

Productivity in Rocky Mountain Lakes: Does dissolved organic matter block phototrophy below treeline?

CESU- Rocky Mountain National Park

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Introduction

Mountain watersheds are like drains; and lakes are the recipients of the hydrologic inflow from the surrounding environment. Rain and snowmelt move downward through the landscape, interacting with the soil and thereby modifying the water chemistry along the way before it ultimately washes into the lake. The properties of the hydrologic inflow can therefore vary substantially depending on the characteristics of the terrestrial environment and how the inflow interacts with the particular type of terrestrial environment (Clow and Sueker 2000). Inlet streams may be the most obvious source of lake inflow, but multiple small feeder streams, surface runoff, and groundwater also contribute to the water inputs to a lake. Lake microorganisms are the ideal taxa to examine the influences of inputs from the surrounding environment because of their direct contact in transferring energy, carbon, and other nutrients up the food web through the microbial loop.



Figure 1. Photographs of an alpine lake on the left (Cony Lake, RMNP) and subalpine lake (Mills Lake, RMNP) on the right. Both lakes were surveyed in this study.

Alpine treelines mark an abrupt shift from a forested to a treeless tundra landscape and dramatically alter terrestrial ecosystem characteristics (Körner 1998, Mayor et al. 2017). Biotic communities above and below treeline, including microbial communities also correspond to their respective ecosystem characteristics (soil bacteria: Thébault et al. 2014, soil fungi: Kernaghan and Harper 2001). Less understood is whether aquatic communities in drainages that cross the alpine-treeline reflect the differences their terrestrial counterparts do. Basic lake characteristics such as water chemistry, temperature, and degree of human impact, have been shown to differ dramatically depending on lake position in relation to treeline (Duff et al. 1998). Lakes situated above treeline (alpine lakes) are known for their extreme environments of cold temperatures, intense ultraviolet light, short growing seasons, and low nutrient contents. Lakes located below treeline, but above the montane zone (subalpine lakes) are generally warmer in temperature and have been found to have higher concentrations of dissolved organic carbon than alpine lakes (Duff et al. 1998). While it is clear that basic characteristics of alpine and subalpine lakes are fundamentally different, research examining differences in subalpine and alpine lake microbial communities is scarce. Studies focusing on mountain phytoplankton are even rarer.

Planktonic organisms are, by definition, drifters. They are microscopic organisms unable to swim against the currents of the waterbody they inhabit. Zooplankton make up the heterotrophic portion of plankters

and include small organisms such as *Daphnia* sp. (also known as water fleas) and other small crustaceans. They generally feed on phytoplankton and are the primary food source for fish and some whales. Phytoplankton are the photosynthetic microscopic organisms inhabiting the pelagic, or open water, portions of waterbodies and include algae and some types of phototrophic bacteria. Freshwater phytoplankton are responsible for around 70% of the world's atmospheric oxygen supply (Reynolds et al. 1984) and provide the base of the aquatic food chain. When unhealthy blooms occur, excessive phytoplankton growth can deplete oxygen and be toxic to organisms that consume them such as fish, humans, and dogs. Maintaining a healthy level of primary production is important on many levels.

Productivity is defined as the amount of photosynthesis occurring within the lake. Chlorophyll-a (chl-a), the pigment required for oxygenic photosynthesis, is often measured to infer rates of photosynthesis by lake phytoplankton. Some organisms can photosynthesize using other pigments and alternate pathways, but do not produce oxygen as a result. These organisms are rare and therefore chl-a is the most widely used measurement of photosynthetic organisms (phototrophs) in lakes. The measurement of chl-a includes the biomass of all oxygenic phototrophs, including algae and Cyanobacteria. Light must penetrate through the water column of a lake for photosynthesis to occur. Thus the lack of clarity in a turbid lake can slow phototrophic growth (growth of photosynthesizing organisms.) Turbidity (or the lack of clarity) can be the result of several mechanisms; for example, sediment can become suspended in the water column during rain events. Clarity can also be obscured by high concentrations of organic matter.

Limnological analyses of organic matter first distinguishes by particle size: dissolved organic matter is the organic matter that can pass through a filter with a very small pore size ($< 0.7 \mu\text{m}$ diameter) and particulate organic matter has a $> 0.7 \mu\text{m}$ diameter and is the carbon left on the filter after filtering a water sample. To make an analogy with coffee, particulate organic matter is analogous to the left over grounds and dissolved organic matter is the resultant coffee after the water has passed through the grounds and filter. Dissolved organic matter can further be classified by its constituents, nitrogen, oxygen, hydrogen, and carbon. Dissolved organic carbon (DOC) makes up approximately 50% of the entire pool of dissolved organic matter and is available for microbial uptake. At high enough concentrations it can slow phototrophic growth by coloring the water brown and is thus examined in relation to potential inhibition of phototrophs in this study.

Lake DOC can come from both internal processes, such as algae production, as well as external processes such as plants and microbes that wash into the lake from the terrestrial environment. The ratio of externally-derived to internally-derived DOC decreases as elevation increases and plant biomass surrounding a lake decreases substantially after crossing the alpine treeline (Rose et al. 2015). Brown colored lake water generally has a higher ratio of plant-derived DOC to algae-derived DOC. As treeline encroaches uphill with climate warming, lakes are predicted to be subjected to increased amounts external DOC washing in from the increase in terrestrial plant biomass (Vlah et al. 2018). If concentrations of DOC become high enough, lake productivity will be hindered.

The main goal of this study was to determine if phytoplankton productivity (as measured by chl-a) differs in lakes above and below treeline to understand potential impacts in future climate regimes where treeline has encroached uphill. The upper elevation of a forest can be limited by a variety of factors like heavy winds and unsuitable soils, but are most often temperature-limited (Körner and Paulsen 2004, Smith et al. 2009). Plant ranges and treelines have been expanding around the world (Lenoir 2008, Harsch et al. 2009, Iverson et al. 2013). Drainages that span treeline are great systems to examine the impacts of varying DOC concentrations because of the differing amounts of organic matter washing into a lake from the terrestrial environment over a relatively short distance.

Methods

Field Methods

During the summer of 2016, I made two sampling visits to 16 lakes in drainages that spanned the alpine-treeline: one in the beginning of the growing season and one at the end. The first visit was made in July, as early as possible after ice-off to safely access the upper most lake in the drainage, and the second visit was made approximately five weeks later. All four drainages were located in the Southern Rocky Mountain ecoregion (U.S. Environmental Protection Agency, 2013); three in Rocky Mountain National Park (RMNP) and one in the Snowy Range of southern Wyoming for comparison. All four lakes in each drainage (two above treeline and two below treeline) were sampled within 36 hours of one another to minimize temporal effects. The lakes ranged in elevation from approximately 2,800 m.a.s.l. to 3,600 m.a.s.l. and span a coniferous treeline dominated by Engelmann spruce (*Picea engelmannii*) and lodgepole pine (*Pinus contorta*). Each drainage contained two lakes above treeline and two lakes below treeline.

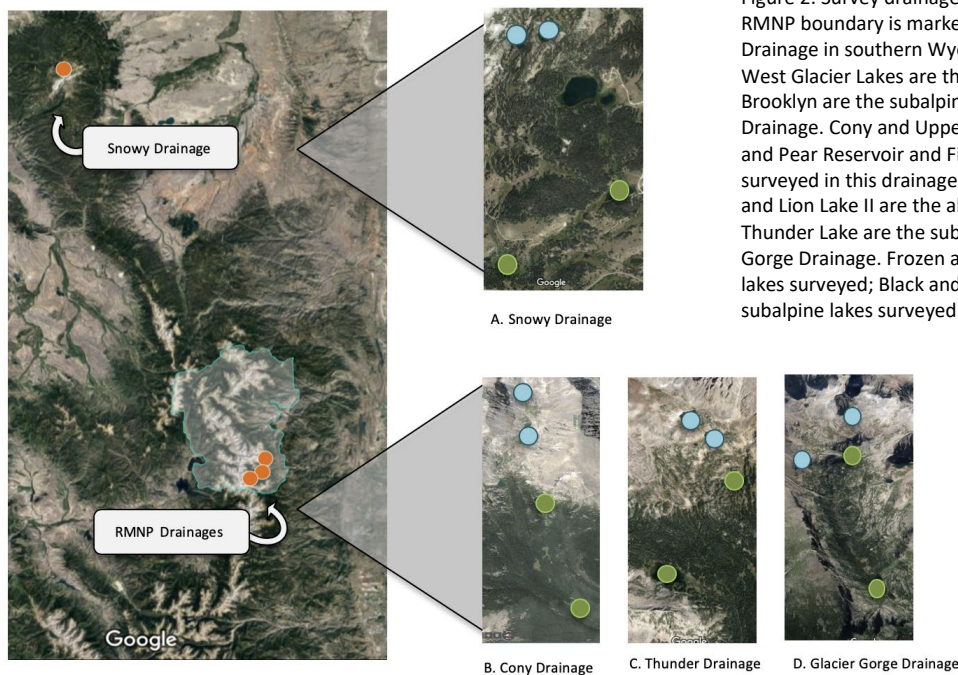


Figure 2. Survey drainages marked in orange circles. The RMNP boundary is marked for reference. A. Snowy Drainage in southern Wyoming, west of Laramie. East and West Glacier Lakes are the alpine lakes and Jeep and Little Brooklyn are the subalpine lakes in this drainage. B. Cony Drainage. Cony and Upper Hutcheson are the alpine lakes and Pear Reservoir and Finch Lake are the subalpine lakes surveyed in this drainage. C. Thunder Drainage. Snowbank and Lion Lake II are the alpine lakes, and Lion Lake I and Thunder Lake are the subalpine lakes surveyed. D. Glacier Gorge Drainage. Frozen and Blue Lakes make up the alpine lakes surveyed; Black and Mills Lake make up the subalpine lakes surveyed.

Table 1. Coordinates of Rocky Mountain National Park Lakes

Lake	Elevation (m)	Lat	Long
Black Lake	3,236	40.2653544	-105.64139
Blue Lake	3,408	40.2679911	-105.63167
Cony Lake	3,508	40.1729817	-105.65806
Finch Lake	3,021	40.1834097	-105.59306
Frozen Lake	3,529	40.2577133	-105.64278
Lion Lake 1	3,373	40.2319444	-105.63861
Lion Lake 2	3,469	40.2377706	-105.64167
Mills Lake	3,030	40.2895964	-105.64167
Pear Reservoir	3,225	40.176742	-105.6267
Snowbank Lake	3,512	40.2402564	-105.64528
Thunder Lake	3,225	40.2222044	-105.64722
Upper Hutcheson	3,412	40.1738431	-105.64778

We accessed backcountry lakes by foot (Figure 3.A) and to avoid potential contamination of pathogens or aquatic invasive species, sampled upper lakes first, and worked our way down the drainage to the lower elevation lakes. At the deepest point of each lake (accessed with a decontaminated inflatable Alpaca raft, Figure 3.B) we recorded lake characteristics, including water temperature, Secchi depth (a measurement of water clarity) and the depth of the deepest point of the lake using a Lucky FF718LiC wireless depth finder. We collected two water samples at the deepest point of the lake: one from the surface of the lake (grab sample) and one from approximately 1 m above the bottom of the lake with a Van Dorn (Figure 3.C). We mixed the surface and the bottom samples to create one representative sample for each lake. Within 12 hours of collection, we filtered between 500 ml of sample water through both 0.7 μm pore size GF/F filters (pre-combusted at 475° C for 4 hours) and 0.2 μm pore size filters in the field. The 0.7 μm filtered lake water was kept for chemistry characterization, the 0.7 μm GF/F filters for chl-a analysis, and the 0.2 μm filters for the cyanobacteria samples. After the water was filtered, the filter was placed in a sterile plastic vial and kept in the shade until it could be transferred to a freezer (-20°C) once in the front-country within 24 hours of filtering.



Figure 3. A) Heinrich Haller, undergraduate crew member backpacking for the first time to collect water samples. B) Prepping the Alpaca raft for water sampling at Lion Lake II in RMNP with Adalee Darling, undergraduate crew member. C) PhD student, Adam Solon transferring water samples from the Van Dorn to HDPE bottles.

Lab Analyses

Chlorophyll-a was measured from the 0.7 μm GF/F filters which were frozen at -20°C and covered in foil until analysis approximately 2 months after collection. The analysis was completed according to lab procedures followed by the Center for Limnology (CU Boulder), using ethanol as the extraction solution and a spectrophotometer for readings.

Cyanobacteria were collected on 0.2 μm filters and identified using high-throughput PCR techniques. Filters were frozen at -20°C until the DNA was extracted up to 2 months later. We extracted DNA from each of the samples according to the manufacturer's protocol for the PowerWater DNA Isolation Kit (MoBio Inc., Carlsbad, CA, USA). We amplified the 16S primer region (Illumina MiSeq), binned sequences to the ~99% similarity level (no more than one base pair difference), and compared sequences to the updated SILVA database (silva_nr_v132_train_set.fa) to determine taxonomy of the exact sequence variants (ESVs). This modern technology provides both relative abundance and taxonomic identity information for the Cyanobacteria.

Results and Discussion

Phytoplankton abundance

The three lakes with the highest chlorophyll-a concentrations were all located in the Snowy Range in southern Wyoming (Figure 4); East Glacier Lake had the highest overall chl-a, followed by Little Brooklyn Lake, and West Glacier Lake in third. The lakes with the highest chl-a concentrations in Rocky Mountain National Park were Thunder Lake followed by Blue Lake.

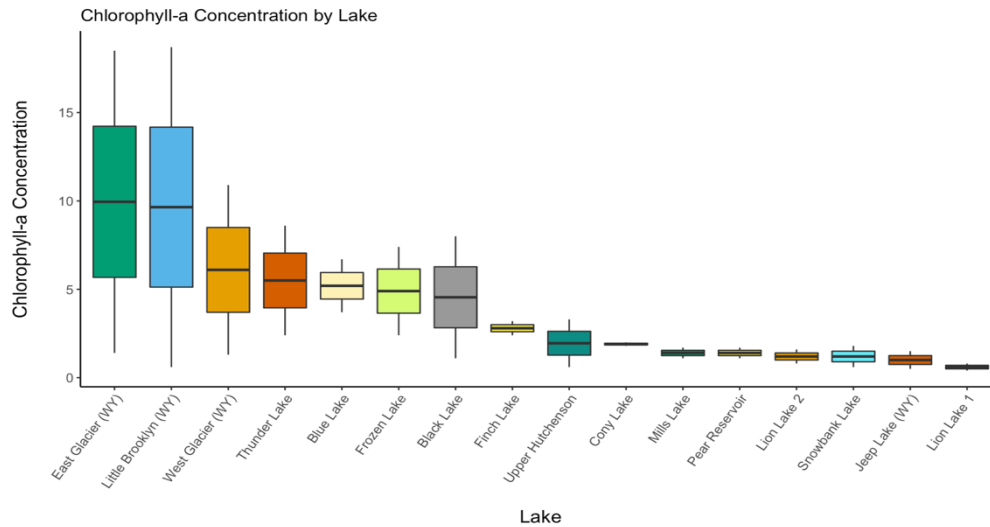


Figure 4. Boxplots displaying chlorophyll-a concentrations for the 16 study lakes. Colored boxes around the median illustrate the dispersion of the two visits for each lake.

The lakes with the highest abundance of Cyanobacteria, on the other hand, were located in RMNP (Figure 5). Mills Lake and Blue Lake, the top two, are both located in the Glacier Gorge drainage, and the third and the fourth lakes, Finch and Pear Reservoir, are in the same Wild Basin drainage.

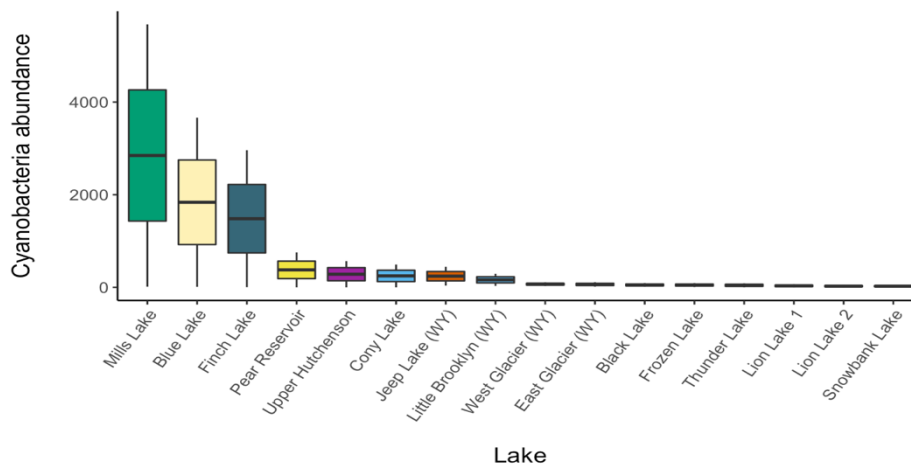


Figure 5. Boxplots displaying Cyanobacteria abundance counts for all of the 16 study lakes. Mills Lake had the highest abundance of Cyanobacteria and the highest dispersion between visit 1 and visit 2, indicative of a bloom.

DOC correlations with chl-a and relative abundance of cyanobacteria

This study aimed to understand whether higher concentrations of DOC would limit phytoplankton production in subalpine lakes. While concentrations of DOC were higher in subalpine lakes than alpine lakes (mean alpine DOC = 1.02 mg/L, mean subalpine DOC = 2.25 mg/L, $p = 0.028$, Figure 5); the overall chl-a concentrations did not differ by lake type (mean alpine chl-a = 4.05, mean subalpine chl-a = 3.36, $p = 0.42$). DOC and chl-a also did not have a significant linear relationship ($p = 0.826$). Cyanobacteria richness (number of species) did not differ between alpine and subalpine lakes ($p = 0.71$) and was not correlated with DOC concentration. Even though DOC was higher in subalpine than alpine lakes, the concentrations were still relatively low. This likely indicates that the concentrations of DOC measured in the subalpine lakes of this study were not high enough to obscure photosynthesis.

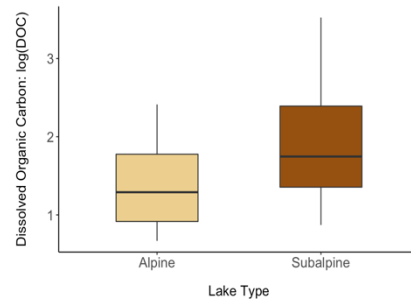


Figure 6. Overall DOC concentrations are higher in subalpine lakes (mean = 2.25 mg/L) than alpine lakes (mean = 1.02 mg/L), $p = 0.028$.

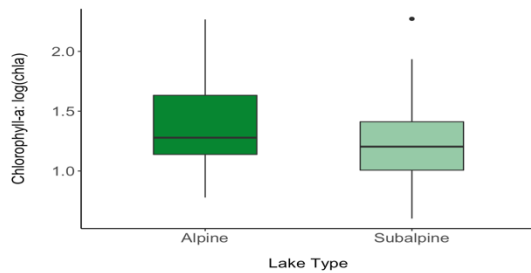


Figure 7. Overall chl-a concentrations do not differ between subalpine lakes ($p = 0.42$).

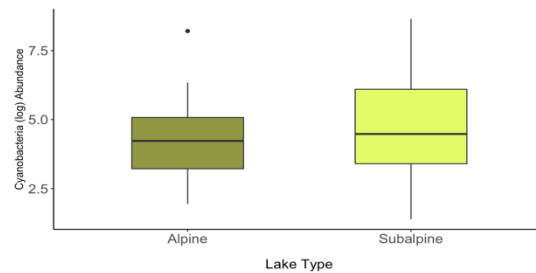


Figure 8. Overall Cyanobacteria richness (number of species) does not differ between alpine and subalpine lakes ($p = 0.71$).

Differences by watershed

Because data were pooled across watersheds and different results in different watersheds could obscure patterns, it was important to test the watersheds separately from one another. However, regardless of the watershed, the pattern remained the same: chl-a concentrations nor relative abundance of cyanobacteria in alpine and subalpine lakes differed significantly in any of the watersheds ($p = 0.68$ and $p = 0.23$ respectively).

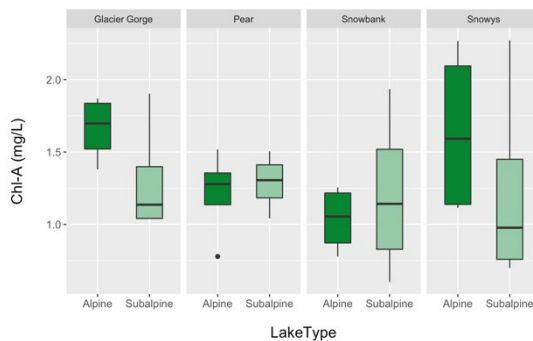


Figure 9. Overall chl-a concentrations by lake type do not differ in any of the drainages ($p = 0.68$).

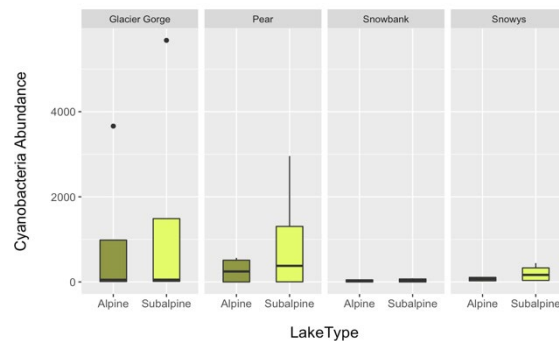


Figure 10. Overall Cyanobacteria abundance by lake type does not differ in any of the drainages ($p = 0.23$).

Growth over the season- comparing Visit 1 and Visit 2

Overall: phytoplankton (chl-a)

As expected, significant phototrophic growth did occur over the season (Figure 11); the total chl-a concentration was higher ($p = 0.029$) on Visit 2 (mean = 5.9 $\mu\text{g/L}$, SE = 1.48) at the end of the summer than it was at the beginning of the season on Visit 1 (mean = 1.5 $\mu\text{g/L}$, SE = 0.22). Phototrophs cannot photosynthesize in the darkness beneath ice cover and thus begin major growth after the lake is ice-free. The overall standard error was higher on the second visit than on the first, indicating higher stochasticity of phototrophic communities throughout the growing season. That is, the difference in productivity between lakes is more pronounced towards the end of the season, where some lakes are much more productive than others.

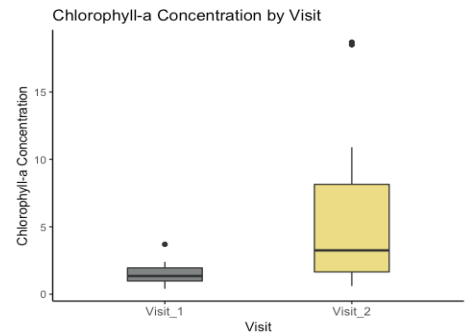


Figure 11. Overall chl-a concentrations are higher on visit 2 than $p = 0.029$.

By Lake Type: phytoplankton (chl-a)

An interaction term was tested to compare whether alpine and subalpine lakes reacted differently between visit 1 and Visit 2. For example, perhaps the warmer temperatures of subalpine lakes increased the phototrophic growth more than in the cold alpine lakes and the difference between Visit 1 and Visit 2 would be greater for subalpine lakes by visit. But alpine and subalpine lakes showed similar growth rates between the two visits ($p = 0.97$, Figure 12).

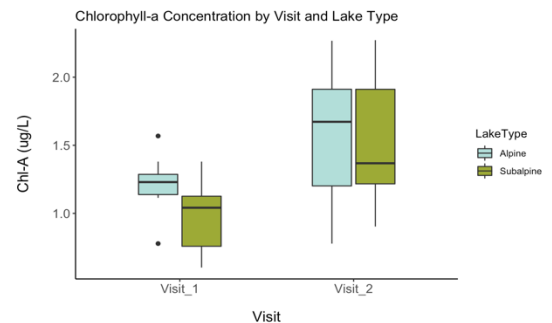


Figure 12. Alpine and subalpine lakes reacted the same overall from visit 1 to visit 2 ($p = 0.97$).

By Watershed: phytoplankton (chl-a)

Interestingly, some watersheds demonstrated greater chl-a growth between the two visits than others ($p = 0.022$, Table 1 shows mean values and Figure 13 shows median values). The mean chl-a concentrations for visit 2 (late summer) are higher than those the first visit (early summer) for all watersheds (table 1). However, the Snowy watershed in Wyoming was the only drainage that resulted in statistically significant differences between Visit 1 (mean = 0.95, se = 0.94) and Visit 2 (mean = 12.4, se = 8.87). Sample size likely limited power to identify significant differences given the presence of outliers for Glacier Gorge and Snowbank watersheds.

Table 1. Mean chl-a concentrations by Watershed and Visit

Watershed	Visit 1 Mean chl-a ($\mu\text{g/L}$)	Visit 2 Mean chl-a ($\mu\text{g/L}$)
Glacier Gorge	2.075	5.95
Pear (Hutcheson Lakes)	1.475	2.55
Snowbank	1.55	2.7
Snowy Range (WY)	0.95	12.4

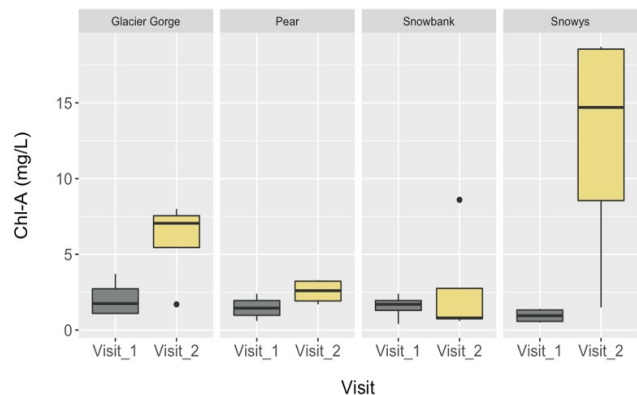


Figure 13. All watersheds increased from visit 1 to visit 2, but the Snowy watershed was the only watershed that showed a statistical significance ($p = 0.45$).

Overall: Cyanobacteria relative abundance

Overall Cyanobacteria abundance showed similar significant increases to chl-a over the season from Visit 1 to Visit 2 ($p = 0.23$, Figure 14); the total Cyanobacteria abundance was higher on Visit 2 (mean = 9,449.91, SE = 2,595.2) at the end of the summer than it was at the beginning of the season on visit 1 (mean = 92.11, SE = 12.7). The outliers shown on Figure 13 indicate that a few lakes in particular had blooms of Cyanobacteria growth.

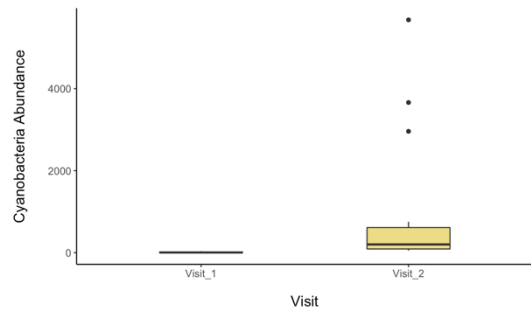


Figure 14. Overall Cyanobacteria abundance are higher on visit 2 than visit 1 ($p = 0.23$).

By Lake Type: Cyanobacteria relative abundance

The difference in mean abundance from Visit 1 to Visit 2 was 1,284.25 for subalpine lakes and only 633.63 for alpine lakes. That is, cyanobacterial growth was twice as high in subalpine lakes than alpine lakes from early summer to late summer. The difference was not statistically significant ($p = 0.46$), but the lack of significance is likely due to a high dispersion of cyanobacterial abundance across lakes, with some lakes demonstrating blooms of particular species.

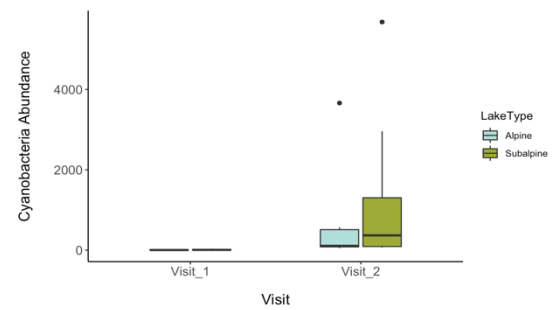


Figure 15. Cyanobacteria abundance in alpine and subalpine lakes increased at a similar rate from visit 1 to visit 2 ($p = 0.46$), but could be due to a wide variability between lakes obscuring any significance.

By Watershed: Cyanobacteria relative abundance

While cyanobacteria increased in abundance over the season, most of the growth can be seen in the Glacier Gorge drainage and Pear drainage in Wild Basin.

Table 2. Mean cyanobacteria abundance counts by Watershed and Visit

Watershed	Visit 1 Mean Cyanobacteria abundance	Visit 2 Mean Cyanobacteria abundance
Glacier Gorge	11.00	2380.75
Pear (Hutcheson Lakes)	1.00	1193.25
Snowbank	0	63.50
Snowy Range (WY)	28.25	238.50

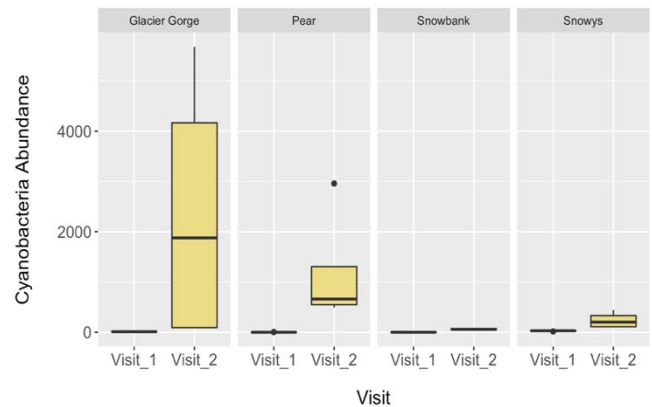


Figure 16. Glacier Gorge and Pear drainage showed the highest growth between visit one and visit 2.

Cyanobacteria species

Here I present the results of the particular Cyanobacteria species present in the lakes with the highest relative abundance. Mills Lake had the greatest relative abundance of cyanobacteria out of all the lakes, but only three cyanobacterial species out of a total of 50 were present in Mills Lake during the study. Additionally, 99.6% of that abundance was due to one particular species belonging to the family Leptolyngbyaceae (ESV_12). This species was found in only 4/32 of the lakes visits and 3/4 lakes where it was present were located in the Glacier Gorge drainage with Mills Lake. Blue Lake had the second highest cyanobacterial abundance with five species present. The most abundant of the five (accounting for 62% of the cyanobacterial abundance in Blue Lake) belonged to the genus *Aphanizomenon_NIES81*, in the Nostocaceae family. This family is known to be capable of nitrogen fixation and producing toxic compounds. It was also only found in 4/32 lake visits overall, but the lakes where it was found were not in the same drainage indicating low dispersal limitation. Finch Lake had the third highest cyanobacterial abundance. Almost half of the abundance found in this lake was due to a

species in the *Cyanobium_PCC-6307* genus. One species of the Vampiromicrobiales order was removed from the analysis because a new assigned phylum has been proposed as Melainabacteria instead of Cyanobacteria (DiRienzi et al 2013), but more importantly because it is not photosynthetic.

Table 3. Species found in the top three lakes for Cyanobacteria abundance

Lake	Cyanobacteria species (to the lowest taxonomy available)
Mills Lake	Oxyphotobacteria; Leptolyngbyales; Leptolyngbyaceae (most abundant) Oxyphotobacteria Oxyphotobacteria;Synechococcales;Cyanobiaceae;Cyanobium_PCC-6307
Blue Lake	Oxyphotobacteria;Nostocales;Nostocaceae;Aphanizomenon_NIES81 (most abundant) Oxyphotobacteria;Nostocales;Nostocaceae;Aphanizomenon_NIES81;ESV_224 Oxyphotobacteria;Leptolyngbyales;Leptolyngbyaceae;NA;ESV_12 Oxyphotobacteria;Pseudanabaenales;Pseudanabaenaceae;Pseudanabaena_PCC-7429 Oxyphotobacteria;Synechococcales;Cyanobiaceae;Cyanobium_PCC-6307
Finch Lake	Oxyphotobacteria;Synechococcales;Cyanobiaceae;Cyanobium_PCC-6307 (most abundant) Oxyphotobacteria;Gloeobacterales;Gloeobacteraceae;Gloeobacter_PCC-7421 Oxyphotobacteria Oxyphotobacteria Oxyphotobacteria;Oxyphotobacteria_Incertae_Sedis;Oscillatoriaceae;Phormidium_CYN64;

Cyanobacteria Diversity

Several diversity indices were measured to take a closer look at some of the patterns of Cyanobacteria presence. Richness (the number of species), evenness (relative evenness of species abundance), and Shannon’s Diversity index (includes both richness and evenness) were compared by Lake, Lake Type (alpine or subalpine), Visit (first or second visit), and Watershed. The p-values for the various tests are shown in table 4.

Table 4. Diversity indices of Cyanobacteria species compared between lakes, lake type (alpine and subalpine), visit (early season and late season), and the four watersheds.

Richness		Evenness		Shannon’s Diversity Index	
Group	p-value	Group	p-value	Group	p-value
Lake	0.080 *	Lake	0.902	Lake	0.811
Lake Type	0.254	Lake Type	0.116	Lake Type	0.055 *
Visit	0.663	Visit	0.034 **	Visit	0.080 *
Watershed	p-value = 0.053 * (Snowbank p = 0.064)	Watershed	0.788	Watershed	0.868

*= $p < 0.1$, and **= $p < 0.05$. Because of the inherent low sample size of alpine lake research, a p value of 0.1 was considered significant to lower the risk of type II errors.

Richness

The Snowy watershed in Wyoming had the highest number of species (richness) and Snowbank had the lowest. No cyanobacteria were detected in either Snowbank Lake or Lion Lake II. Cony Lake had one species present at low abundance on the first visit and none by the second visit. West Glacier, Little Brooklyn, and Blue Lake all had the highest number of cyanobacteria species (6 per lake). The limited success of cyanobacteria in many of the lakes could be indicative of either tight environmental parameters of survival, or dispersal limitation. Alpine and subalpine lakes showed similar richness ($p = 0.254$) and the number of species (richness) did not change between Visit 1 and Visit 2 ($p = 0.663$).

Pielou’s Evenness

Visit was the only variable with a significant relationship with evenness ($p = 0.034$) and indicates that the relative abundance was fairly equal amongst samples just after ice-off, but differed later in the season.

After having the time to grow, some species bloomed and others did not, resulting in a greater dispersion of abundance by the second visit. The differences in evenness corroborates the blooms of certain species seen in Mills, Blue, and Finch Lake (Figure 4). Relative abundance was fairly even between lakes (Pielou's evenness by Lake, $p = 0.902$), alpine vs. subalpine lakes (Pielou's evenness by Lake Type, $p = 0.116$), and watershed (Pielou's evenness by Watershed, $p = 0.788$).

Shannon's Diversity Index

Like Pielou's evenness, diversity, as measured by Shannon's diversity index (including both richness and evenness), differed between Visit 1 and Visit 2 ($p = 0.080$). Additionally, a comparison between Lake Type, i.e. alpine and subalpine lakes yielded a significant (at the $p < 0.1$ level) result ($p = 0.055$). In other words, diversity was higher in subalpine lakes (mean = 1.35, SE = 0.62) than in alpine lakes (mean = 0.95, SE = 0.93). This could be indicative of either 1) dispersal through directional hydrologic connections (the species in alpine lakes flow down to subalpine lakes, but not in the reverse direction), or 2) subalpine lakes provide the environment conducive to Cyanobacterial growth, or both.

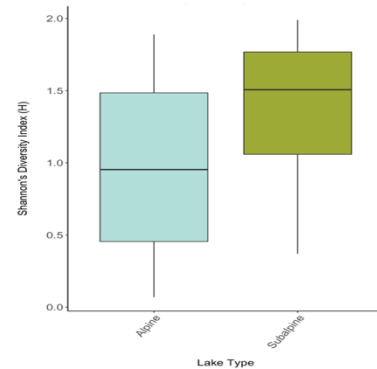


Figure 17. Shannon's diversity index was higher in subalpine lakes than alpine lakes when tested at the 0.1 significance level ($p = 0.055$).

Conclusion

While high concentrations of DOC have been shown to block phototrophy from occurring (Feuchtmayr et al 2019, Oosthoek, 2016), those measured in even the highest of the lakes of the present study are not high enough to obscure photosynthesis. If treeline were to encroach uphill in Rocky Mountain National Park, phototrophy in alpine lakes would likely not be affected because the concentrations wouldn't be high enough to obscure light penetration into the lake water column.

However, it is important to note that blocking phototrophy is not the only potential consequence of increased terrestrially-derived DOC. Aquatic food webs would likely still be altered by the increased DOC concentrations because terrestrially-derived carbon regulates lake food web structure and ecosystem metabolism (Pulido-Villena et al. 2005) and microbial communities often diverge based on metabolism of DOC origin (Wetzel 2003, Wu et al. 2018). Some bacteria specialize in the metabolism of plant-derived DOC. Thus an increase in plant-derived DOC would likely cause a shift in bacterial communities, with potential consequences of altered food webs up trophic levels. Alpine lakes provide habitat to a unique community of microorganisms that thrive in the oligotrophic water and respond quickly to changes in their environment. An altered microbial community may infer altered biogeochemical processing as different species are responsible for the cycling of different nutrients and at different rates.

Given the sensitivity of alpine lakes to their environment (Woodward et al. 2010), research has long predicted that changes to climate would impact these high elevation lakes. Major shifts in the structure and function are predicted as minor increases in temperature can induce earlier ice melt, earlier onset of and a higher degree of stratification, and warmer surface temperatures (Austin et al. 2007, Williamson et al. 2009) Climate change will likely impact alpine lakes substantially, but the phototrophs are not likely to be altered by the increase in terrestrially-derived DOC.

Citations

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