Figure 4. Burned white (or hybrid) spruce stands. Post fire vegetation is commonly mixed shrub, forb, and grass on well-drained upland sites.



Figure 5. Sensor mast in burned black spruce / tussock. Tussocks commonly dominate the post-fire surface in poorly drained sites.

That's the tradeoff, I guess. Moving fast between sensors, I can watch for things that help me sharpen the questions, but there is no time to ponder the processes, to vacate my mind of the need to hurry and thus achieve focus amid this vast silence. Analyzing the data on a computer screen later is a faster way to a publication, but not necessarily the path I originally sought. What might I know if I had made those 10,000 hourly observations, closer to a million across all sensors, or even all those in similar distributed sites between here and southern Alaska? Boredom, surely, but it's a question worth asking – how many ways are there to be 30 C° or -40 C°? In the last three years, at this site anyway, the answer to the latter is none, but the former is not clear without other data. Tomorrow, I will lug batteries around for sap flux sensors that can say how many ways there are to be 30 C° if you happen to be a *P. mariana* big enough to wear a sensor. I worry there are not more than three that big, that straight, in the whole valley.

What we can do in science with such tools is incredible. But what do we miss when we rely only on sensors, big data, and analysis with digital tools (some elegant and nearly surgical, but some closer to an excavator)? Not all that is numerically possible is worthwhile, and certainly not always scientifically defensible. That's what the field is for – checking our tendency to fool ourselves into thinking we know things we don't actually know, or, worse, discounting things we suspect or know dimly but choose to ignore (Figs. 6, 7). And although my own relationship with wilderness has complicated considerably by adding fieldwork to it, I take no small joy in simultaneously walking through a lot of it and measuring its processes. With 24 hours of sun-above-the-horizon daylight available to me today, it could be quite a trip.

-All photos by the author



Figure 6. Smoke and spruce. A common early summer interior view – spruce emerging from a haze of smoke.



Figure 7. Boreal summer “sunset”. The sun stays high, but we are privileged to get a real sunset thanks to a nearby fire.

DID YOU SEE IT?

This section of Mountain Views relates sense-based encounters with mountain weather, climate, and environments. Jim Blanchard has contributed mountain photographs to prior issues of Mountain Views. Here he shares a taste of his many mountain adventures involving encounters with extreme weather. As Jim and I have been colleagues since 1969, I can claim to know that although safety is his highest concern with his students and clients, Jim has been known to push the risk envelope himself. Some of the adventures he describes below should not be tried “at home.” —Editor

Weather Lessons Learned (or not) in the European Alps

Jim Blanchard
University of Oregon (retired)
Eugene, Oregon

I've always enjoyed thunderstorms, and look forward to the dozen or so that pass each year over my home in Eugene, Oregon. And as an avid backpacker, climber, skier and kayaker I've occasionally found myself cowering from the wind, rain, small hail and lightning during storms in the Cascades and Sierra Nevada, but these events have, with rare exceptions, been more exhilarating than scary. It was not until the late 1960s, when I began spending a lot of time in the European Alps, that I began to appreciate just how dangerous and unpredictable thunderstorms can be. In the early 1980s I started a small trekking business, which for the next several decades enabled me to wobble around in the Alps for a month or more each summer. Eventually, I was

able to explore parts of every significant range in the long arc of mountains from Slovenia and Austria to eastern France.

How Not to Avoid Lightning

A Close Call in the Dolomites

In 1995, I led a trekking group through the Dolomites of northern Italy, where we spent a night at Rifugio Brogles, which sits at the foot of the dramatic, jagged spires and peaks of the Puez-Odle-Geisler Group (Fig. 1). We arrived at about 2:00 pm, the time at which we always tried to arrive at our evening's lodgings, to avoid the almost daily thunderstorms that in July typically start in



Figure 1. The Odle-Geisler peaks from Seceda. Rifugio Brogles is in the valley to the left, and the ridge is the one that hid the approaching storms from us.

mid-afternoon. Sure enough, the rain began within minutes of our arrival, soon followed by rumbles of thunder.

Thunderstorms in the Dolomites usually last about 30 minutes, with one or two other storms following at intervals of 30 minutes to an hour. This time, however, they seemed never to end. Before the flashes, booms, and heavy rain of one storm had faded, another storm was upon us. As the succession of storms passed over the area, Pete Mason (my assistant) and I became eager to escape from the crowded hut, so we began timing the lightning, hoping for a significant gap between storms. Eventually, a 20-minute spell of quiet and some spots of blue sky convinced us that there were no storms closer than 8 or 9 miles away. The two of us quietly left through the back door, as we were not feeling confident enough to invite our clients to join us. Passing behind the hut, we then turned and walked past the small, low roofed barn that sits about 100 feet up the hill (Fig. 2), then another 200 feet or so to a large, flat topped rock, on which we sat and enjoyed the fresh air and spectacular scenery.



Figure 2. Rifugio Brogles. The Odle-Geisler peaks are in the background.

About 15 minutes later we heard a faint rumble of thunder to the southwest. This was concerning, as we couldn't see more than a few hundred yards in that direction due to the steep Odle-Geisler ridge looming above us. Moments later, with no clouds visible over the ridge, and no additional thunder or flashes of lightning to warn us, the hair on both of our heads stood straight up, and sparks ("St. Elmo's Fire") began to crackle from a nearby metal peg (an anchor for rock climbing practice)!

We were off of that rock in a flash, and we ran down the hill and across the meadow, headed straight for the hut, as the first big raindrops began to pelt us. As we passed between the barn and

the hut, lightning arced over our heads, from the metal gutters of the barn and the hut. The gutters of the hut were well grounded, but apparently those of the barn were not. Clients watching us from inside the hut said the arc passed just a couple of feet over our heads! The simultaneous flash and bang left us seeing colors and with ringing ears, and one of mine took nearly a year to recover. And, our hair was curled at the tips—resulting in some difficulty combing our hair, and the need to trim off the tips.

St. Elmo's Fire from a Vie Ferrate Cable in Puez-Odle N.P.

Long before World War I, a few enterprising hutmasters in the Dolomites of the South Tirol began adding fixed ropes, foot pegs and wooden ladders at dangerous places along some of the more important access trails and some of the climbing routes near their huts, hoping to increase their business and reduce the number of injuries and fatalities among hikers and climbers. Since then the fixed ropes have in most (but not all) cases been replaced by wire rope cables, and countless metal pegs, steps, and ladders have been installed. There are now more than a thousand such routes in the Alps, with the majority of them in the Dolomites. The remains of the original wooden pegs and ladders can still be seen along some routes. These routes are now widely known by their Italian name, "via ferrata", except by German speakers, who prefer "Klettersteig" (Fig. 3).



Figure 3. A typical via ferrata, with two people using harnesses and a pair of rope leads attached by carabiners to the cable.

In late July, 1997 I led a trekking group through the Dolomites that included a walk past the Odle-Geisler ridge. After a night at the very comfortable Rifugio Firenze, my assistant Rick Troxel and I shepherded our flock up the valley to the small pass we had to cross before descending to Rifugio Puez (Fig. 4). After a series



Figure 4. The Odle Geisler peaks from the pass between Rifugio Firenze and Rifugio Puez.

of zigzag traverses we finally arrived at the top of the scree and talus, from where a short (100 yard) but steep crest of rock must be ascended to reach the actual top of the pass. At this point the trail becomes a via ferrata. We put on our helmets, harnesses and “via ferrata gear”, a system of rope leads and carabiners that allows attachment to the cables and provides shock absorption in the event of a fall.

Until this point, the sky had been mostly clear, with no sign of any large cumulus development. However, just as we were about to start up the cables, we heard the distinctive, though faint, rumble of thunder. Uh oh! Having previously underestimated the sneakiness of storms, I was seriously worried. The last place you want to be in a thunderstorm is attached to the steel cable of a via ferrata. It was only 8:30 am and thunderstorms don’t often occur so early in the morning, but I wasn’t about to take any chances. So, I asked everyone to add clothing to ward off the morning chill, and we waited for what seemed like a very long time. After about an hour we had heard no more rumbles, and we had reached a time when we had to either continue on toward Rifugio Puez, or descend 3900 feet in elevation to the village of Wolkenstein.

We decided that the best plan was for Rick to scurry up the via ferrata to the crest, as he would then have a better view. If he

saw no storms approaching and if by that time we had heard no thunder, I would follow with the group. Rick walked uphill toward the end of the first cable, and just as he was about to reach for it a shower of sparks sprayed from the frayed ends of the wire rope, followed by a few seconds of classic St. Elmo’s Fire. Just a few seconds later he would have been attached to cable, and at least part of the current would have flowed through him. Needless to say, we immediately headed down the trail at a snappy pace, not even stopping to take off our helmets and via ferrata gear until we were down to the base of the pass, by which time the storm had loomed over the ridge and we were being pelted by a mix of rain and small hail, accompanied by nearly continuous thunder. It’s a long walk down to the valley from that point, but the thought of a snug, dry hotel in Wolkenstein kept everyone energized.

A Hair-Raising Experience near the Matterhornhutte

One evening in July, 2003 my wife Robyn and I were about 100 yards above the Hornlihütte/Matterhornhütte complex on the Matterhorn, near the steep buttress at the foot of the Hornli Ridge, admiring the view. We were leading a trek in the eastern Alps, and we had escaped from the crowded hut while our clients were having dinner. There were thunderstorms in the area, but all of them were more than ten miles distant, and moving to the

northeast, away from us. We had good visibility to the north, south and east, but not to the southwest, as we were pressed up against the base of the peak. We could hear no thunder, and we could see nothing but blue sky at the edges of the Matterhorn.

A few minutes later, as I was looking through the viewfinder of my camera and framing a picture of Robyn and the hut, I noticed that her long blonde hair seemed to be blowing upwards. A second or two later it dawned on me that there was no breeze whatsoever—it was dead calm (Fig. 5). Just as the implications of that observation began to sink in, Robyn hollered at me that MY hair was standing straight up! In a split second we were running as fast as we could down to the hut. As we ran past the restaurant windows along the right side of the Matterhornhütte a big bolt hit the lightning rod on the roof. Our clients, who once again were watching as we dashed past the windows, reported that we were suddenly illuminated by the blue light of the bolt, just as the thunder shook the hut.

This was a classic example of the guide(s) doing something that they would not allow their clients to do. If any of the clients had suggested going up on the ridge, we would have discouraged them as there were thunderstorms in the area and we knew that approaching storms could not be seen, as the Matterhorn was in the way. In this case I let my desire to get away from the throngs at the hut, and the prospect of getting a good photograph, outweigh my common sense.



Figure 5. Robyn and the Matterhornhütte, at the foot of the Matterhorn's Hornli Ridge. Note her hair, lofted by static electricity.

It should be noted that all of the above incidents had one thing in common—poor visibility in the direction from which thunderstorms travel in that part of the world. At least I'm not alone in making this mistake. It's well known in the realm of mountaineering that a disproportionate fraction of lightning injuries occur on routes and at locations where it's not possible to see approaching storms early enough to allow actions that might reduce risk. This was the third time I'd made the same mistake, for which I can offer no worthwhile excuse.

Sparks in the Casini Group Generated by a Distant Thunderstorm

While leading a trek in the Dolomites in early August, 1997 our group stayed at Rifugio Fonda-Savio, which sits on a ridge crest in the Casini Group, above Lago Misurina. Rifugio Fonda-Savio is a favorite destination for many people as the scenery is magnificent and the food is exceptionally good. Originally, the supplies for the hut were carried up from Lago Misurina by people and pack animals. Later, a small single-cable supply lift was installed, running from a site near the lake to the downhill side of the hut. A decade later, an extra bunkhouse and washroom were needed to accommodate increasing tourism, but the only suitable site for these structures was on the north side of the hut. So, it is now necessary to step over the lift cable (a quarter-inch wire rope about a foot above the ground) get from the main hut to the bunkhouse, toilets and washroom (Fig. 6). When the lift is not in use, getting over the cable is only minor inconvenience—no problem at all so long as you pay attention and don't trip. The location of the hut on a narrow ridge provides no other good options for getting around the cable.

At about 3:00 in the afternoon we could see an impressive and ominous cumulonimbus forming far to the southwest. Several of us sat on the deck admiring the storm as it grew to immense size by about 3:45 pm. At this point, the storm appeared to be about 15 miles away. It was too far away to hear any thunder, and we saw only one bolt of lightning, a ground strike, as the day was too bright and sunny to see smaller bolts or flashes. The lift was not in use, and a few of our clients were in the bunkhouse or using the toilets or washroom.

Suddenly, we heard a loud yelp from someone who seemed quite scared or distressed. The cry came from the direction of the bunkhouse. When we turned to look, two people were standing about 10 feet behind the lift cable and looking, wide-eyed, at it. When we inquired as to the problem they said a big spark had jumped from the cable and that it had barely missed them. A few seconds later, as I was walking quickly toward the distressed clients, while keeping an eye on the cable, it happened again—



Figure 6. Rifugio Fonda-Savio in the Casini Group, with the Drei Zinnen in the distance. The cable lift runs straight down the valley from the left side of the hut. The bunkhouse and washroom are out of sight, directly behind the hut.

sparks a foot or so in length flashed straight to the ground, and others three feet or more in length arced to the metal frame of the housing for the main pulley. Each spark produced a sharp snapping sound. The storm was still so far off that we had not yet heard any thunder! I instructed the clients to quickly return to the bunkhouse, which was well protected by grounded lightning rods, and asked them to keep everyone inside. Meanwhile, our flock of cloud watchers scurried into the hut. Despite the ferocious appearance of the storm, which eventually drifted right over us, there were only a few nearby strikes, apparently on some of the great spires near the hut. The storm had drifted far past us before anyone had the courage to cross that cable (Fig. 7).

Witnessing such dramatic and potentially dangerous effects was a good reminder for all of us that thunderstorms can be dangerous even when they are far beyond the range at which thunder can be heard. In this case the storm was probably at least 14 miles away when the first sparks were generated.

Extreme Winds, Hail and Snowfall

An Exceptionally Violent Squall Line in Bavaria

The Carl V. Stahlhaus sits perched near the 5700 foot Torrener Joch (pass) on the German-Austrian border in the Bavarian Alps above Berchtesgaden (Fig. 8). In 1991 I led a group of trekkers to the Stahlhaus, where we watched in awe as a particularly violent squall line swept over the Watzmann (the 8900 foot peak that dominates the area), down across the Konigsee (7500 feet below), then up over the hut (Fig. 9). The extremely powerful winds, laden with hail, swept the heavy picnic tables and benches off the deck of the hut and rolled a large oil barrel uphill, but the most dramatic scene was of the cows being knocked over as they tried to make it up and over the pass, trying to reach the shelter of the downwind side. If the cows got their rears too far out of line the wind flipped them onto their sides! All this was accompanied by nearly continuous lightning and thunder, often with no discernible lag between the flashes and booms. This was certainly the most spectacular squall line I have ever seen.



Figure 7. The thunderstorm that generated the sparks approaching Rifugio Fonda-Savio.

The long time hutmaster, Helmut Pfitzer, had wisely sealed up the hut as soon as he saw what was coming, so we watched the events by peering through small openings in the shutters. Later, our group spent a couple of hours helping Helmut locate and return the somewhat battered benches and tables. Fortunately, to the best of my knowledge there were no serious injuries or loss of life caused by the event, human or bovine.

Giant Hail Stones near Rifugio Genova

In late July, 1993, while leading a trek in the Dolomites, we found ourselves an hour or more behind schedule on the long walk from Rifugio Raschotz to Rifugio Genova. Once again, we had intended to reach the rifugio by 2:00 pm to outwalk the thunderstorms. Sure enough, cumulus clouds had been slowly growing since about noon. Unfortunately, our pace had been slowed by a client's sprained ankle, so at 3:30 pm, when we felt the first drops of rain, we were still nearly a mile from the rifugio. By the time we were about 1/2 mile from the rifugio the rain had increased, as had the winds, which were strong enough that most of us put away our umbrellas.

As we continued up the trail, we were pelted by a series of hailstorms, with each successive shower consisting of larger stones. The showers were intense enough to turn much of the ground white with acorn sized stones—hail big enough to sting if it hit your head. At this point I suggested, but didn't require, that everyone put on their climbing helmets, and I put on mine to set a good example. Most of the clients also put on their helmets. The shower of acorns slowed down after a few minutes, as we continued up the trail. A few minutes later I saw a few stones that looked like golf balls mixed in with the more numerous acorns. Within a few seconds the big stones became much more numerous, and I took a noisy, hard hit on my helmet. We had drilled the clients on the proper response in such circumstances, so those who were not wearing their helmets quickly took off their packs and held them over their heads, as there was no place to hide on the exposed ridge-top trail.

In a move I quickly regretted, I opened my umbrella, hoping to deflect the big stones. It was a poor decision, as several of the stones blasted holes right through the fabric, and one of those left my hand bloodied. About 10 minutes later, when the large stones



Figure 8. Torrener Joch (pass) and the Carl V. Stahlhaus.



Figure 9. The Königsee with the Watzmann in the background.

quit falling, there was a nearly contiguous layer of them on top of the layer of acorn-sized hail (Fig. 10). When we arrived at the rifugio only a few minutes later I found that most of those who had held their packs over their heads had bloodied knuckles, and everyone who was wearing shorts had red marks, which later became bruises, on their legs and any other exposed parts (Fig. 11). The hut had taken quite a hit, with many windows on the south and west sides broken or missing. The Rifugio Genova is accessible to the managers by private road, and all three vehicles parked near the rifugio (a small truck and two cars) had lost one or more windows and their tops and hoods were covered with dozens of deep dents. Interestingly, during the whole event we heard only a few distant rumbles of thunder.

Anyone who has spent a lot of time in the mountains has probably encountered big hail, or noticed golf-ball sized craters in the mud or soil. Many people have experienced big hail in urban settings, as there are parts of the world where such events are fairly common, including parts of the central and southern United States. However, there is nothing quite like being outside during such a storm, with no place to hide.

Snow and Lightning at Rifugio Puez

In late July, 2001 Robyn and I walked from Rifugio Firenze to Rifugio Puez in some of the hottest weather I'd experienced at that elevation (about 8000 feet). We were leading a trek in the Dolomites, and everyone in the group was sweltering in shorts and t-shirts. When we arrived at Rifugio Puez at about 2:30 in the afternoon dozens of other hikers were sunbathing on the grassy areas near the hut (Fig. 12).

Within an hour of our arrival small cumulus clouds started appearing in all directions, all of them slowly tracking from southwest to northeast. Less than an hour later, several of the clouds southwest of us had grown to massive size and a few were beginning to develop anvils. Soon thereafter we felt the first drops of rain, and heard a few rumbles of thunder. By 4:30 pm everyone was cowering inside the hut to avoid the heavy rain and small hail. There was almost continuous thunder, and a few nearby bolts produced deafening bangs almost simultaneous with the lightning. Nevertheless, at this point we were still intent upon an evening hike to a nearby viewpoint, as such storms rarely last more than an hour or two.

The rains and hail never let up, so we finally gave up on the idea of going for a walk. To our amazement, the rains and lightning continued well past dark, when most people headed for bed. I stayed up, along with a few other avid fans of wild weather, to enjoy the spectacular fireworks and the sight of rain blowing sideways in the increasingly strong winds. By 9:00 pm only a couple of us were still pressed to the windows, the others having opted for sleep in anticipation of the long walk planned for the next day. Shortly after 9:00 a few snowflakes appeared amid the raindrops, and soon thereafter, to our amazement the rain had changed to pure snow! The sight of simultaneous snow and lightning at night was something I'd seen only a few times previously, and the night at Puez still ranks as the most impressive display I've ever seen. The lightning, filtered through the snow, produced brilliant purple flashes that lit up the interior of the hut, often accompanied by nearly simultaneous sharp cracks of thunder. Finally, at about midnight, I grudgingly hit the



Figure 10. Large hailstones near Rifugio Genova in the Dolomites.



Figure 11. Bruised legs as a result of the hail.



Figure 12. Rifugio Puez on an exceptionally hot day.



Figure 13. Snow at Rifugio Puez after an all-night summer snowstorm.

sack, knowing that I needed to get some rest in preparation for the following day.

It was still snowing at first light, though the lightning had stopped. Most of the people in the hut were outside of the hut before breakfast, marveling at the overnight change of scenery from bare ground to deep drifts of snow. At about 7:00 am the snowfall finally stopped and the sky began to clear. We measured 11 inches of snow in most level places, with drifts that topped three feet. A light dusting of snow isn't unusual in the mountains in late July, but this much snow in a single overnight storm is quite remarkable (Fig. 13).

Our intended route to Passo Gardena was covered with more than enough snow to obscure the otherwise distinctive paint marks on rocks (Fig. 14) that are used to define most alpine trails in the Alps. At about 8:00 am we decided to make a go of it as I knew the route well, but after an hour of post-holing and wasting time trying to find the trail, we gave up and returned to the hut. After

a short rest we then fought our way downhill, finally dropping below the snow line about 1200 feet below the hut. A few hours later we were checking in at various small hotels in Wolkenstein, as there were no single establishments in the small village able to accommodate an unexpected 15 guests.

From the perspective of an outdoor leader or guide, this type of event is extremely beneficial when it occurs near the beginning of a trip. From that time on, no arm-twisting is required to get people to carry plenty of spare warm clothes, even on what promises to be a hot, sunny day.

While good planning and thorough preparation are essential, luck plays a role as well—if you spend enough time in the mountains the odds are that you will eventually encounter an unusually powerful storm. Some of the potentially dangerous situations I've experienced could have avoided if I had used better judgment. I hope those who read this article will learn from my mistakes, as not everyone will be so lucky.



Figure 14. A typical trail marker in the Dolomites.

NEWS AND EVENTS

MtnClim 2016: The Biennial Conference of CIRMOUNT (Consortium for Integrated Climate Research in Western Mountains)

MtnClim 2016: Mountains Without Snow, What Are The Consequences?

Sleeping Lady Resort in Leavenworth, Washington, October 17-21, 2016

The 2016 Mountain Climate Conference will continue the tradition of excellence established by over a decade of MtnClim meetings by working at the intersection of climate and a host of other scientific disciplines including hydrology, ecology, and glaciology. The 7th Mountain Climate Conference will explore the central theme: Mountains Without Snow: What are the Consequences? In sessions on current science themes, climate policy and decision-support, MtnClim 2016 will look for opportunities to interweave discussions of the roles snowpack plays in water resources, power generation, ecophysiology, and human communities, with particular focus on the question: How ready are we to foresee the full range of consequences of mountains without snow? Every MtnClim meeting includes oral and poster presentations featuring keynotes by thought leaders in the field as well as highlighting exceptional early-career scientists, providing forums for resource managers, and integrating undergraduate and graduate students.

Visit <http://www.mtnclim.org> for more information
and note that early registration and abstracts are due by **July 14, 2016**.



Sleeping Lady Resort in Leavenworth, Washington.



Mountain Research Initiative BLOG Posts

CIRMOUNT's big-sister and mentor, the international Mountain Research Initiative (MRI; <http://mri.scnatweb.ch/en/>), based at the University of Bern, Switzerland, has a rich and diverse website that you will enjoy exploring if you haven't yet had the chance. Among the offerings is a section containing a large set of blog posts on mountain research (and musings) representing regional networks around the world. Two years ago, MRI Executive Director, Greg Greenwood, strong-armed me into accepting a role as blogger for CIRMOUNT, a role I took hesitantly, but feel is important in representing the consortium. You can find the Blogs, CIRMOUNT's as well as the other regional networks, at: http://www.blogs-mri.org/?page_id=43

I am grateful for the special contributions to CIRMOUNT's blog by our colleagues. Jill Baron (USGS) posted a blog for CIRMOUNT, and Solomon Dobrowski (University of Montana) is blogging our June post. If you would be interested to write a short article on behalf of CIRMOUNT, please let me know.

—Connie Millar



Pacific coast near Asilomar.

PACLIM Workshop: March 5-8, 2017

CIRMOUNT modeled its flagship MtnClim conferences after the decades-long model of PACLIM. PACLIM (Pacific Climate) is a multidisciplinary workshop that broadly addresses the climatic phenomena occurring in the eastern Pacific Ocean and western North America. The purpose of the workshop is to understand climate effects in the region by bringing together specialists from diverse fields including physical, social, and biological sciences. Time scales from weather to the Quaternary are addressed in oral and poster presentations. Workshops convene at the Asilomar State Conference Center, Pacific Grove, California.

Write Michelle Goman, goman@sonoma.edu, or Scott Mensing, smensing@unr.edu, for information.

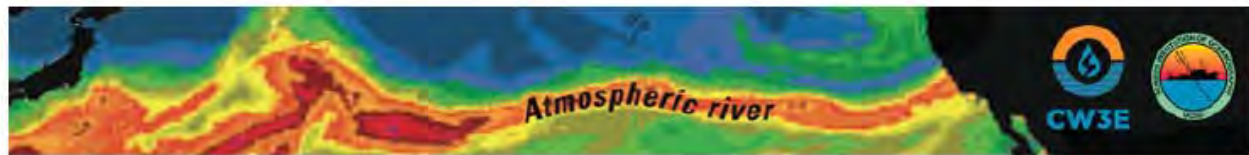
From CIRMOUNT'S Post on March 21, 2016:

"The Great Basin, USA: One-Quarter Empty or 100% Full?"

<http://www.blogs-mri.org/?p=1021>

Feral domestic horses, errantly referred to as "wild horses" (*Equus caballus*), roam low basins to high mountains, here in the valley below the Diamond Mountains, Nevada (2943 m). Although horses evolved in proto-North America, native species went extinct in the Late Pleistocene. Modern feral horses descend from steeds brought by 19th-century European settlers. Without native predators (which also went extinct in the Late Pleistocene), horse populations have exponentially increased. Throughout Great Basin mountains and basins horses now create widespread damage to springs and wetlands, meadows, prairies, and even upland forests.





2016 International Atmospheric Rivers Conference

Scripps Institution of Oceanography

La Jolla, California | 8-11 Aug 2016

Many regions face either drought or flood, or are challenged by regional water management issues. Recent advances in atmospheric sciences and hydrology have identified the key role of atmospheric rivers (ARs) in determining the distribution of strong precipitation events in mid-latitudes. Combined with related phenomena, the frequency, position, and strength of atmospheric rivers determines the occurrence of many water extremes. This conference brings together experts from atmospheric, hydrologic, oceanic and polar science, water management, and civil engineering fields to advance the science and explore needs for new information.

Conference Goals

★ Evaluate the current state and applications of the science of the mid-latitude atmospheric water cycle, with particular emphasis on ARs and associated processes. ★ Discuss differing regional perspectives. ★ Assess current forecasting capabilities. ★ Plan for future scientific and practical challenges.

Conference website: <http://cw3e.ucsd.edu/ARconf2016/>

Questions? Contact Mike Dettinger mddettin@usgs.gov

Mountains 2016

Conference website: <http://cimo.esa.ipb.pt/mountains2016/>



Mountains 2016 is an international event aiming to promote sustainable development in mountains, based on science, knowledge, and innovation.

Mountains 2016 will combine two different events: the X European Mountain Convention and the I International Conference on Research for Sustainable Development in Mountain Regions.

The **X European Mountain Convention** continues a 20-year tradition of addressing cutting-edge political, economic and social topics in European mountains by **Euromontana**, the European Association for the Development of Mountain Areas. It will cover a broad range of subjects, from agriculture to energy and from innovation to governance, this year centered around the topic of “Adaptation to climate change”.

The **I International Conference on Research for Sustainable Development in Mountain Regions** is a scientific meeting aiming to share and discuss methods, tools, results, applications, trends and challenges in research in mountain systems. It will be organized for the first time in Bragança, under the theme “Ecosystem services and sustainable development”.

By bringing together the European mountain community and a broader international community of scientists and stakeholders, *Mountains 2016* will create a unique opportunity for individuals and institutions to share experiences and to establish information and collaboration networks. By jointly addressing climate change adaptation and ecosystem services in mountain regions, it will provide an exceptional occasion to present important contributions to science and sustainable development in the mountains of Europe and the rest of the world.

Mountains 2016 is a collaboration organized by the Mountain Research Centre (CIMO) of the Polytechnic Institute of Bragança (IPB), in Portugal, with the active involvement of local, national and international institutions. The event relies in part on a connection between Portugal and Brazil, established between CIMO/IPB and Embrapa, which gives the initiative a particular Lusosphere context. One goal of the conference is to involve the global Portuguese-speaking community to the greatest extent possible.

X European Mountain Convention

3-5 October 2016

The European Mountain Convention is organised every two years by Euromontana, the European Association for the Development of Mountain Areas, in different parts of Europe in collaboration with one of their 75 members. In 2016, it will be organised with IPB-CIMO in Bragança – Portugal from the 3rd to the 5th October 2016 and it will focus on “climate change in mountain areas”.

I International Conference on Research for Sustainable Development in Mountain Regions

5-7 October 2016

The I International Conference on Sustainable Development in Mountain Environments (ICSDME) aims to share knowledge on mountain systems – agricultural, semi-natural, and natural – concerning research methods, tools, results, applications, and trends and challenges. Another key goal will be to link research in mountain areas in several regions of the world, with an emphasis on Europe and South America and Portuguese-speaking countries.

CONTRIBUTING ARTISTS

In this issue of *Mountain Views* we complement the mountain lakes research theme and feature a selection of mountain lake paintings, photographs, and poems by CIRMOUNT colleagues.

Adrienne Marshall is a graduate student at the University of California, soon to begin an advanced degree at the University of Idaho. She has interests in hydrology, watershed studies, and mountain systems. Adrienne is an avid mountain walker, and has spent considerable time in the Sierra Nevada of California, where she sketches mountains, lakes, skies, trees, and animals. You can view paintings on her gallery site at: <https://adriennehikes.wordpress.com/>

Bob Coats is a research hydrologist with Hydroikos Ltd. in Berkeley, CA. Bob has been studying climatic, hydrologic, and ecological processes in the Lake Tahoe Basin—and writing poetry—for more than 40 years. His poems have appeared in *Orion*, *Zone 3*, *Windfall*, *The Acorn*, and the *Pudding House* anthology, *Fresh Water: Poems from the Rivers, Lakes and Streams*, *Harsh Green World*, and elsewhere.

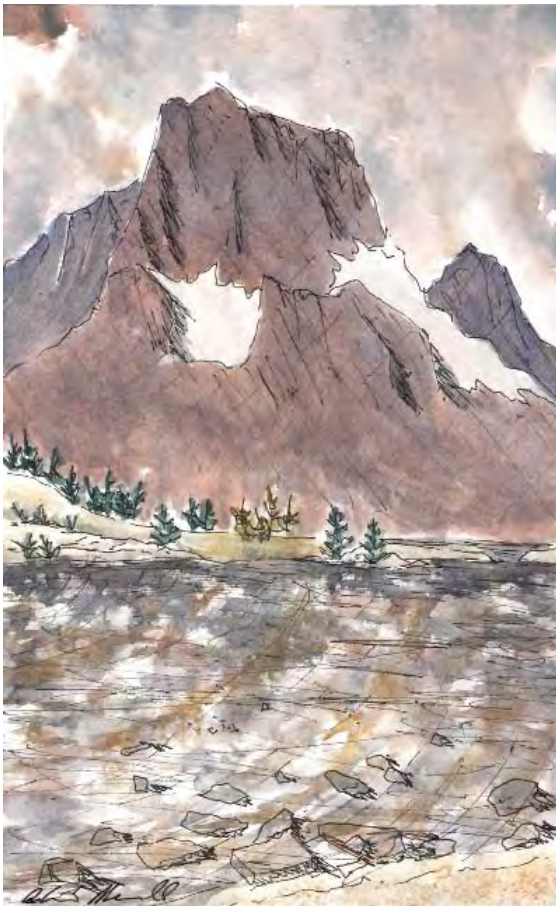
Valerie Cohen is a nationally renowned landscape artist who lives and works in the Sierra Nevada, California. She often accompanies the GLORIA alpine plant monitoring crews in the White Mountains, where her studies have led to series of paintings on bristlecone pine, other botanicals, and mountain landscapes. Valerie also has portfolios of Sierran mountain lakes, one painting of which we feature. See more of Valerie's work at: <http://valeriepcohen.com/>

In addition to authors' photos in the body of their articles, photographers who contributed views of mountain lakes to this issue include:

Megan Otu is a biologist with Fisheries and Oceans Canada, Winnipeg, Manitoba, Canada, formerly at INSTAAR and the University of Colorado.

Steve Sadro is an assistant professor in limnology, Department of Environmental Science and Policy, University of California, Davis.

Jeff Wyneken is a production editor with University of Stanford and University of California Presses.



Thousand Island Lake with Banner Peak, Sierra Nevada, California.
Adrienne Marshall.

MOUNTAIN VISIONS

EAST WIND AT TAHOE

Driven through the night
the lake seethed and roared,
sucking cobbles, spitting moonlit ice.

Hearing it growl from the house
we spoke of power and process,
of deep changes wrought by wind.

By morning it rolled sun-struck blue,
wind-danced, white capped,
turbid near shore.

Strewn on the shingled beach,
heavy with sheaths of ice:
shattered aspen, bent alders.

Now at dusk it heaves slate-gray,
saffroned by alpenglow on eastern peaks,
Aldebaran rising.

—Robert Coats, 2/74; rev. 1/98, 10/03



June Snow on Tenaya Lake, Yosemite, #2. Valerie P. Cohen
Watercolor, 22" x 30". valeriepcohen.com

