THESIS

EVALUATING SUBALPINE LAKE DELTA CARBON STORAGE IN THE COLORADO FRONT RANGE AND WASHINGTON CENTRAL CASCADES

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ABSTRACT

EVALUATING SUBALPINE LAKE DELTA CARBON STORAGE IN THE COLORADO FRONT RANGE AND WASHINGTON CENTRAL CASCADES

Mountainous regions are important contributors to the terrestrial organic carbon (OC) sink that affect global climate through the regulation of carbon-based greenhouse gases. However, mountain OC dynamics are poorly quantified. I sought to explore OC storage in subalpine lake deltas in the Washington Central Cascades and Colorado Front Range with the objectives of determining the magnitude of carbon storage and understanding the differences in storage between the two ranges. I used field, laboratory, and GIS techniques to determine the magnitude of and controls on the subaerial portion of the subalpine lake delta OC sink in 26 subalpine lake deltas, 14 in the Front Range and 12 in the Cascades. Soil moisture, texture, and delta valley confinement are significantly correlated with soil carbon on deltas. Average soil OC content on subalpine lake deltas ranges from 3 to 41%, and 140 to 1256 MgC/ha. Surprisingly, the carbon stocks of subalpine lake deltas are not significantly different between regions. I present a conceptual model that invokes basin-scale carbon dynamics to offer an explanation for how two regions with very different climate and tectonics have unexpectedly similar carbon stocks in their subalpine lake deltas. This conceptual model suggests that carbon is more likely to reach subalpine lake deltas from the upstream basin in the Colorado Front Range compared to the Washington Central Cascades. This points to a complex interaction among carbon production, transport, and stability in each region, and supports the idea that mountainous regions are complex carbon reactors.

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1. Introduction

Terrestrial waters play a significant role in the global carbon cycle [*Dean and Gorham*, 1998; *Cole et al.*, 2007; *Battin et al.*, 2009; *Tranvik et al.*, 2009; *Aufdenkampe et al.*, 2011]. Terrestrial OC entering freshwaters is either transported to the oceans, stored in sediment or living tissue, or released to the atmosphere, where it may act as a greenhouse gas, affecting global climate [*Houghton*, 2007; *Aufdenkampe et al.*, 2011]. An understanding of and the ability to manage global climate depends on our examination of terrestrial OC dynamics [*Battin et al.*, 2009]. Namely, we must determine how the concentration of carbon varies longitudinally through a river basin, and how carbon varies across regions with varying tectonics and climate. Questions also remain regarding the effects of land use and changing biota on carbon dynamics.

Mountainous regions in the western U.S. exhibit very high gross primary productivity [*Schimel et al.*, 2002]. In addition, headwater channels receive high inputs of organic matter and non-recalcitrant carbon [*Wagener et al.*, 1998], and efficiently transport carbon due to their relatively high unit sediment discharge [*Leithold et al.*, 2006]. This means that mountain rivers have the potential to act as neutral pipes for carbon [*Schlesinger and Melack*, 1981], transporting accumulated carbon through the headwaters to lower in the basin. However, recent work has shown that mountain river basins are indeed not neutral pipes, but actually store, transport, and release carbon in different parts of the network [*Sutfin et al.*, 2015].

The mountainous carbon sink has recently been recognized to be an important contributor to the terrestrial carbon sink [*Wohl et al.*, 2012; *Beckman and Wohl*, 2014; *Hoffmann et al.*, 2014a, 2014b]. Headwater regions, especially unconfined valley segments [*Wohl et al.*, 2012] and lakes [*Mulholland and Elwood*, 1982; *Downing et al.*, 2008; *Tranvik et al.*, 2009], have been shown to exhibit high organic carbon (OC) concentrations. Subalpine lakes, in particular, act to segment the hydrologic and sediment connectivity of headwater catchments [*Arp et al.*, 2007]. This points to such lakes as potential integrators of upstream processes, especially processes that affect the transport and stability of carbon in a mountainous region.

Baron et al. [1991] demonstrated that the carbon inputs to a subalpine lake in Rocky Mountain National Park, Colorado were dominated by allochthonous carbon, which must travel through the upstream basin before reaching the lake. Carbon stored in lake sediments is mostly OC, unless the surrounding basin is comprised of sedimentary lithologies or the basin is closed [*Einsele et al.*, 2001]. Lake carbon commonly remains very stable in the anoxic conditions that prevail in lake bottom sediment [*Bastviken et al.*, 2004; *Battin et al.*, 2009; *Tranvik et al.*, 2009]. It is also worth noting that although subalpine lakes are usually small relative to the size distribution of all global lakes, small lakes have been found to comprise the majority of all lake area on Earth [*Downing et al.*, 2006]. These lines of evidence point to small lake basins as potentially very important reservoirs of terrestrial carbon.

Subalpine lake deltas, however, have yet to be characterized in terms of their effects on carbon dynamics or sediment and water transport. These deltas may act as a sediment and carbon filter upstream of subalpine lakes. They are capable of catching coarse particulate organic matter and sediment and may act as the first subaerial sediment sink in a basin [*Carvalho and Schulte*, 2013]. As such, subalpine lake deltas could provide an environment in which the carbon dynamics (production, transport and storage) of headwater catchments are reflected in the form of carbon storage. I examine OC storage in subalpine lake deltas of the Washington Central Cascades (hereafter referred to simply as the Cascades) and the Colorado Front Range (hereafter referred to simply as the Front Range) to compare carbon dynamics between these two regions with differing tectonic history, climate, and biota.

1.1 Objective and Hypotheses

The broad objective of this work was to characterize subalpine lake delta OC storage and, in doing so, compare two mountain ranges exhibiting very different climatic and tectonic regimes. My secondary purpose was to determine whether subalpine lake deltas could contribute significantly to the mountain carbon sink. With regards to comparing the Cascades and the Front Range on a regional scale, I hypothesize that:

H1: The Cascades contain more subalpine lakes per unit area, but fewer lakes with deltas, than the Front Range.

H1 is based on the idea that the greater relief in the Cascades allows for more individual lake basins, but the increased rate of colluvial inputs and hillslope steepness prevents delta formation by preventing the generation of low-gradient areas above lakes on which deposition could occur.

I also seek to develop a model to predict OC content in subalpine lake delta soil from soil properties and local geomorphology. I hypothesize that:

H2: OC content in subalpine lake delta soils is determined primarily by the energy level of the inlet channel and delta, after taking into account soil moisture.

H3: OC content in subalpine lake delta soils varies with the textural class of the soil.

OC content is generally greater in stable environments with fine grain sizes. I expect that low energy deltas, which have a combination of low gradient, low sediment discharge inlet channels and little colluvial input, are more stable and have a higher OC content. Soil moisture has been found to be a strong control on carbon respiration [*Howard and Howard*, 1993; *Yuste et al.*, 2007], making it prudent to account for soil moisture in a model of soil OC before attempting to identify other predictors. *H3* is based on prior research that has found a strong positive correlation between the proportion of clay and silt in a soil and the OC content of that soil [*Pinay et al.*, 1992; *Bergamaschi et al.*, 1997; *Jobbágy and Jackson*, 2000; *Appling et al.*, 2014].

With regards to comparing the OC storage of the Front Range and the Cascades in an integrated manner, I hypothesize that:

H4: Subalpine lake deltas store more carbon per unit area in the Cascades than in the Front Range.

H4 is based on the inference that greater precipitation and biomass in the Cascades lead to a greater carbon stock and slower decomposition of soil OC. The alternative to this hypothesis is that the OC content in subalpine lake deltas is not related to the total basin carbon stock and instead depends on a more complex array of carbon dynamics.

This project originally also included a component examining the geomorphic relationships present in subalpine lake basins. I originally hypothesized that as the outlet of a lake incised into the material damming the lake, the lake level would drop, exposing more land to the air and expanding the subaerial depositional zone at the head of the lake, provided that the land surface at the head of the lake was low gradient. This would result in an expansion of the delta (if one existed) at the head of the lake as the lake level falls. Thus, I expected that the height of a delta should correlate well with the incision of the outlet of the lake. I was unable to rigorously examine this hypothesis due to inappropriate field methods. Please see Appendix C for detailed methods and results regarding this component, as well as a justification for pursuing it differently in the future.

1.2 Field Areas

I collected data in two field areas with very contrasting climate, vegetation, and tectonic regimes in order to characterize a range of conditions that may impact soil carbon. Soil samples were taken in two focused areas within each broad region to maximize access to lakes due to the difficulty of obtaining samples in such remote areas. The entirety of each study region defined below (Figure 1) was used in determining the abundance of subalpine lakes and deltas. Characteristics of each region are summarized in Table 1.

1.2.1 Washington Central Cascades

I constrained my study area in order to minimize the variability in factors that could potentially affect soil carbon storage or the abundance of subalpine lake deltas. The Cascade Range exhibits a trend of increasing peak altitude to the north. This trend has a significant non-surficial component that is yet unexplained, but is partially due to increasing valley incision in the northern Cascades and variation in valley spacing and slope [*Mitchell et al.*, 2009]. The region has a high exhumation rate, which increases along an elevation gradient from the Puget Sound Lowlands east to the divide [*Reiners et al.*, 2003]. I defined my study region as the extent of the Snoqualmie and Skykomish watersheds east of the mountain front and west of the divide. This selection maintains low variability along the north-south trend identified by *Mitchell et al.* [2009] and is within the spatial range of high but relatively constant exhumation rate identified by *Reiners et al.* [2003]. This constraint also minimizes variation in climate and vegetation.

The lithology of this region consists of dominantly granitic rocks [*Tabor et al.*, 1993, 2000], producing very little carbon from bedrock. The vegetation in the region is dominated by Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), Pacific silver fir (*Abies amabilis*), western redcedar (*Thuja plicata*), and mountain hemlock (*Tsuga mertensiana*).

The fire recurrence interval for subalpine forests in the Pacific Northwest ranges from 29 to over 1500 years [*Agee*, 1993]. The region receives an average of 2.54 m of precipitation annually, has a mean annual temperature of 5.4° C, and spends an average of 36.3 days entirely below freezing, as recorded at the NOAA Snoqualmie Pass climate station (approximate elevation 831 m).

The topography of this region was sculpted by alpine glaciation, which culminated approximately 22 ka before present [*Easterbrook*, 1986]. Holocene glacial advances have been proposed to have happened as recently as ~ 8 ka before present [*Beget*, 1981; *Waitt et al.*, 1982], with potential glacial expansion episodes having occurred as recently as 1 ka before present [*Beget*, 1984]. Due to the high precipitation in this region, exhumation rate is quite high, reaching a maximum of 0.33 mm yr^{-1} approximately two-thirds of the way up the western flank of the Cascades, which corresponds with the location of much of the Alpine Lakes Wilderness [*Reiners et al.*, 2003]. This results in a landscape characterized by high local relief (1-1.3 km) and steep, confined valleys [*Reiners et al.*, 2003]. The deltas in the region are generally densely forested or have thick, shrubby wetland vegetation, with hummocky topography created by incised streams and fallen wood (Figure 2).

1.2.2 Colorado Front Range

I defined my study area in the Colorado Rocky Mountains to encompass the entirety of the Front Range east of the Continental Divide. Glaciation in the Front Range, which peaked most recently in the late Pleistocene during the Pinedale (which, most recently, peaked around 22 ka before present) and Bull Lake glaciations [*Madole et al.*, 1998], incised much deeper valleys east of the Continental Divide, creating a topographic contrast between the east and west side of the divide [*Anderson et al.*, 2006]. This contrast made it necessary to constrain my examination to the east side of the divide in order to ensure low topographic variation across the study area.

I focused my field data collection around the Rawah Wilderness and Comanche Peak Wilderness, both within the limits of Pleistocene glaciation defined by *Madole et al.* [1998]. The Rawah Lakes are underlain by deposits of the Pinedale and Bull Lake glaciations, as well as Precambrian gneiss, schist, and migmatite. The Comanche Peak Wilderness is underlain by glacial deposits as well as felsic and hornblendic gneisses [*Braddock and Cole*, 1978]. The lithology of this region produces very little carbon from rock weathering due to its composition of igneous and metamorphic rocks. Glacial advances have been proposed to have occurred as recently as ~ 8 ka before present [*Benson et al.*, 2007]. Laramie Lake, in the region of the Rawah Lakes (Figure 1), is the only studied lake to have some human influence. There is a small, breached man-made dam at the mouth of the lake that has since been modified by beaver activity. I chose to include this lake in my analyses because the timescale at which carbon storage operates in lakes and mountainous regions is likely far greater than the amount of time that has elapsed since human modification of the lake. Vegetation is dominated by lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), limber pine (*Pinus flexilis*), and quaking aspen (*Populus tremuloides*). Subalpine forests in the region experience a fire recurrence interval that is typically greater than 100 years and often greater than 400 years. However, low severity fires can occur with intervals of 5-30 years, but are generally not as likely to kill mature trees [*Veblen and Donnegan*, 2005]. The region receives an average of approximately 1.13 m of precipitation annually, experiences a mean daily temperature of 0.6° C, and spends an average of 50 days entirely below freezing, as recorded at the Joe Wright SNOTEL site (3085 m elevation).

Compared to the Central Cascades, this region has lower local relief in the headwaters [*Anderson et al.*, 2006]. The exhumation rate is also much lower than the Central Cascades, ranging from 0.025 to 0.028 mm yr^{-1} [*Garber*, 2013]. The deltas in this region are generally sparsely vegetated or characterized by thick patches of willow (*Salix*) or other shrubs interspersed with grasses and sparse trees (Figure 3).

2. Methods

2.1 Measuring Delta Volume and Abundance

To determine the total magnitude of the carbon sink in subalpine lake deltas, it was necessary to obtain estimates of delta volume in the studied deltas, and the abundance of deltas in the studied mountain ranges. This allowed me to test *H1*.

Delta volume was obtained by approximating each delta as a tilted cone, the volume of which can be calculated using the surface area of the base of the cone and the height of the cone. In the field, I took GPS waypoints at the delta margins where the margins were difficult to identify using aerial imagery, then overlaid those GPS points on Google Earth (Figure 4). Using the polygon tool in Google Earth, I was able to obtain approximate surface areas for each delta. This measurement of surface area represents the base of the tilted cone. The height of the tilted cone was obtained by measuring subaerial delta height (the height of the delta that is exposed to air at some point during the year, inferred mostly by vegetation) in the field using a laser rangefinder. Three measurements were taken from the upstream end to the downstream end of each delta to obtain the difference in elevation between the two points. The laser measurements were commonly blocked by water covering the downstream end of the delta. In these cases, a depth measurement was taken from the water surface to the actual downstream end of the delta and added to the vertical measurement obtained using the laser to obtain an actual delta height.

I suspect that these measurements of delta height underestimate the total delta height, as it is likely that deltaic sediments extend beneath the downstream end of the delta. Although I did not thoroughly examine the structure of the studied deltas, I inferred from their surface characteristics that they were likely Gilbert-type deltas. This is substantiated by the findings of

Smith and Jol [1997], who determined that a mountain lake delta in Banff National Park, Canada was Gilbert-type through the use of radar imaging. Although I was able to infer some structure and depth from sediment cores, it was not feasible to determine the total height of the delta from sediment cores because of the difficulty in determining the total vertical distance between the surface of the delta at a particular core and the highest point on the delta. I also may have reached refusal on a coarse layer that was not bedrock, giving a false representation of the true depth of the delta.

Delta abundance in each study region was estimated using a census of USGS 7.5' by 7.5' historical topographic maps and aerial/satellite imagery provided by Google Earth. USGS topographic maps were downloaded to cover the full extent of each region. I measured the surface area covered by one map in the approximate center of the region and used that area as an approximation for the surface area covered by all other maps in the region. Because each region had a limited latitudinal extent, the error generated by doing this is minimal. For maps that intersected the boundary of a particular study region, I manually measured the map area by overlaying the map in Google Earth and using the polygon tool to obtain an area. With these measurements, I could obtain a total area for each study region.

Within each map, I identified subalpine lakes as those that were below the tree line (as shown by aerial/satellite imagery) and that were shown on both the USGS historical topographic maps and the aerial/satellite imagery. I identified and removed from the census lakes that appeared to be man-made. These lakes were manually identified as those with distinct, straight-line boundaries on their downstream end (indicating a dam) or a regular shape in the vicinity of agricultural land (indicating an agricultural pond). For each identified lake, I examined aerial/satellite imagery to determine whether the lake appeared to have a delta. It is worth noting that due to the low resolution of aerial/satellite imagery, some alpine lakes could have been erroneously counted as subalpine lakes, due to non-forest vegetation appearing as forest.

I calculated the proportion of subalpine lakes with deltas as the number of lakes with deltas divided by the number of lakes in each region. I calculated the areal density of subalpine lake deltas by multiplying the average delta area for each region (taken from the sample of deltas from which I took soil samples) by the number of lakes with deltas in each region, and then dividing by the total area of each region. These calculations also yielded a total area of subalpine lake delta soil for each region, allowing for a quantification of the total subalpine lake delta carbon stock in each region. Because I took a census of the number of lakes and the proportion of lakes with deltas in each region, I was able to directly compare those values between regions, treating each region as a population.

2.2 Determining Carbon Content, Moisture, and Texture in Soil Samples

I sampled each delta using a randomly located cluster sampling technique for mineral sediment and organic soil carbon. Based on previous work showing that the structure of a subalpine lake delta is probably gilbert-type [*Smith and Jol*, 1997], I assumed no underlying, stratified structure. I randomly located 3 core locations across the delta (I was only able to retrieve two cores from one lake due to sample losses). Each core taken was considered a cluster of sample points, with each sample point being an approximately 20-40 cm deep section of core. Each core was taken to a depth of either refusal (assumed to be the base of the delta or a coarse layer, usually rocky material impenetrable by hand auger) or where I was unlikely to be able to remove the auger if I cored any deeper (e.g., there was a very dense clay layer that caused the auger to become very difficult to remove from the ground). I collected disturbed soil samples with an AMS stainless steel, 69.85 mm diameter, hand-operated bucket auger (Figure 5). This system was used because of its compactness, which allowed it to be transported to remote sampling locations, and its ability to sample substrates ranging from clay to coarse sand and pebbles. Unfortunately, because such an auger collects disturbed soil samples, I was not able to calculate soil bulk density directly for my samples.

Each sample was poured out on a tarp, mixed, then bagged in a 1 quart Ziploc bag. Samples were taken from the field and placed in an insulated cooler to maintain a cool temperature. As soon as was reasonably possible (never more than 3 days), samples were placed in a freezer and kept below freezing until lab analysis. Samples were removed from the freezer to defrost and return to a workable temperature before analysis.

Samples that contained a mixture of mineral sediment and organic matter were sent to the Colorado State University Soil Testing Lab for moisture and total OC analysis using a CHN furnace [*Sparks*, 1996]. Due to budgetary constraints, samples with dominantly organic matter or that were suspected to contain very low OC levels due to being dominantly comprised of coarse sand were analyzed for total OC using loss-on-ignition. This method was deemed adequate because of the very low levels of inorganic carbon (ranging from 0.00% to 0.49%) found in samples analyzed by the Soil Testing Lab. Loss-on-ignition was performed with a muffle furnace (Figure 6). Samples were hand mixed to form a homogenous sample, then subsampled (into samples ranging from approximately 30 to 40 g of wet soil) into crucibles for moisture and carbon analysis. Each crucible sample was weighed, then dried at 100° C for 24 hours and weighed again to determine moisture content. Immediately following drying, samples were burnt at 550° C for 24 hours and weighed again to determine mass lost on ignition. To convert from mass lost on ignition to OC content, I used a regression based on soil texture class [*Vos et al.*, 2005a]. This regression corrects for potential clay-held water that could obscure the relationship between mass lost on ignition and OC content.

Soil texture analysis was performed by feel in a laboratory setting on all soil samples. Each sample was categorized into one of the USDA soil texture classes (e.g., sand, clay loam, silty clay) following a decision tree for assigning texture by feel modified from *Thien* [1979]. Samples with abundant coarse material (>2 mm) were sieved through a 2 mm sieve prior to texture analysis. I performed textural analysis on the burnt fraction of samples that had been burned through loss-on-ignition, which eliminated the influence of organic material, as well as samples that had not been burnt to determine whether organic material might have an influence on this type of analysis. Many samples were very rich in organics and were classified as being dominantly organic if the texture was difficult to ascertain due to the abundance of organic matter.

To determine carbon content per unit area, I needed to estimate bulk density for each sample. For samples burnt through loss on ignition, I used a regression based on loss-on-ignition weight to determine bulk density [*Vos et al.*, 2005b]. For samples analyzed by the soil testing lab, I estimated loss-on-ignition weight using the soil texture and the OC content [*Vos et al.*, 2005a] in order to estimate bulk density. Carbon content per unit area was determined for each sample by multiplying the bulk density by the OC content and thickness of the sample. The OC content per unit area for each sample was summed for all samples in each core, then averaged between all the cores in a delta to determine an OC content per unit area for each delta.

2.3 Determining Lake Valley Geometry and Environmental Conditions

To study the geomorphology of subalpine lake deltas and their surrounding valleys, as well as collect data on potential predictor variables for a model to understand the controls on carbon content in subalpine lake deltas, I measured the valley confinement, lake outlet incision, dominant aspect, drainage area, and mean basin slope of each delta.

Valley confinement was measured in Google Earth as the ratio between the valley width perpendicular to the longitudinal axis of the delta and the width of the lake downstream of the delta (Figure 7). The valley width was measured as the distance between the top of the ridge closest to the delta and the point on the opposite valley wall at the same elevation as the top of the closest ridge. The width was measured at the approximate longitudinal midpoint of the delta (halfway between the mouth and the head of the delta). Lake width was determined by first measuring the area of the lake in Google Earth, then measuring the length of the lake from the inlet channel to the outlet channel of the lake. The lake area was divided by the lake length to determine the lake width.

The dominant aspect of each delta was measured in Google Earth. I measured the azimuth of a line going from the head of the delta to the midway point of the mouth of the delta. Because identification of the exact location of the head of the delta and the midway point of the mouth of the delta using aerial imagery is difficult and subjective, I converted the azimuth measured in Google Earth to a cardinal direction. For example, any azimuth between 315° and 45° would be considered north facing, and the exact azimuth would not be used in analysis.

The drainage area and mean basin slope of the watershed upstream of each delta were measured using the Washington and Colorado StreamStats tools [*U.S. Geological Survey*, 2012].

2.4 Statistical Analysis

All statistical analyses were performed using the R statistical package [*R Core Team,* 2014]. I used a 95% confidence level for all analyses. Any representations of uncertainty represent this 95% confidence interval (CI). I tested each sample population for normality when necessary using the Shapiro-Wilk test [*Shapiro and Wilk*, 1965] and visual methods such as boxplots and histograms. I compared the Cascades and the Front Range in terms of the OC content by mass, OC content per unit area, volume, valley confinement, drainage area, moisture, and mean basin slope of each subalpine lake delta (n = 12 for the Cascades, n = 14 for the Front Range). I modeled OC storage in subalpine lake deltas in both the Cascades and Front Range (n = 26) using delta aspect, valley confinement, moisture, mean basin slope, and drainage area as potential predictors. I compared textural classes of all soils sampled (n = 201) as well as only soil samples that had been burnt using loss-on-ignition (n = 88) in terms of OC content.

2.4.1 Estimating the Subalpine Lake Delta Carbon Stock and Comparing the Cascades and the Front Range

I averaged the depth-weighted OC content for each core to obtain an average OC content for each core. I then averaged the three cores to obtain an average OC content for each subalpine lake delta. Soil OC content per unit area [MgC/ha] for each sample was calculated as the product of the OC content, the thickness of the sampled sediment, and the estimated bulk density of the sample. For each core, the OC content per unit area was summed across all samples to determine the total OC content per unit area integrated over the depth of the entire core. The OC content per unit area values for each core were then averaged to determine an average value for each subalpine lake delta.

With datasets of OC content [%] and OC content per unit area [MgC/ha], I was able to test for significant differences between the subalpine lake delta OC stock in each region to test *H4*. I used the same statistical methods to compare datasets of OC content and OC content per unit area. Because both samples were found to be non-normal, I used the nonparametric Kruskal-Wallis Rank Sum test [*Kruskal and Wallis*, 1952] to determine whether the two samples could have come from the same population. I used a similar method to test for significant differences between the delta volume, valley confinement, drainage area, moisture, and mean basin slope samples in each region. For samples that exhibited normality, a t-test was used to test for differences between samples. Otherwise, the Kruskal-Wallis Rank Sum test was used.

2.4.2 Examining the Relationship between OC Content and Texture

This analysis was performed on the dataset comprised of all soil samples from both regions, because the OC content was found to be insignificantly different between the two regions. To account for potential error in the assignment of detailed texture classes, I grouped unburnt samples into sands (sands, loamy sands, sandy loams, loams, and silt loams), clay loams (sandy clay loams, silty clay loams and clay loams), clays (sandy clays, silty clays, clays), and organics (samples whose texture was difficult to determine due to the abundance of organics). I grouped burnt samples into sands (sands, loamy sands, sandy loams, loams, silt loams) and fines (sandy clay loams, silty clay loams, clay loams, sandy clays, silty clays, clays).

I found the datasets to be non-normal, and hence used visual and nonparametric methods to perform comparisons between texture groups and test *H3*. I performed this analysis on all samples (grouped into sands, clay loams, clays, and organics), as well as a subset of samples that had been burnt through loss-on-ignition grouped into sands (as above) and fines (including clay loams and clays, as above) to remove the potential error due to the presence of organic material. I performed a Kruskal-Wallis Rank Sum test between each category [*Kruskal and Wallis*, 1952] to test for differences between groups.

2.4.3 Modeling OC Content using Multiple Linear Regression

To understand the controls on OC content in subalpine delta soils and test *H2*, I selected a model to predict OC content using drainage area, mean basin slope, soil moisture, valley confinement, and dominant aspect as potential predictors. For this model, I used a sample of all subalpine lakes in both regions, because the OC content was found to be insignificantly different between regions.

First, I checked the dataset including all predictor variables and the response variable for multicollinearity, which can skew multiple linear regression inferences, and found no multicollinearity. I performed all subsets regression to calculate the corrected Akaike information criterion (AICc) for every potential model that could be made with subsets of the predictor variables, including interaction terms between valley confinement, mean basin slope, and drainage area. The inclusion of these interaction terms was an attempt to estimate stream power, which may be a better representation of energy level. However, without field measurements of the slope of inlet channels, I was unable to accurately quantify stream power on or near the delta. The AICc was used due to the small sample size of the model (n = 26) [*Hurvich and Tsai*, 1989]. I used AICc weights to evaluate potential models [*Wagenmakers and Farrell*, 2004]. I performed standard model diagnostics on the appropriate models and determined that the multiple linear regression assumptions were met.

Finally, I tested whether drainage area and delta volume significantly correlated by modeling delta volume using a linear, zero intercept (reasoning that as drainage area approaches zero, so does the size of the resulting delta) model. This allowed me to understand how the size of each individual subalpine lake delta carbon sink might relate to the size of the basin, and allowed me to interpret drainage area as a potential predictor in my model of OC content in subalpine lake delta soil.

3. Results

3.1 Abundance of Lakes and Deltas in the Washington Central Cascades and Colorado Front Range (H1)

In the Front Range, I counted 718 natural lakes, 373 of which (approximately 52%) had visible deltas, across an area of 446,400 ha. This yielded a lake density of 0.001608 lakes per ha (or 0.000836 delta-bearing lakes per ha). Given an average delta area of 0.58 ± 0.39 ha, the proportion of land area in the Front Range taken up by subalpine lake deltas is 0.048 ±0.033%, or 215.15 ± 147.32 ha.

In the Cascades, I counted 624 natural lakes, 228 of which (approximately 37%) had visible deltas, across an area of 273,263 ha. This yielded a lake density of 0.002284 lakes per ha (or 0.000834 delta-bearing lakes per ha). Given an average delta area of 1.47 ± 1.33 ha, the proportion of land area in the Cascades taken up by subalpine lake deltas is 0.12 ± 0.11%, or 334.22 ± 303.15 ha.

Comparing the Front Range and the Cascades, I found that the Cascades do indeed have a higher density of lakes, but fewer lakes with deltas, supporting *H1*. However, the number of delta-bearing lakes per ha is remarkably similar between the Front Range and the Cascades, and the total percentage of area taken up by subalpine lake deltas is not significantly different between the two regions.

3.2 Modeling OC Content in Subalpine Lake Delta Soil (H2)

Based on my model selection, I chose two potential best models to compare (Table 1). These models differ only by inclusion of mean basin slope. Based on the AICc weight comparison procedure outlined by *Wagenmakers and Farrell* [2004], I found that model 1 was

1.65 times more likely to be the best model than model 2. Thus, model comparison focuses on whether mean basin slope should be included in the model. In model 2, the p value corresponding to the probability that the coefficient for mean basin slope is nonzero is 0.19. I can conclude that the coefficient of the mean basin slope term is not significantly different from 0 and that mean basin slope likely should not be included in the model. Thus, I conclude that OC in subalpine lake delta soils is best predicted using a multiple linear regression model with only soil moisture and valley confinement as predictors. A summary of both models is given in Table 1. Summary values for all potential model predictors and the response are given in Table 2. This result indicates that energy level, as represented by valley confinement, is a dominant control on soil OC in subalpine lake deltas when moisture is accounted for, supporting *H2*.

3.2.1 Comparing the Cascades and Front Range in Terms of Basin and Soil Properties

I compared my two study regions in terms of valley confinement, soil moisture, drainage area, mean basin slope, and delta volume. From the results of the Kruskal-Wallis Rank Sum test (or t test where appropriate), the two regions do not differ significantly in terms of soil moisture ($p = 0.14$), drainage area ($p = 0.92$), and delta volume ($p = 0.44$). The two regions differ significantly in terms of mean basin slope ($p = 0.001$) and valley confinement ($p = 0.040$). The Cascades have a higher mean basin slope (mean = 49.63 ± 10.65 %) than the Front Range (mean = 29.01 ± 4.93 %) and valleys in the Cascades are more confined (median = 2.32, 95% CI between 1.96 and 5.56) than those in the Front Range (median = 4.17, 95% CI between 2.56 and 6.79).

3.3 OC Variation with Texture in Subalpine Lake Delta Soils (H3)

The Kruskal-Wallis Rank Sum test indicated that there is no significant difference in the medians of each texture class (clays, clay loams, organics, and sands) ($p = 0.25$). When these texture groups are visually examined in terms of their OC content, it is evident that there is little difference between groups (Figure 9). However, when this analysis is performed on only samples burnt through loss-on-ignition, there is a distinct and statistically significant difference between samples finer than sand and sand samples ($p = 0.01$) (Figure 10). Thus, I conclude that texture is likely a control on soil OC in subalpine lake delta soils, supporting *H3*, and corroborating past work.

3.4 Subalpine Lake Delta Carbon Stock in the Washington Central Cascades and Colorado Front Range (H4)

The median OC content and OC per unit area (MgC/ha) were found to be insignificantly different between the Front Range and the Cascade lake deltas (Figure 8), which does not support *H4*. Thus, I report here values for the entire dataset of subalpine lake deltas, including both regions.

The median OC content for subalpine lake delta soils, including fine organic matter and mineral soil, is 13% (95% CI between 8 and 17%). The median OC per unit area is 478.54 MgC/ha (95% CI between 360.73 and 624.61 MgC/ha). Across both study areas, I estimate a total carbon stock of approximately 262,900 Mg of OC. Based on a total ecosystem carbon stock of approximately 754 MgC/ha [*Smithwick et al.*, 2002] (for a total of 0.206 Pg C) for the Washington Cascades, and approximately 287 MgC/ha [*Bradford et al.*, 2008] (for a total of 0.128 Pg C) for the Colorado Front Range, I estimate a total carbon stock between both the Cascades and Front Range in my study areas of approximately 0.334 Pg C. Thus, subalpine lake deltas account for approximately 0.079% of the mountainous carbon sink across these two regions, while taking up approximately 0.00076% of the total area. From this, I conclude that they are enriched relative to the rest of upland regions in terms of OC content, and are disproportionately important in terms of their contribution to the OC storage in mountainous regions.

4. Discussion

4.1 Abundance of Lakes and Deltas in the Washington Central Cascades and Colorado Front Range

I hypothesized that the Cascades would contain more subalpine lakes per unit area, but fewer lakes with deltas, than the Front Range (*H1*). This hypothesis is supported by my census of lakes and deltas in each area. However, it is interesting to note that although the number of lakes and the number of lakes with deltas is different between the two areas, the delta-bearing lake density in the Front Range is only 0.2% less than that of the Cascades, and the proportion of land taken up by deltas in each region is not significantly different. Thus, although the difference in lake density in each area may have implications for sediment dynamics, it appears that there is no significant difference in the size of the subalpine lake delta OC sink between the two regions.

4.1.1 Does There Exist a Feedback between Landscape Evolution and Sediment Storage in Subalpine Lake Deltas?

Because of the high variability in delta areas in the two regions, it is difficult to determine whether the magnitude of sediment storage and OC storage in deltas in each region actually differs. However, based on this small dataset of delta areas, it appears that sediment storage in subalpine lake deltas is remarkably similar between these two regions. From a landscape evolution and sediment budgeting perspective, this implies that there may be a positive feedback between landscape evolution and the distribution of sediment storage in subalpine lake deltas. As valleys become more unconfined, it may become less likely that a lake will form, due to more material being required to create a depression in a valley (effectively, the landform that dams the lake will require more material). However, with more unconfined valleys, the likelihood of depositional surfaces such as deltas forming may be increased. As depositional areas become more likely, the number of lakes with deltas may also increase. Although the absolute number of lakes may decrease, if the number of deltas correspondingly increases, the volume of sediment stored in subalpine lake deltas may remain constant.

There may exist a relationship between the evolution of a range and the amount of sediment storage in subalpine lake deltas. As glacial cycles erode a mountain range, each cycle may cause a slight change in the topography, depending on the rate of uplift of the range. Glaciers acting on a range may change the location and geometry of topographic depressions in the landscape that act as sediment sinks (e.g., lake basins). As the uplift rate of a mountain range decreases, glacial activity may have the effect of altering the topography so as to create less confined valleys. This may decrease the total number of lakes that will form during an interglacial period, but potentially increase the number of lakes with deltas. Assuming that average delta area and depth remain roughly constant throughout glacial cycles, the total volume of sediment storage in subalpine lake deltas may remain constant over the evolution of the mountain range. This could maintain a relatively constant volume of OC storage in subalpine lake deltas throughout the evolution of the range.

Further work is required on a much broader scale than was done in this project to evaluate this potential trend and examine other potential feedbacks in carbon storage throughout the development of a mountain range. Such work might include measuring the abundance of lakes, the proportion of lakes with deltas, and delta areas for a number of other mountain ranges, such as the Himalayas and the Appalachians. This would allow one to evaluate whether the total proportion of land area comprised by subalpine lake deltas remained roughly the same across a wide range of uplift rates. A better conceptual understanding of the evolution of carbon reservoirs throughout the evolution of mountain ranges could lead to a better understanding of the complex feedbacks between climate and landscape evolution.

4.2 Controls on OC Content in Subalpine Lake Delta Soils

From the combination of my model predicting OC content in subalpine lake deltas and my comparison of textural classes in terms of OC storage, I can conclude that energy level, as reflected by valley confinement and soil texture that may be a direct result of valley confinement, is a control on OC content in subalpine lake delta soils, supporting *H3*. Coarser texture, which may reflect an inlet channel of higher stream power, limits the storage of OC on the delta. Although texture could also be related to lithology, this potential effect is likely controlled for in this study because of how similar the study basins are in terms of lithology. A relatively high valley confinement could lead to a stream with higher stream power, increasing texture size. It could also result in a greater rate of migration of the inlet channel across the delta, although I do not have the data to examine sediment turnover as a potential control on OC content in subalpine lake deltas.

As has been repeatedly found in previous work [*Pinay et al.*, 1992; *Howard and Howard*, 1993; *Bergamaschi et al.*, 1997; *Jobbágy and Jackson*, 2000; *Yuste et al.*, 2007; *Appling et al.*, 2014], texture and moisture strongly relate to soil OC content. Soil moisture on a subalpine lake delta reflects variation in lake level, which is related to the discharge of the inlet channel relative to that of the outlet channel and/or short-term fluctuations in the height of the dam at the outlet of the lake. I have observed short-term (on the scale of a few months) fluctuations in lake level due to changes in the height of a wood jam at the outlet of Rainy Lake, in the Central Cascades, which caused variation in lake level and the depth of standing water on the delta. Although short-term alterations in moisture on the delta likely do not affect OC decomposition, which tends to occur on the scale of months to many years, it is still unclear over what time scales moisture fluctuations on the delta would have to occur to significantly affect carbon. However, the correlation between moisture and OC content indicates that a long-term drop in lake level has the potential to dramatically affect OC storage on the delta by exposing deltaic soil to low moisture conditions as a result of the drainage of groundwater towards a lower lake surface.

OC content positively correlates with the amount of surface area available to interact with OC molecules, meaning that finer sediment textures with more surface area available will be able to store more OC. My texture analysis supports this idea. However, it is interesting to note that when textural analysis was performed on all samples, including those with abundant organic matter, the relationship between texture and OC content breaks down. I suspect that this is due to the error associated with doing texture by feel on samples with abundant organic material, which can obscure the accurate assignment of texture. I therefore conclude that texture analyses done by feel should be done only after a sample's organic material has been removed. Indeed, when this was done, the relationship between texture and OC content became evident.

Excluded from the model of OC content in subalpine lake delta soils were mean basin slope, dominant delta aspect, and drainage area. I initially expected mean basin slope to be related to energy level on the delta. However, from the results of my model selection, it appears that the effects of mean basin slope may be mixed in each basin, and not consistently relate to OC stability. For instance, while a high mean basin slope could lead to greater rate of transport for soil carbon to the delta (i.e., higher rates of hillslope erosion and less of a chance for OC to be respired before reaching a stable environment such as the delta), high mean basin slope could also increase groundwater drainage rate, lowering hillslope soil moisture and increasing OC decomposition on the hillslope. Groundwater dynamics and their resultant effects on OC dynamics may be strongly influenced by lithology, which was not considered as a potential variable in this analysis. It is possible that a much more detailed examination of mean basin slope as a potential control on OC content in depositional zones could yield a more definitive result. For example, there may be a threshold mean basin slope above which the direction of the relationship between mean basin slope and OC changes, which probably could not be resolved in my analysis.

Delta aspect was hypothesized to control OC content because of the idea that a delta that receives more exposure to sunlight (i.e., is dominantly south-facing), may have more primary production of autochthonous OC on the delta. I suspect that the failure of delta aspect to predict OC content comes primarily from the fact that sunlight exposure is dominantly controlled by canopy cover over the small areas taken up by most subalpine lake deltas. I observed canopy cover to vary significantly between deltas and it was not well-described by aspect alone. In the case of confined valleys, local topography around the delta likely matters much more than aspect in terms of sunlight exposure (e.g., if the delta is perched on a valley wall or is near a pass). Deltas are very low-gradient surfaces, and, in the case of unconfined valleys, I suspect that aspect matters very little, as large trees capable of shading the delta could occur in patches almost anywhere on the delta and would have a larger effect on sunlight exposure than the direction the delta faces.

Drainage area was hypothesized to control OC content because of the assumption that a larger contributing area would generate more total OC, which would then be deposited in the delta. However, it is equally likely that a larger drainage area would produce a larger delta, spreading the OC over a larger sediment reservoir. Indeed, drainage area does positively correlate with delta volume for my dataset. This indicates that greater absolute primary production (due to a larger basin area) is likely compensated for by a larger delta.

4.3 Significance of the Subalpine Lake Delta Carbon Stock

I sought to determine whether subalpine lake deltas could provide a significant carbon reservoir in the context of terrestrial carbon storage. Recent work [e.g., *Wohl et al.*, 2012; *Beckman and Wohl*, 2014] has shown the importance of unconfined valley segments and wood in mountainous carbon storage. However, the spatial distribution and concentration of OC in mountainous landscapes is poorly constrained, making it very difficult to compare subalpine lake deltas to other landforms. My results suggest that subalpine lake deltas store a very small proportion of the total OC on the landscape. Although the density of OC in subalpine lake deltas is high relative to other parts of the basin (hillslope soils, many parts of the floodplain), subalpine lake deltas do not constitute much of the land area of most basins, and hence do not provide a large carbon reservoir. Although I lack the data to confirm this, it is likely that subalpine lake deltas are more stable than steeper regions of the subalpine landscape. If that is true, subalpine lake deltas would provide a more stable reservoir for OC in headwaters compared to other parts of the basin.

OC content in the upper 13 to 20 cm of subalpine lake bottom sediment sampled from 4 lakes in the Front Range varies from approximately 3 to 16% [*Alex Wolfe, Personal Communication*, 2015]. OC content ranges from 9 to 12% in the top 8 cm of Findley Lake in the Central Cascades [*Birch et al.*, 1980]. These values fall within the range found for subalpine lake deltas examined in this study (approximately 3 to 41% average OC content). Due to the lack of data on subalpine lake sediment depth and the low number of lakes sampled, it is difficult to know whether subalpine lakes or their deltas are more significant OC sinks. However, from this small dataset, I estimate that the contribution of subalpine lake deltas could be similar to that of subalpine lakes. To better constrain the total carbon storage in subalpine lakes relative to other parts of a basin, it would be necessary to understand sediment depth and volume and variations in OC content with sediment depth in such lakes.

Because small lakes comprise the majority of the lake surface on Earth, it would be worth examining whether the magnitude of carbon storage in lake deltas in lowland regions is similar to that of subalpine lake deltas. It is certainly possible that small lake deltas could provide a significant terrestrial carbon sink if the carbon stocks found in this study are comparable to those in small lake deltas in lowland regions. Such an examination would likely need to be done on a single watershed, which has yet to be done. Although one study examines the longitudinal trend in OC storage in lake bottom sediment through a basin in western Washington [*Birch et al.*, 1980], the lowland lakes studied are anthropogenically influenced, and deltas were not examined.

4.4 How Do Two Distinct Mountain Ranges Have Similar Carbon Stocks in Subalpine Lake Deltas?

I seek to understand how two mountain ranges with very different climate, tectonics, vegetation, and topography can be so similar in terms of not only their carbon stocks, but also the physical characteristics that may influence soil carbon storage. The stark differences between these two ranges led me to expect very dissimilar carbon stocks. Subalpine lake deltas could be expected to reflect carbon dynamics of the upstream basin very clearly in that they may form the first stable depositional site for carbon in the headwater network. I will attempt to explain why my original hypothesis was not supported, and infer how carbon dynamics produce similitude in the carbon stocks of subalpine lake deltas in the Front Range and Cascades. The question that I seek to address is how the Cascades, with a total upstream ecosystem carbon stock ranging from 463 to 1050 MgC/ha [*Smithwick et al.*, 2002], and the Front Range, with a total upstream ecosystem carbon stock ranging from 261 to 333 MgC/ha [*Bradford et al.*, 2008], have insignificantly different carbon stocks in their subalpine lake deltas.

4.4.1 Dominant Contrasts between the Front Range and the Cascades

The Cascades experience a wetter but warmer climate than the Front Range (2.54 m precipitation and 36.3 days below freezing versus 1.13 m precipitation and 50 days below freezing annually). This substantial difference in precipitation produces much greater biomass in the Cascades [*Smithwick et al.*, 2002; *Bradford et al.*, 2008], which tend to be much more densely vegetated.

The second dominant contrast between these regions is their exhumation rate and resulting topography. The Cascades experience an order of magnitude greater exhumation rate than the Front Range (0.33 mm yr^{-1} versus 0.028 mm yr^{-1}). This results in much higher relief [*Reiners et al.*, 2003] and much greater mean basin slope and valley confinement. Notably, the Cascades regularly exhibit hillslopes that are in excess of the commonly designated threshold slope of 30°, which are likely to produce much greater rates of episodic (e.g., landslide) erosion [*Montgomery*, 2001; *Montgomery and Brandon*, 2002; *Larsen and Montgomery*, 2012]. I originally expected this to produce deltas with larger grain size (due to the higher probability of colluvial inputs to the delta), but more frequent burial events. Although the larger texture would decrease OC storage capacity in the mineral soil, I expected the more frequent burial to increase overall OC stability in the soil by increasing the likelihood of anoxic conditions occurring and preventing soil turnover on the delta.

However, I did not notice any qualitative evidence of increased rates of colluvial deposition on deltas in the Cascades compared to the Front Range. I did observe greater abundance of colluvial deposits near deltas in the Cascades compared to the Front Range, but these colluvial deposits either did not reach the delta or acted only to constrain the extent of the margin of the delta, as opposed to covering the delta. Thus, although topography appears to have altered the geometry of deltas, it does not seem to affect the carbon storage within delta soils, or the total volume of available carbon storage on the delta.

These contrasts between the Cascades and the Front Range led me to expect a larger carbon stock in Cascade subalpine lake deltas compared to the Front Range. However, as I have shown, that hypothesis is not supported. The following sections explore potential explanations for the similarity between these two disparate mountain ranges in terms of their carbon stock in subalpine lake deltas.

4.4.2 Similarities between the Front Range and the Cascades

Subalpine lake deltas in the Front Range and the Cascades do not significantly differ in terms of soil moisture, drainage area, and delta volume. Regional climate does not appear to significantly influence subalpine lake delta soil moisture. Instead, it is more likely that the water table of the delta itself (which is likely very poorly drained) controls soil moisture. It is likely that most samples were near saturation (indeed, most samples were observed to have excess pore water that drained as soon as the sample was removed from the auger).

The fire recurrence interval in the subalpine zones of each region is similar, suggesting that there is no significant difference in biomass disturbance history. It is difficult to determine whether the fires that occur in each region are dominantly low-impact, or whether high intensity fires occur regularly in the studied basins. Given the high range of fire recurrence intervals and the lack of knowledge regarding the detailed fire history of each region, it is difficult to know whether there may be a difference in disturbance regime between the two regions.

All of these similarities may at least partially explain why the subalpine lake delta carbon stock is so similar between these two regions. However, if the Cascades have a much larger store of carbon in the upstream basin than the Front Range, it would seem that even if both ranges were exactly the same in terms of all other factors that influence carbon storage and transport, the carbon stock in subalpine lake deltas would still be different, as the input of carbon to deltas in the Cascades would be higher than the Front Range. Thus, there must be differences in the magnitude of certain carbon dynamics in each range that cause the carbon stock in subalpine lake deltas to be lower than the upstream basin carbon stock in the Cascades but higher than the upstream basin carbon stock in the Front Range. The following section presents a conceptual model to explain what those differences could be and how they might explain my results.

4.4.3 Dominant Contrasts between the Cascades and the Front Range that may Explain Similarities in Subalpine Lake Delta Carbon Stocks

I present a conceptual model (Figure 11) that outlines the contrasts between the Cascades and the Front Range and that may explain their similarity in subalpine lake delta carbon stock. The conceptual model describes factors influencing the likelihood of OC reaching the subalpine lake delta as OC is transported from the upstream basin.

Subalpine lake deltas could be relatively stable environments compared to the rest of the headwater basin. Thus, I start the model with the total, upstream ecosystem carbon stock (including live carbon stored in living biomass and dead carbon stored in soil and dead wood) in each region, reasoning that any OC in the upstream basin has a non-negligible chance of being deposited and stabilized on the subalpine lake delta. From the upstream basin, OC must be transported through the river networks and hillslopes to subalpine lake deltas. During this transport period, the rate at which the OC decays, especially as particulate organic matter such as coarse wood, will partially determine the likelihood of that OC reaching the subalpine lake delta. Dissolved organic carbon (DOC) is much less likely to settle out into sedimentary deposits than particulate organic carbon (POC), and will instead likely be transported through a subalpine lake delta and into the lake water, possibly settling through flocculation [*von Wachenfeldt and Tranvik*, 2008]. Thus, a higher ratio of DOC to POC will decrease the likelihood of OC being deposited on the subalpine lake delta. Longer wood turnover times will increase the proportion of POC relative to DOC that remains on hillslopes, enters soils, or is transported downstream to deltas, increasing the likelihood of the OC being retained on the delta. Soil OC decomposition will depend primarily on the soil moisture and texture in the upstream basin, which I did not quantify for my study sites and hence have left out of my conceptual model. Also related to the nature of OC transport through a river network is the geometry of the river valleys. As I have shown, valley confinement plays an important role in determining the concentration of OC on a subalpine lake delta. More confined valleys decrease the likelihood of OC being stabilized on the delta, possibly by coarsening soil texture on the delta or increasing the rate of soil turnover and export of OC from the delta. Finally, the conditions on the delta itself will affect OC decomposition and the stability of the OC. Delta soil moisture is therefore included in my conceptual model as a potential control on OC storage in subalpine lake deltas.

The upstream carbon stock in the Cascades ranges from 463 to 1050 MgC/ha [*Smithwick et al.*, 2002], compared to a range of 261 to 333 MgC/ha [*Bradford et al.*, 2008] in the Front Range. This means that the potential quantity of OC that could reach the subalpine lake delta is higher in the Cascades than the Front Range. However, the wood turnover rate in the Cascades ranges from 100 to 200 years [*Sollins et al.*, 1987], compared to a range of 400 to 760 years [*Kueppers et al.*, 2004] in the Front Range. The rapid rate of wood decay in the Cascades decreases the likelihood of OC reaching and being retained on the delta from the upstream basin relative to the likelihood of OC reaching and being retained on the delta in the Front Range, which exhibits a slow rate of wood decay. The DOC concentration in subalpine waters in the Cascades ranges from 0.007 to 0.016 g/L [*Edmonds*, 1982], compared to a range of 0.0001 to 0.0049 g/L [*Baron et al.*, 1991; *Wohl et al.*, 2012] in the Front Range. The higher concentration of DOC in the Cascades may further decrease the likelihood of OC being stored on the delta relative to the Front Range. My data show that subalpine lake delta valleys in the Cascades have a median confinement ratio of 2.32, which is significantly more confined than the Front Range (4.17). More confined valleys result in lower OC storage of subalpine lake deltas, as shown by the model of OC content in subalpine lake delta soil (Table 1). This can also be thought of in a probabilistic manner: more confined valleys decrease the likelihood of OC being stored on the subalpine lake delta. The two regions are not significantly different in terms of soil moisture, so that property likely does not change the relative likelihood of OC being stabilized on the delta in either region.

Figure 11 summarizes the above information and shows, graphically, how the Cascades and the Front Range reach a similitude in terms of carbon stocks in subalpine lake deltas. From this conceptual model, I propose that OC is more likely to reach subalpine lake deltas in the Front Range than in the Cascades, which may result in the similar values of OC storage in subalpine lake deltas between the two regions.

One notable difference in the OC stocks in subalpine lake deltas between the two regions studied is that there is much greater variability between deltas in the Front Range. The lower median valley confinement in the Front Range may explain this. A confined valley is very likely to have a confined, high energy channel [*Livers and Wohl*, 2015]. An unconfined valley, in contrast, may have an unconfined, low energy channel, or a channel that has incised into the valley floor, essentially acting as a confined channel. This allows for more potential variability in energy level for unconfined channels, such as those in the Front Range, which may explain a higher variability in OC stocks in that region compared the Cascades.

5. Conclusions

It is important to note that the conceptual model relies on data collected in areas other than my field sites and does not rigorously examine the carbon dynamics of each basin in a way that would produce a more definitive explanation for the similitude between the two regions. A more rigorous examination of the carbon dynamics of an entire headwater basin is needed to quantify the stability of carbon on the landscape and the partitioning of carbon between different transport modes (DOC vs. POC). Key data gaps that could be solved by such an examination include better constraining the ratio of DOC to POC in different parts of a basin, determining other landforms (such as colluvial hollows or alluvial fans) as being stable or unstable carbon reservoirs, and the distribution of soil moisture and texture throughout a basin. Notably, measuring all of the quantities mentioned in the conceptual model for a single basin would provide a more reliable understanding of carbon dynamics, as opposed to using regional estimates. However, I propose that a conceptual model such as this could be used to compare two distinct regions in terms of carbon dynamics.

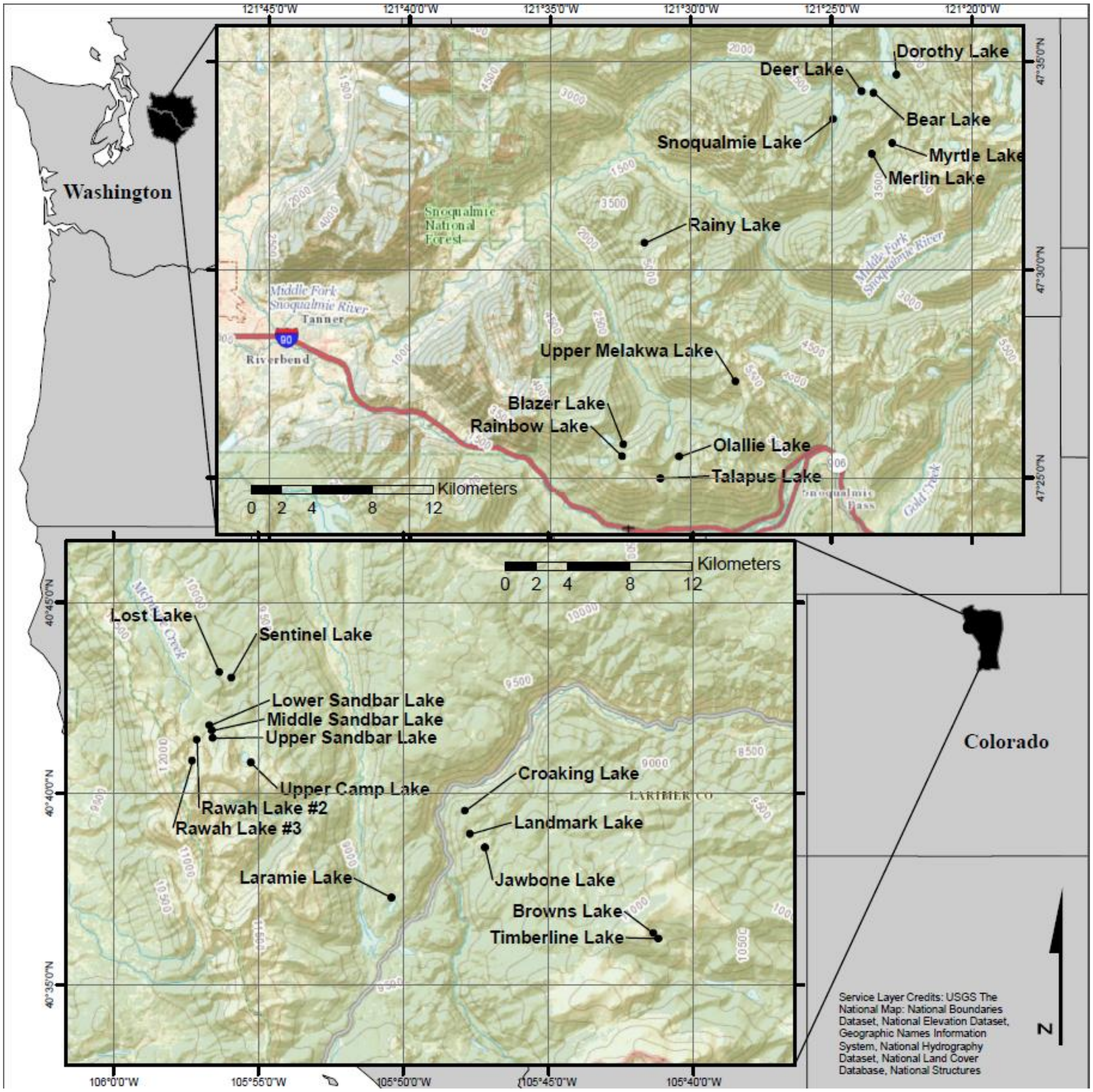
My thesis focused on OC storage in subalpine lake deltas and the comparison of two very different mountain ranges in terms of carbon dynamics. *H1* was unsupported by the quantification of the carbon stock in subalpine lake deltas: the Front Range and the Cascades store similar quantities of carbon in their subalpine lake deltas. *H2* was strongly supported by the census of lakes in each region: the Cascades have more lakes per unit area, but fewer lakes with deltas than the Front Range, although the total size of the subalpine lake delta carbon stock is similar between the two regions. *H3* was supported by the model of OC content in subalpine lake delta soils: OC content can be predicted accurately by moisture content and valley confinement.

H4 was supported by the comparison of texture groups by soil OC content: sandy soils contained significantly less OC than finer textured soils.

Because management of the natural world is becoming increasingly focused on mitigating climate change by preventing carbon release to the atmosphere, it is essential to have a broad understanding of where carbon is stored on the landscape, so that we can focus our efforts to make the most impact possible. Whereas previously, one might have expected that carbon reservoirs in the Cascades might matter more in terms of global climate, I show that at least one carbon reservoir does not follow the same pattern as the rest of the region. This illustrates the need for a more detailed look at carbon dynamics in mountainous regions, which are quickly being recognized as very complex and disproportionately important (relative to their total land area) carbon reactors.

Because carbon is relatively unstable in the high energy, frequently re-worked depositional areas of a basin, it is important to focus on parts of the basin that may store carbon over long time periods. I show that we cannot take a regional generalization of carbon stocks (e.g., that the Cascades contain more carbon per unit area than the Front Range) and apply that generalization to the parts of the landscape that may matter most in terms of affecting climate. We must examine mountain basins in a holistic manner in order to guide our management efforts. As such, future work should focus on basin-scale characterizations of carbon dynamics, including where carbon is stored on the landscape, the processes that control that storage, and the modes by which carbon is transported through the basin. This would facilitate better conceptual understanding of how carbon is distributed across the landscape and allow us to make a better prediction of where management efforts may be most effective.

Figures



Service Layer Credits: USGS The National Map: National Boundaries Dataset, National Elevation Dataset, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures

Figure 1: Map of field sites. Sampled deltas are marked and labeled.

Figure 2: Talapus Lake Delta. Shrubs tend to be ~2-4 m tall. Water depth in small pond is ~ 1m.

Figure 3: Rawah Lake #3 Delta. Note the author (small white dot near center of delta) for scale. Shrubs tend to be ~0.5-1.5 m high.

Figure 4: Google Earth image of the Merlin Lake Delta. Waypoints were placed along the margins of the delta that were difficult to identify using aerial imagery alone. The margins of the delta were traced in Google Earth to obtain a surface area for the delta (highlighted in red).

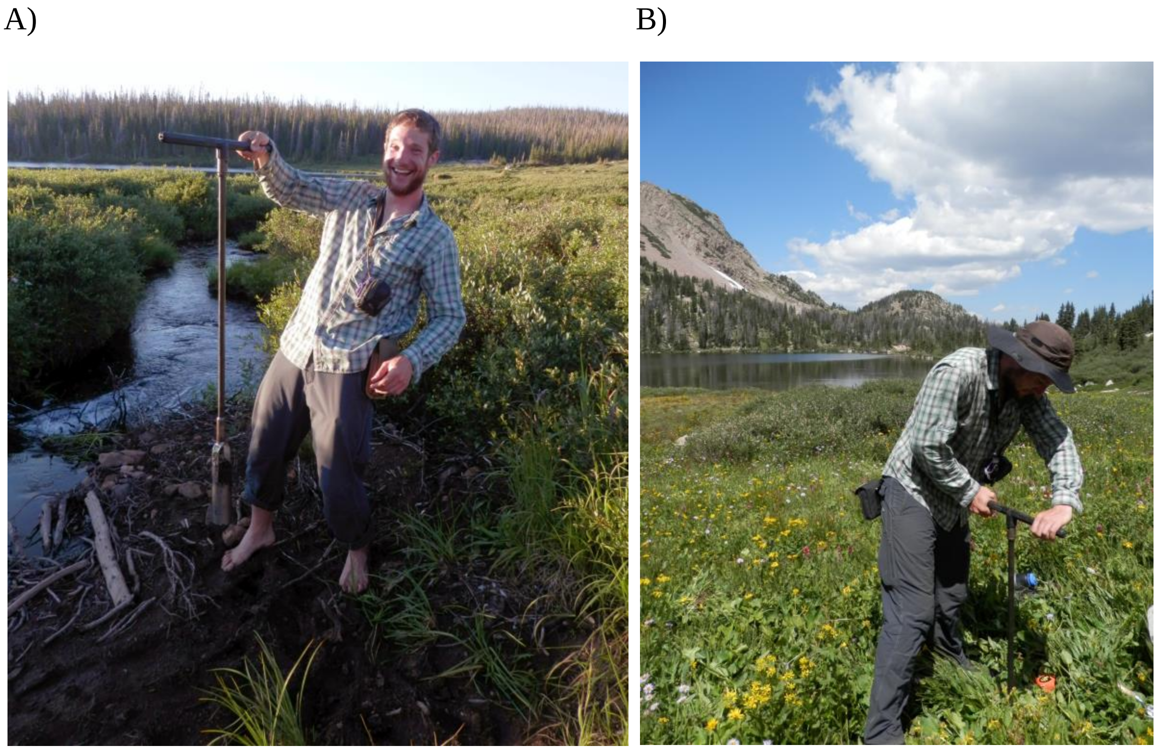


Figure 5: The author holding up an auger full of soil taken from a subalpine lake delta (A). The author coring a subalpine lake delta with an auger (B)

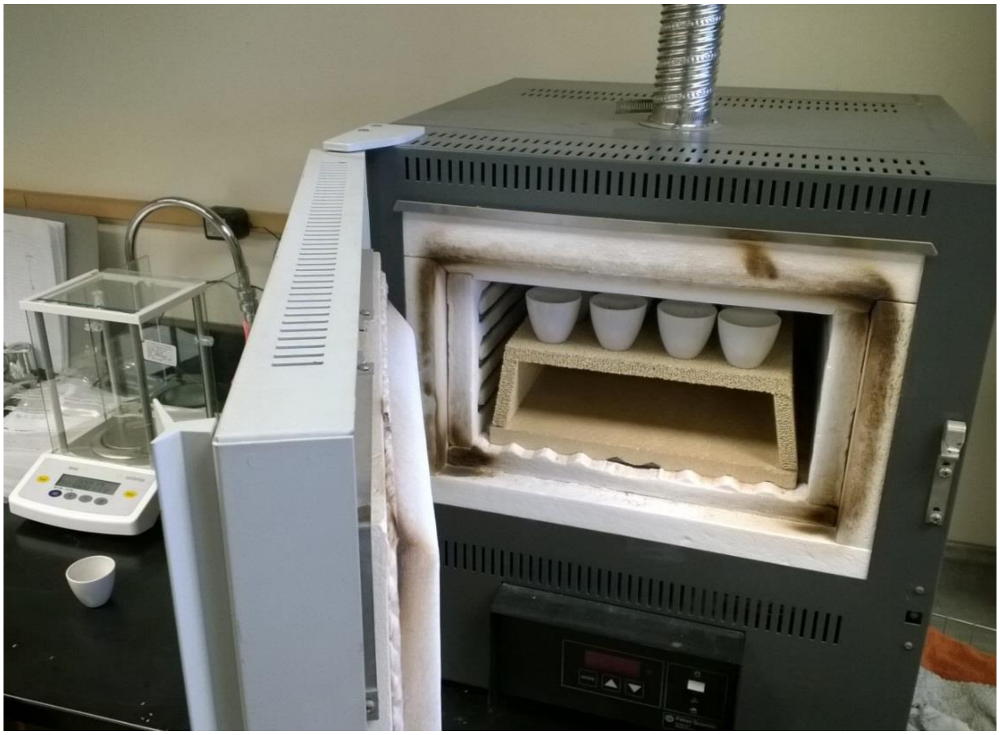


Figure 6: A muffle furnace filled with samples in crucibles.

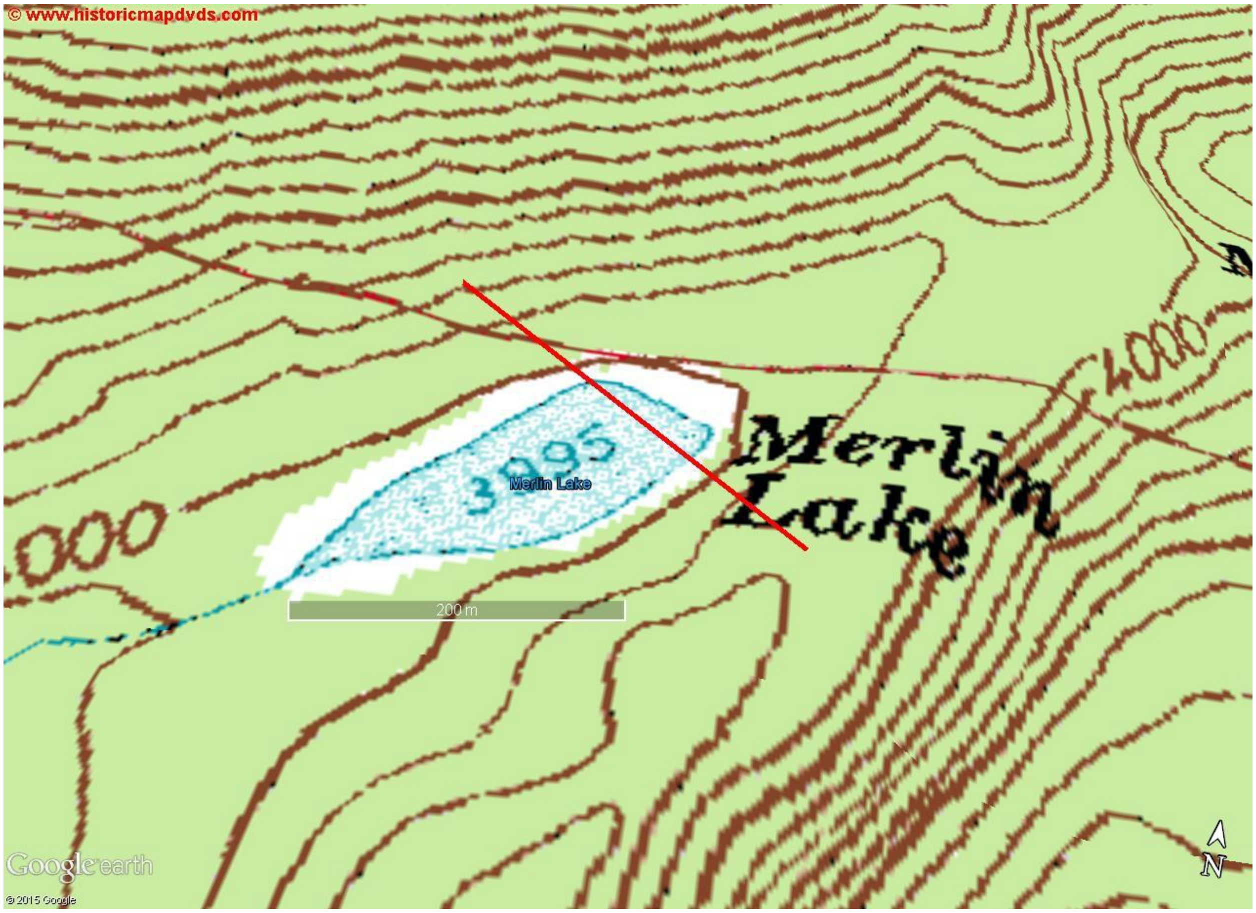


Figure 7: Google Earth image showing an example of a valley width measurement. USGS topographic map is overlaid to show topography. The red line delineates one measurement of valley width.

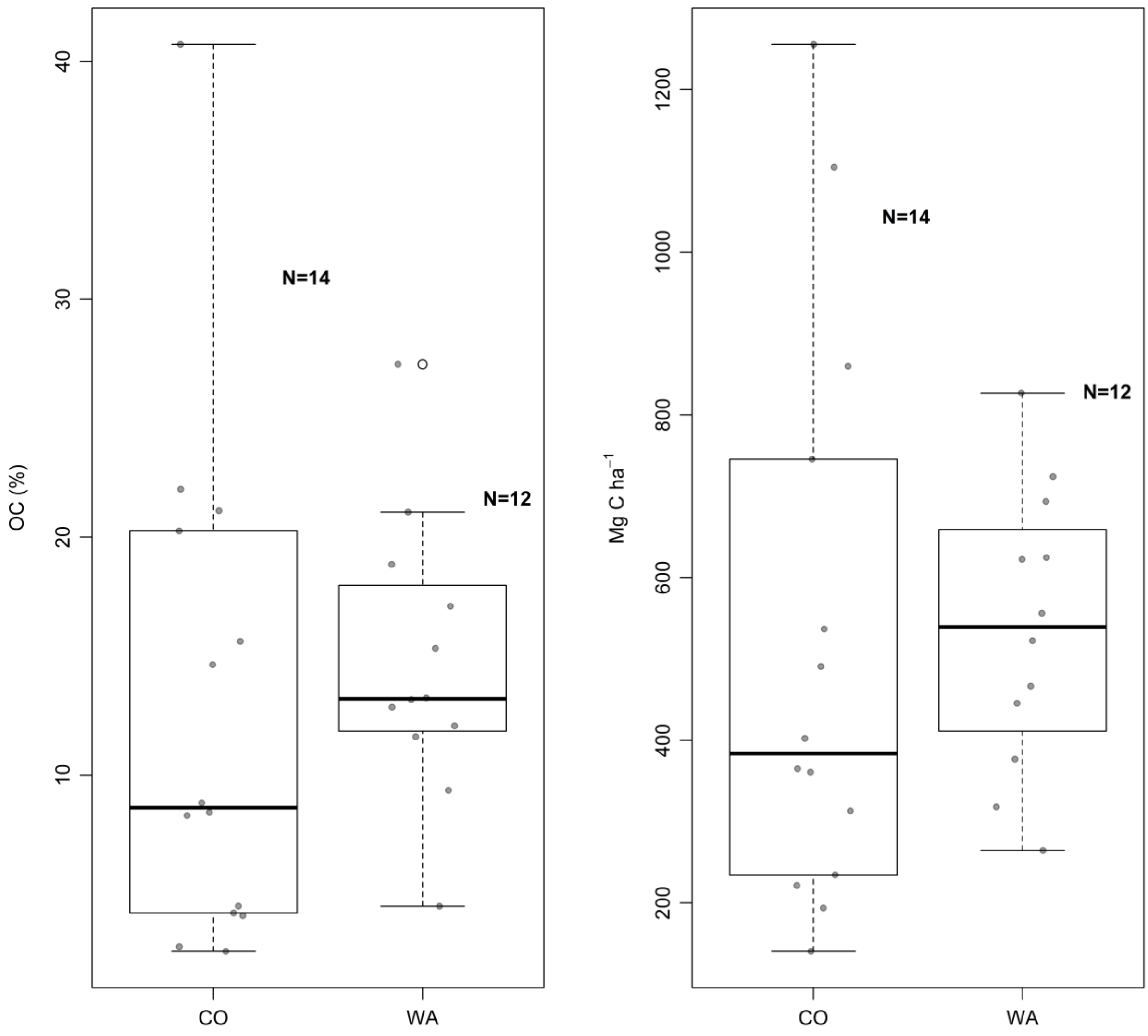


Figure 8: Box plots of OC content (%) and OC content per unit area (MgC ha^{-1}) for the Colorado Front Range (CO) and the Washington Central Cascades (WA). Data points are shown for each box plot along the Y axis. The whiskers indicate the minimum and maximum values of the dataset, excluding outliers. The ends of the boxes indicate the 25th (lower) and 75th (upper) percentiles of the dataset. The median is indicated by the bold line in the box. Outliers (circles) are values that do not fall within three times the interquartile range of the median. Sample size (N) is given for each box plot.

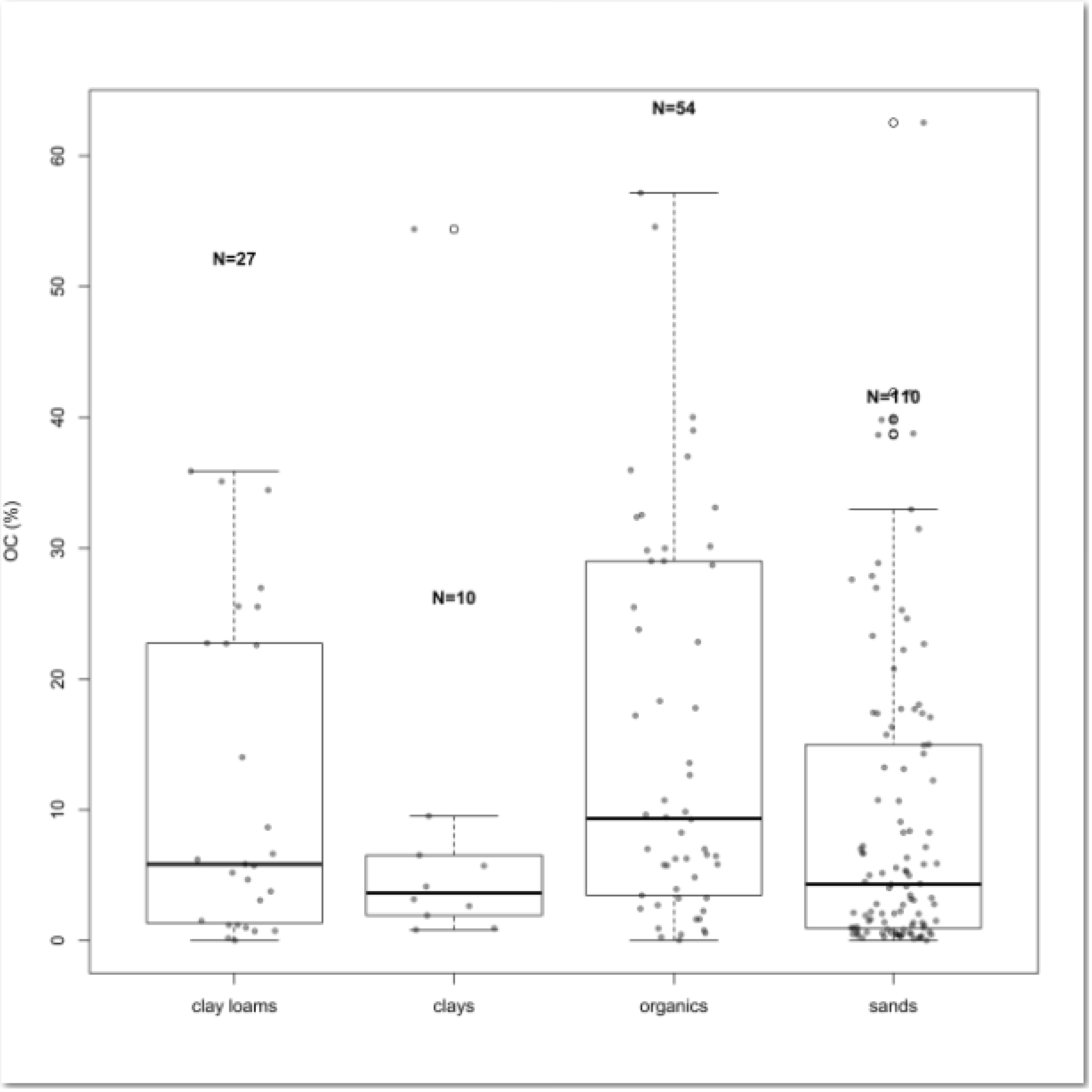


Figure 9: Box plots of OC content across texture groups for all subalpine lake delta soils sampled. Data points are shown for each box plot along the Y axis. Sample size (N) is given for each box plot.

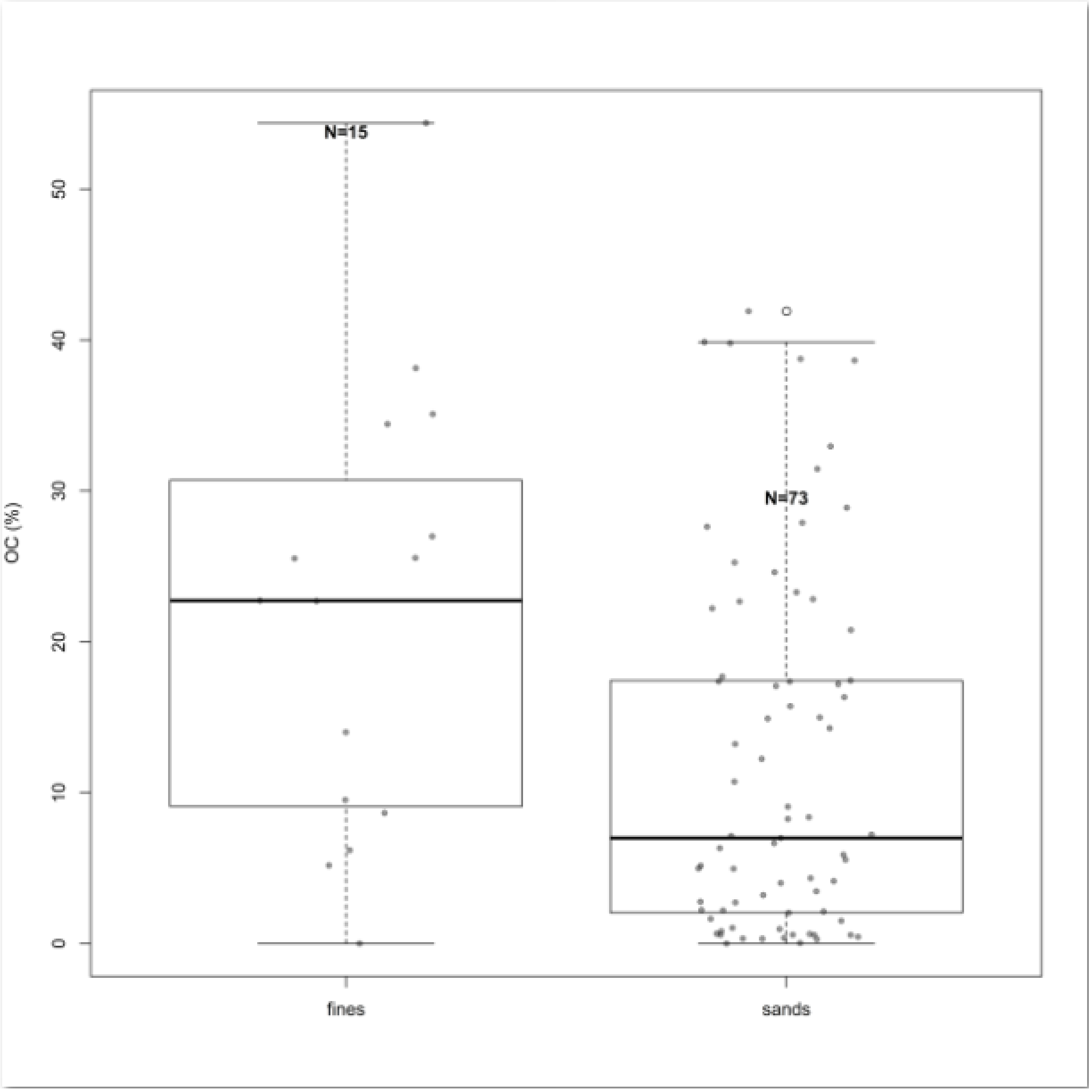


Figure 10: Box plot of OC content for fines (clay loams and clays) and sands for only samples burnt through loss-on-ignition. Data points are shown for each box plot along the Y axis. Sample size (N) is given for each box plot.

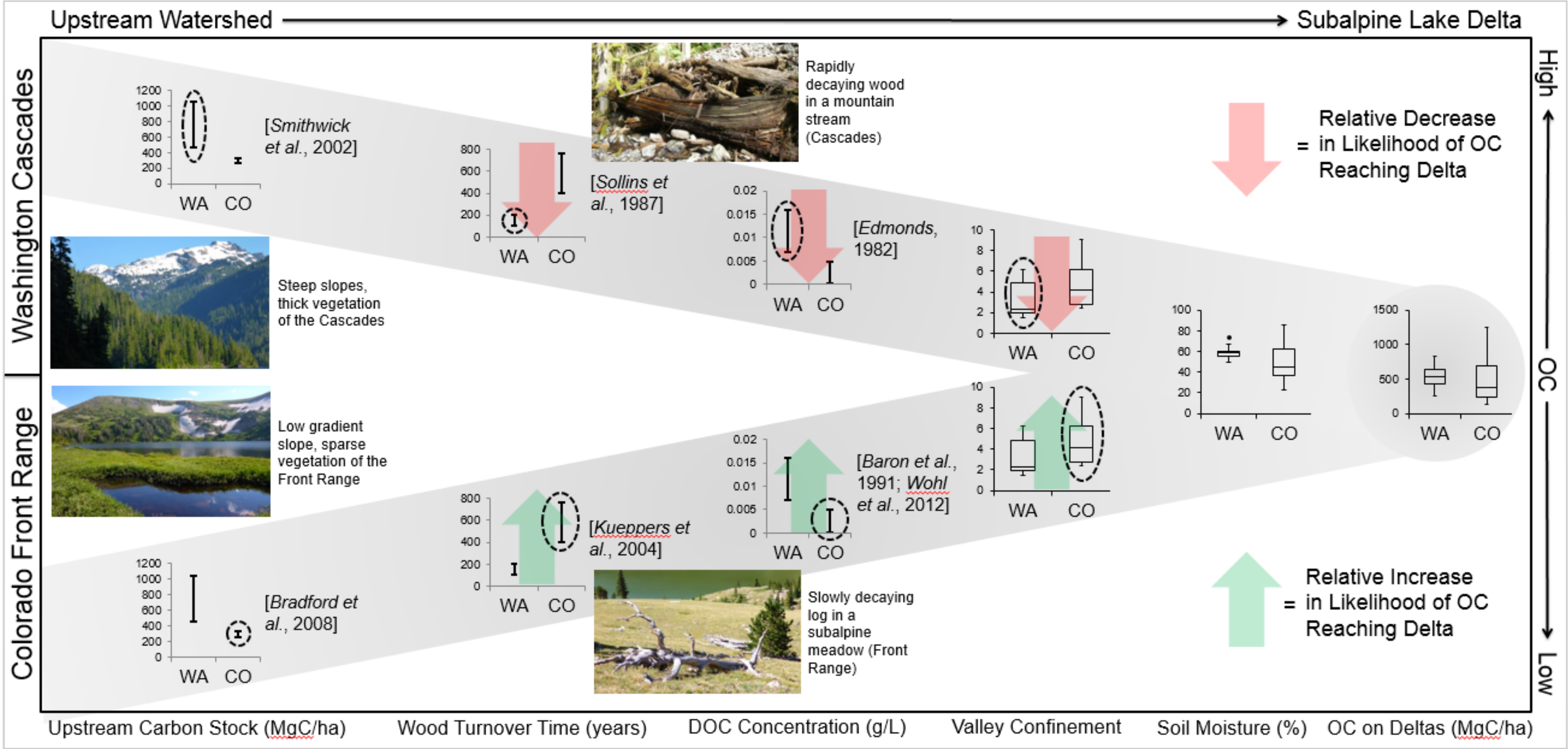


Figure 11: Conceptual model of carbon dynamics for the Washington Central Cascades (top branch) and Colorado Front Range (bottom branch). Each branch shows how the likelihood of OC reaching the delta changes from the upstream basin to the delta, and offers a potential qualitative explanation for how the two regions have similar magnitudes of OC storage on subalpine lake deltas. Each factor influencing the potential OC storage on a subalpine lake delta is shown on the bottom horizontal axis. The upstream carbon stock, wood turnover time, and DOC concentration for each region are shown by range plots. The valley confinement, soil moisture, and OC storage on subalpine lake deltas are shown as box plots, and come from data presented in this thesis. Arrows are shown on some plots to illustrate whether the process increases or decreases the likelihood of OC reaching the delta.

Tables

Table 1: Coefficient estimates, p values, and adjusted R^2 for the two best models. OC (%) is the response in each model. The estimated coefficient for each predictor (excluding the intercept) is the amount OC will increase for a unit increase in the predictor. The p values represent the probability that the estimated coefficient is not zero.

		Coefficient Estimate	***p***	***Adjusted R^2***
Model 1				0.79
	Intercept	-17.53	< 0.0001	
	Moisture	0.49	< 0.0001	
	Valley Confinement	1.24	0.004	
Model 2				0.80
	Intercept	-18.76	< 0.0001	
	Moisture	0.47	< 0.0001	
	Valley Confinement	1.22	0.004	
	Mean Basin Slope	0.07	0.19	

Table 2: Summary values of potential predictor and response variables for multiple linear regression model to predict OC content.

	OC (%)	***Drainage Area (ha)***	***Mean Basin Slope (%)***	***Moisture (%)***	***Valley Confinement***	***Aspect Category***	***Count***
Minimum	2.59	6.71	12.10	23.12	1.49	**E**	6
Median	13.01	97.12	35.60	56.91	3.52	**N**	10
Mean	13.63	154.96	38.53	53.29	4.06	**S**	6
Maximum	40.71	986.79	90.10	86.14	9.03	**W**	4

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Appendix A: Supplemental Data Tables

Table 1: Data collected for each subalpine lake delta studied.

Region	***Lake***	***Average OC (%)***	***Moisture (%)***	***Average OC (MgC/ha)***	***Delta Area (km^2)***	***TOC (Mg)***	***Drainage Area (km^2)***	***Mean Basin Slope (%)***
WA	Olallie Lake	15.32	52.78	826.85	0.5942	491.33	0.41	46.70
WA	Talapus Lake	9.35	54.13	556.15	3.9911	2219.64	2.10	54.90
WA	Rainy Lake	17.09	55.73	318.02	0.5250	166.96	0.60	59.10
WA	Snoqualmie Lake	18.85	63.00	693.54	1.3006	902.03	5.10	55.80
WA	Bear Lake	12.85	58.09	445.37	0.3425	152.54	1.11	42.80
WA	Deer Lake	12.07	60.38	522.34	0.1143	59.71	0.18	33.90
WA	Dorothy Lake	11.61	59.45	622.28	6.6076	4111.79	9.87	52.20
WA	Merlin Lake	13.17	59.69	466.51	0.3888	181.36	0.13	46.70
WA	Myrtle Lake	27.27	73.87	724.14	3.4259	2480.82	1.55	56.70
WA	Rainbow Lake	4.49	50.10	624.61	0.1040	64.96	0.18	25.10
WA	Blazer Lake	13.24	58.94	376.57	0.1110	41.78	0.10	31.50
WA	Upper Melakwa Lake	21.05	58.38	264.37	0.0856	22.64	0.83	90.10
	Median (WA):	*13.21*	*58.66*	*539.24*	*0.4569*	*174.16*	*0.71*	*49.45*
	Average (WA):	*14.70*	*58.71*	*536.73*	*1.4659*	*907.96*	*1.85*	*49.63*
CO	Croaking Lake	8.30	44.98	364.90	0.1328	48.46	0.28	26.40
CO	Landmark Lake	4.49	36.43	234.37	0.1207	28.29	0.14	16.10
CO	Jawbone Lake	21.10	74.80	859.92	1.4397	1238.01	0.28	25.90
CO	Sentinel Lake	40.71	86.14	1104.57	0.4447	491.16	0.18	31.90
CO	Browns Lake	4.08	50.31	221.33	0.0283	6.27	1.99	23.00
CO	Timberline Lake	2.59	25.86	360.73	0.1350	48.68	2.41	25.30

CO	Lost Lake	15.61	43.87	313.15	0.2195	56.45	0.07	38.80
CO	Laramie Lake	4.20	35.38	193.56	1.7812	344.77	1.14	12.10
CO	Middle Sandbar Lake	8.42	36.60	536.64	0.1382	74.14	1.99	29.60
CO	Upper Sandbar Lake	8.83	36.86	490.58	1.9883	975.42	1.76	30.60
CO	Lower Sandbar Lake	14.64	62.93	745.47	0.1006	74.99	2.12	28.70
CO	Upper Camp Lake	20.26	62.09	402.11	0.0489	19.67	0.09	37.30
CO	Rawah Lake #2	22.01	61.71	1255.60	0.9632	1209.40	3.81	41.10
CO	Rawah Lake #3	2.79	23.12	140.38	0.5342	74.99	1.84	39.40
	Median (CO):	*8.63*	*44.43*	*383.51*	*0.1788*	*74.57*	*1.45*	*29.15*
	Average (CO):	*12.72*	*48.65*	*511.95*	*0.5768*	*335.05*	*1.29*	*29.01*
	Median (All):	*13.01*	*56.91*	*478.54*	*0.37*	*113.77*	*0.97*	*35.60*
	Average (All):	*13.63*	*53.29*	*523.39*	*0.99*	*599.47*	*1.55*	*38.53*

Table 1 Continued

Region	***Lake***	***Delta Aspect***	***Valley Confinement Ratio***	***Delta Volume (m^3)***	***Latitude (degrees)***	***Longitude (degrees)***	***Elevation (m)***
WA	Olallie Lake	S	5.56	3317.68	47.4237	-121.5129	1155
WA	Talapus Lake	E	3.46	39911.12	47.4171	-121.5255	996
WA	Rainy Lake	W	6.18	2712.57	47.5113	-121.5372	1147
WA	Snoqualmie Lake	N	1.97	13006.18	47.5609	-121.4182	959
WA	Bear Lake	N	1.96	3805.61	47.5710	-121.3969	1100
WA	Deer Lake	W	1.96	825.60	47.5705	-121.3994	1092
WA	Dorothy Lake	N	1.49	95442.65	47.5768	-121.3812	932
WA	Merlin Lake	S	4.61	1511.82	47.5488	-121.3975	1218
WA	Myrtle Lake	S	2.48	11038.90	47.5529	-121.3855	1151
WA	Rainbow Lake	E	2.16	127.11	47.4268	-121.5431	1301

WA	Blazer Lake	E	2.13	283.55	47.4289	-121.5402	1240
WA	Upper Melakwa Lake	S	5.76	1027.69	47.4541	-121.4715	1375
	Median (WA):		*2.32*	*3015.13*			*1149*
	Average (WA):		*3.31*	*14417.54*			*1139*
CO	Croaking Lake	W	6.79	413.19	40.6578	-105.8028	2860
CO	Landmark Lake	E	4.04	402.38	40.6479	-105.8015	2951
CO	Jawbone Lake	N	2.38	4798.95	40.6466	-105.7921	2940
CO	Sentinel Lake	E	9.03	10869.49	40.7136	-105.9377	3136
CO	Browns Lake	S	2.56	66.11	40.6058	-105.6906	3211
CO	Timberline Lake	E	5.04	509.84	40.6040	-105.6870	3210
CO	Lost Lake	N	4.29	1902.60	40.7189	-105.9413	3095
CO	Laramie Lake	S	2.67	15832.82	40.6206	-105.8426	2843
CO	Middle Sandbar Lake	N	8.06	337.74	40.6943	-105.9478	3260
CO	Upper Sandbar Lake	N	2.43	14580.87	40.6913	-105.9486	3260
CO	Lower Sandbar Lake	N	5.67	391.22	40.6962	-105.9488	3252
CO	Upper Camp Lake	N	6.35	288.00	40.6817	-105.9238	3268
CO	Rawah Lake #2	N	3.04	9632.04	40.6921	-105.9548	3270
CO	Rawah Lake #3	W	3.57	10684.06	40.6827	-105.9610	3314
	Median (CO):		*4.17*	*1206.22*			*3210*
	Average (CO):		*4.71*	*5050.67*			*3134*
	Median (All):		*3.51*	*2307.58*			*2851*
	Average (All):		*4.06*	*9373.84*			*2213*

Table 2: Data organized by sample. Soil texture codes are as follows: sa (sand), ls (loamy sand), sal (sandy loam), sil (silty loam), l (loam), sacl (sandy clay loam), sicl (silty clay loam), cl (clay loam), sac (sandy clay), sic (silty clay), c (clay).

Lake Name	***Sample ID***	***Soil Texture***	***Moisture (%)***	***TOC (%)***	***Top Depth (cm)***	***Bottom Depth (cm)***	***Bulk Density (g/cm^3)***
Bear Lake	BeL1 0-27	ls	46.00	6.57	0	27	1.18
Bear Lake	BeL1 27-38	sacl	51.82	9.42	27	38	1.00
Bear Lake	BeL2 22-40	sacl	56.88	6.25	22	40	1.10
Bear Lake	BeL2 0-22	sacl	68.14	22.76	0	22	0.69
Bear Lake	BeL3 25-44	ls	64.95	5.78	25	44	1.22
Bear Lake	BeL3 44-54	sal	49.63	2.26	44	54	1.37
Bear Lake	BeL3 0-25	l	73.94	28.88	0	25	0.54
Blazer Lake	BL1 30-36	ls	60.19	10.72	30	36	1.03
Blazer Lake	BL1 0-30	sa	65.45	15.74	0	30	0.76
Blazer Lake	BL2 22-30	ls	62.67	9.62	22	30	1.06
Blazer Lake	BL2 0-22	sal	65.59	25.28	0	22	0.61
Blazer Lake	BL3 44-55	sal	59.61	3.08	44	55	1.32
Blazer Lake	BL3 55-66	ls	39.88	4.28	55	66	1.29
Blazer Lake	BL3 21-44	sa	50.11	7.14	21	44	1.09
Browns Lake	BrL1 18-40	sal	50.17	8.27	18	40	1.08
Browns Lake	BrL1 40-58	ls	34.97	4.01	40	58	1.30
Browns Lake	BrL1 0-18	ls	43.83	5.16	0	18	1.24
Browns Lake	BrL2 39-60	sa	37.20	3.47	39	60	1.30
Browns Lake	BrL2 60-77	sa	23.52	0.96	60	77	1.51
Browns Lake	BrL3 24-34	sal	77.59	17.38	24	34	0.80
Croaking Lake	CL1 25-39	c	33.99	4.13	25	39	1.17
Croaking Lake	CL1 9-25	c	47.52	9.52	9	25	1.00
Croaking Lake	CL3 22-35	sacl	48.08	3.75	22	35	1.18
Croaking Lake	CL3 0-22	sa	65.21	17.09	0	22	0.72
Croaking Lake	CL4 22-40	c	44.51	3.15	22	40	1.21

Croaking Lake	CL4 40-53	sic	38.75	2.64	40	53	1.23
Croaking Lake	CL4 53-68	sic	38.35	0.82	53	68	1.31
Croaking Lake	CL4 68-82	c	36.08	0.93	68	82	1.30
Croaking Lake	CL4 82-100	sacl	28.79	1.50	82	100	1.27
Croaking Lake	CL4 100-115	sacl	25.52	0.99	100	115	1.30
Croaking Lake	CL4 115-120	sacl	22.86	0.18	115	120	1.34
Croaking Lake	CL4 0-22	ls	65.50	32.95	0	22	0.48
Deer Lake	DL1 19-34	ls	51.65	1.62	19	34	1.45
Deer Lake	DL1 34-55	sil	50.99	1.13	34	55	1.40
Deer Lake	DL1 55-72	sil	48.45	0.19	55	72	1.47
Deer Lake	DL1 72-93	ls	44.95	2.43	72	93	1.39
Deer Lake	DL1 93-122	ls	45.15	0.12	93	122	1.60
Deer Lake	DL1 178-206	sal	28.13	0.04	178	206	1.55
Deer Lake	DL1 0-19	sal	63.46	17.44	0	19	0.80
Deer Lake	DL1 122-178	sal	24.02	0.00	122	178	1.59
Deer Lake	DL2 0-30	org	73.17	28.72	0	30	0.85
Deer Lake	DL3 24-44	sil	73.17	0.46	24	44	1.45
Deer Lake	DL3 44-56	sil	54.81	0.49	44	56	1.45
Deer Lake	DL3 56-109	l	48.45	0.44	56	109	1.44
Deer Lake	DL3 0-24	sil	77.09	22.69	0	24	0.67
Dorothy Lake	DoL1 20-39	sal	25.07	10.68	20	39	1.00
Dorothy Lake	DoL1 39-51	sal	61.61	8.26	39	51	1.08
Dorothy Lake	DoL1 51-61	sicl	58.33	3.07	51	61	1.21
Dorothy Lake	DoL1 0-20	sal	62.11	17.71	0	20	0.79
Dorothy Lake	DoL2 22-40	ls	53.14	13.12	22	40	0.95
Dorothy Lake	DoL2 40-60	sacl	57.81	4.66	40	60	1.15
Dorothy Lake	DoL2 60-75	cl	54.85	5.84	60	75	1.11
Dorothy Lake	DoL2 0-22	sacl	63.86	25.54	0	22	0.63
Dorothy Lake	DoL3 21-54	sal	69.16	17.21	21	54	0.80

Jawbone Lake	JL1 32-54	sicl	62.17	6.27	32	54	1.10
Jawbone Lake	JL1 54-85	sil	76.93	0.03	54	85	1.48
Jawbone Lake	JL1 0-32	sal	69.51	14.29	0	32	0.88
Jawbone Lake	JL2 75-91	sicl	77.21	22.60	75	91	0.69
Jawbone Lake	JL2 13-75	sicl	78.33	35.09	13	75	0.46
Jawbone Lake	JL3 40-62	sicl	68.14	9.85	40	62	0.99
Jawbone Lake	JL3 0-40	sil	86.05	38.64	0	40	0.35
Laramie Lake	LaL1 0-23	sal	49.95	4.84	0	23	1.23
Laramie Lake	LaL1 23-44	c	49.95	1.92	23	44	1.26
Laramie Lake	LaL1 44-53	sacl	34.25	0.74	44	53	1.31
Laramie Lake	LaL2 0-20	ls	25.93	4.98	0	20	1.25
Laramie Lake	LaL3 27-50	ls	29.91	0.25	27	50	1.59
Laramie Lake	LaL3 0-27	ls	41.08	8.38	0	27	1.11
Landmark Lake	LL1 20-44	c	35.40	5.71	20	44	1.12
Landmark Lake	LL1 0-20	ls	60.45	14.93	0	20	0.90
Landmark Lake	LL2 35-61	sacl	31.09	0.71	35	61	1.31
Landmark Lake	LL2 13-35	ls	37.09	4.97	13	35	1.27
Landmark Lake	LL3 0-20	sal	37.60	3.22	0	20	1.31
Landmark Lake	LL3 20-59	ls	16.97	0.58	20	59	1.55
Lost Lake	LoL1 0-23	sacl	49.80	6.20	0	23	1.10
Lost Lake	LoL2 40-70	sal	53.92	62.54	40	70	0.05
Lost Lake	LoL2 0-40	l	66.73	23.30	0	40	0.66
Lost Lake	LoL3 0-20	ls	25.97	0.92	0	20	1.51
Lost Lake	LoL3 20-39	ls	25.17	0.45	20	39	1.56
Lost Lake	LoL3 63-89	sa	18.04	0.29	63	89	1.62
Lost Lake	LoL3 89-103	sa	17.58	0.33	89	103	1.61
Lost Lake	LoL3 39-63	sa	20.68	0.65	39	63	1.55
Lower Sandbar Lake	LSL1 19-35	sal	78.27	0.84	19	35	1.47
Lower Sandbar Lake	LSL1 0-19	ls	41.68	6.66	0	19	1.18

Lower Sandbar Lake	LSL2 40-70	sal	31.59	17.79	40	70	0.79
Lower Sandbar Lake	LSL2 70-91	sal	77.28	13.58	70	91	0.90
Lower Sandbar Lake	LSL2 0-40	l	76.03	27.62	0	40	0.57
Lower Sandbar Lake	LSL3 40-59	ls	62.54	6.46	40	59	1.19
Lower Sandbar Lake	LSL3 0-40	l	71.82	24.63	0	40	0.63
Merlin Lake	MeL1 33-43	ls	58.05	29.84	33	43	0.54
Merlin Lake	MeL1 0-33	sacl	67.74	14.02	0	33	0.88
Merlin Lake	MeL2 20-43	sal	71.56	5.27	20	43	1.21
Merlin Lake	MeL2 43-58	sal	58.40	26.98	43	58	0.57
Merlin Lake	MeL2 0-20	l	69.20	20.79	0	20	0.72
Merlin Lake	MeL3 0-24	sa	49.79	5.57	0	24	1.17
Middle Sandbar Lake	MSL1 20-39	sal	18.08	3.26	20	39	1.31
Middle Sandbar Lake	MSL1 0-20	sal	46.22	10.74	0	20	0.99
Middle Sandbar Lake	MSL2 38-60	sal	36.55	3.25	38	60	1.31
Middle Sandbar Lake	MSL2 60-78	sa	36.60	0.19	60	78	1.64
Middle Sandbar Lake	MSL2 0-38	sal	56.11	17.38	0	38	0.80
Middle Sandbar Lake	MSL3 37-58	ls	19.88	2.07	37	58	1.42
Middle Sandbar Lake	MSL3 58-77	ls	24.93	0.35	58	77	1.57
Middle Sandbar Lake	MSL3 77-107	sal	28.18	1.36	77	107	1.43
Middle Sandbar Lake	MSL3 0-37	sal	65.22	22.84	0	37	0.66
Myrtle Lake	MyL1 30-58	l	69.55	17.72	30	58	0.79
Myrtle Lake	MyL1 0-30	sacl	74.99	38.13	0	30	0.41
Myrtle Lake	MyL2 20-37	sal	70.39	6.72	20	37	1.14
Myrtle Lake	MyL2 0-20	sal	56.38	9.08	0	20	1.05
Myrtle Lake	MyL3 0-21	org	85.97	54.57	0	21	0.50
Myrtle Lake	MyL3 21-50	ls	85.97	38.98	21	50	0.37
Olallie Lake	OL1 60-80	ls	74.10	5.83	60	80	1.21
Olallie Lake	OL1 80-97	sa	39.48	12.66	80	97	0.87
Olallie Lake	OL1 97-115	sa	62.28	2.71	97	115	1.35

Olallie Lake	OL1 0-60	sil	85.30	41.91	0	60	0.30
Olallie Lake	OL2 50-77	sal	49.05	7.01	50	77	1.13
Olallie Lake	OL2 77-126	ls	58.12	6.99	77	126	1.16
Olallie Lake	OL2 0-50	sal	76.12	39.87	0	50	0.32
Olallie Lake	OL3 38-63	sa	29.79	0.45	38	63	1.59
Olallie Lake	OL3 0-22	ls	37.90	1.64	0	22	1.45
Olallie Lake	OL3 24-38	sa	30.97	0.57	24	38	1.57
Olallie Lake	OL3 63-82	sa	29.12	0.37	63	82	1.60
Rawah #2	R2L1 0-53	org	84.20	29.03	0	53	0.84
Rawah #2	R2L1 53-92	ls	77.00	33.08	53	92	0.48
Rawah #2	R2L1 92-114	ls	76.66	29.02	92	114	0.56
Rawah #2	R2L2 38-80	sal	64.56	25.49	38	80	0.60
Rawah #2	R2L2 0-38	cl	79.80	34.42	0	38	0.48
Rawah #2	R2L3 25-38	ls	24.60	0.57	25	38	1.55
Rawah #2	R2L3 0-25	sacl	42.75	8.66	0	25	1.02
Rawah #3	R3L1 0-27	sal	24.29	2.78	0	27	1.33
Rawah #3	R3L1 27-51	ls	23.10	2.13	27	51	1.41
Rawah #3	R3L2 0-30	sal	28.77	1.91	0	30	1.39
Rawah #3	R3L2 30-50	ls	20.11	1.51	30	50	1.46
Rawah #3	R3L3 0-24	sal	21.22	4.14	0	24	1.26
Rainbow Lake	RaL1 63-154	ls	70.98	3.46	63	154	1.33
Rainbow Lake	RAL1 36-63	sa	45.95	5.89	36	63	1.15
Rainbow Lake	RaL2 56-70	sa	42.73	0.60	56	70	1.56
Rainbow Lake	RaL2 70-81	ls	44.09	1.36	70	81	1.47
Rainbow Lake	RAL2 26-56	sa	47.84	2.73	26	56	1.35
Rainbow Lake	RaL3 78-107	ls	55.53	18.04	78	107	0.81
Rainbow Lake	RaL3 136-162	sa	33.34	1.05	136	162	1.50
Rainbow Lake	RaL3 129-136	sa	31.03	0.63	129	136	1.56
Rainbow Lake	RaL3 107-129	sa	40.43	2.23	107	129	1.39

Rainbow Lake	RaL3 39-78	sal	74.34	22.23	39	78	0.68
Rainy Lake	RL1 22-45	ls	71.38	57.16	22	45	0.07
Rainy Lake	RL1 0-22	sicl	69.27	26.98	0	22	0.61
Rainy Lake	RL2 23-50	sal	62.22	18.31	23	50	0.77
Rainy Lake	RL3 0-24	sa	32.21	2.05	0	24	1.40
Rainy Lake	RL3 50-65	sa	37.07	2.20	50	65	1.39
Sentinel Lake	SL2 35-55	ls	87.42	32.52	35	55	0.49
Sentinel Lake	SL2 55-75	ls	80.97	32.36	55	75	0.49
Sentinel Lake	SL2 75-95	ls	86.01	36.99	75	95	0.40
Sentinel Lake	SL2 95-115	ls	84.22	35.96	95	115	0.42
Sentinel Lake	SL2 115-135	ls	86.34	40.00	115	135	0.35
Sentinel Lake	SL2 135-165	ls	80.35	30.14	135	165	0.54
Sentinel Lake	SL3 0-22	sic	88.06	54.39	0	22	0.17
Snoqualmie Lake	SnL1 30-45	ls	58.01	8.26	30	45	1.11
Snoqualmie Lake	SnL1 45-68	sal	38.63	3.93	45	68	1.27
Snoqualmie Lake	SnL1 0-30	sacl	70.96	22.72	0	30	0.69
Snoqualmie Lake	SnL2 45-67	sal	72.10	23.79	45	67	0.64
Snoqualmie Lake	SnL2 0-45	sil	83.23	38.75	0	45	0.35
Snoqualmie Lake	SnL3 28-43	sal	47.08	4.49	28	43	1.24
Snoqualmie Lake	SnL3 0-28	sal	63.87	12.25	0	28	0.95
Timberline Lake	TiL1 32-45	sacl	49.50	5.74	32	45	1.11
Timberline Lake	TiL1 45-82	l	35.98	1.49	45	82	1.37
Timberline Lake	TiL1 82-115	sacl	40.04	1.19	82	115	1.29
Timberline Lake	TiL1 115-154	c	29.92	6.53	115	154	1.09
Timberline Lake	TiL1 0-32	l	48.72	6.33	0	32	1.14
Timberline Lake	TiL2 0-21	sacl	23.32	0.00	0	21	1.46
Timberline Lake	TiL2 36-44	sa	16.43	0.57	36	44	1.57
Timberline Lake	TiL2 21-36	ls	15.35	0.32	21	36	1.58
Timberline Lake	TiL3 0-29	ls	17.23	0.77	0	29	1.53

Timberline Lake	TiL3 44-70	sacl	20.10	6.63	44	70	1.09
Timberline Lake	TiL3 70-88	sacl	20.16	5.73	70	88	1.12
Timberline Lake	TiL3 29-44	ls	16.00	0.57	29	44	1.55
Talapus Lake	TL1 0-38	sal	63.57	5.83	0	38	1.18
Talapus Lake	TL1 38-52	sa	51.52	3.20	38	52	1.31
Talapus Lake	TL1 52-68	sa	48.92	2.80	52	68	1.34
Talapus Lake	TL1 68-87	sa	55.62	1.63	68	87	1.44
Talapus Lake	TL1 87-108	sa	35.37	0.83	87	108	1.53
Talapus Lake	TL1 108-140	sa	46.99	1.17	108	140	1.49
Talapus Lake	TL1 140-170	sa	45.51	0.96	140	170	1.51
Talapus Lake	TL2 22-45	ls	45.42	2.06	22	45	1.42
Talapus Lake	TL2 45-65	l	48.93	5.33	45	65	1.18
Talapus Lake	TL2 0-22	ls	49.78	7.23	0	22	1.15
Talapus Lake	TL3 30-58	ls	49.42	9.26	30	58	1.08
Talapus Lake	TL3 0-30	l	79.97	31.45	0	30	0.49
Upper Camp Lake	UCL1 0-37	cl	73.03	25.57	0	37	0.63
Upper Camp Lake	UCL2 0-22	ls	59.51	13.24	0	22	0.95
Upper Camp Lake	UCL2 22-42	sa	20.90	0.82	22	42	1.53
Upper Camp Lake	UCL3 0-20	sal	73.03	27.88	0	20	0.55
Upper Melakwa Lake	UML1 0-20	sal	86.86	39.80	0	20	0.32
Upper Melakwa Lake	UML2 0-15	ls	34.02	7.01	0	15	1.16
Upper Melakwa Lake	UML3 0-31	sal	54.25	16.34	0	31	0.83
Upper Sandbar Lake	USL1 24-45	sal	33.38	1.40	24	45	1.43
Upper Sandbar Lake	USL1 45-66	sal	26.51	0.48	45	66	1.50
Upper Sandbar Lake	USL1 66-82	sal	23.02	0.26	66	82	1.53
Upper Sandbar Lake	USL1 0-24	sal	30.14	4.34	0	24	1.25
Upper Sandbar Lake	USL2 39-59	sacl	33.37	1.19	39	59	1.29
Upper Sandbar Lake	USL2 59-77	sal	31.47	0.49	59	77	1.50
Upper Sandbar Lake	USL2 0-39	cl	41.82	5.19	0	39	1.13

Upper Sandbar Lake	USL3 39-70	ls	29.85	30.00	39	70	0.54
Upper Sandbar Lake	USL3 0-39	sal	63.68	15.00	0	39	0.86

Appendix B: Field Site Descriptions

1. Washington Central Cascades

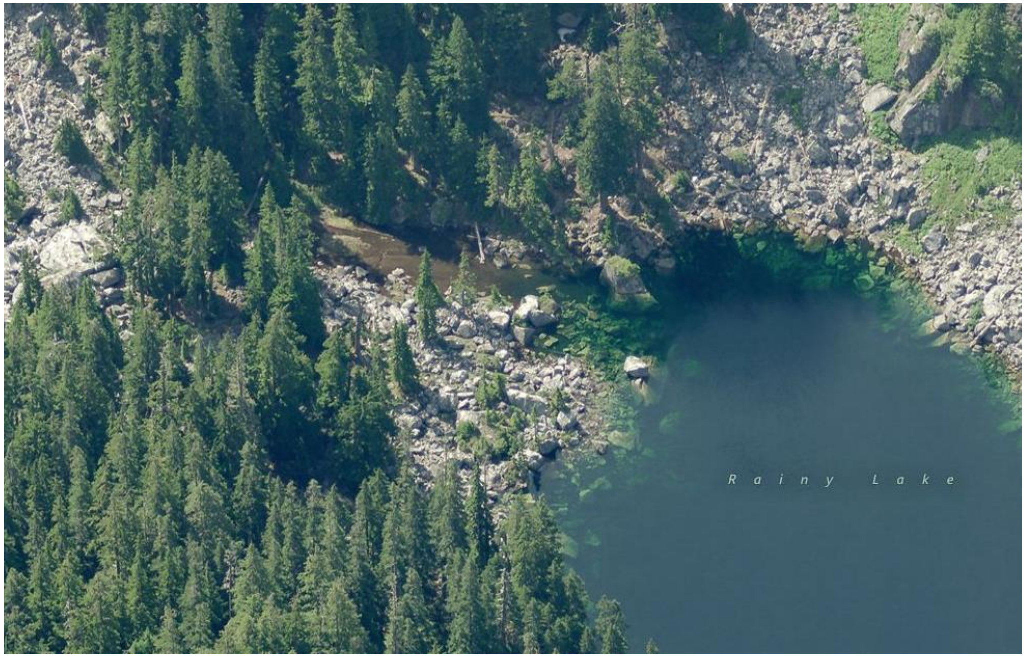
1.1 Olallie Lake Delta

The Olallie Lake delta is dominantly forested, with a small grassy portion at the edge of the lake. The inlet channel is deeply incised and appears to be stabilized by large trees on its banks. The delta slopes gently downward as it enters the lake, exhibiting a long, grassy shelf that terminates in a steep drop. The delta is surrounded by steep, forested hillside. The pictures above show the mouth of the delta. Notice the large, decaying log in the right photograph.

1.2 Talapus Lake Delta

The Talapus Lake Delta is densely vegetated, with patches of mature to old-growth forest and broad areas of dense shrubs. Some parts of the delta are so densely vegetated that they are very difficult to navigate. I often found myself walking on shrubs ~1-1.5 m off the ground, suspended over a pond or a small channel and unable to move forward. There are large areas of standing water on the delta, some of which appear to be caused by beaver dams. Behind beaver dams, I often found thick deposits of wood chips comprising the bottom of the ponds. The delta is surrounded by steep, forested hillside and talus slopes. The left picture above shows the density of vegetation and a channel on the delta. Notice the old-growth cedar in the left portion of the photograph. The right picture above is taken from a talus slope above the delta.

1.3 Rainy Lake Delta



The Rainy Lake delta is surrounded on its south side by a large, granite cliff. On the east side, a talus slope drains into the delta. On the north side, there is a steep, forested gulley. The delta is a mixture of very large boulders (on the scale of 2 to 15 m in diameter) and muddy grassy, flat regions, with only a few conifers and very sparse shrubs on the delta itself. The inlet channel is confined to the river left (south) side of the delta by the large boulders on the delta, and becomes very wide before entering the lake. The delta does not extend very far into the lake, and the lake-bottom topography drops off suddenly at the end of the delta. Large boulders, however, extend above the surface of the water further into the lake than the delta extends. The aerial photograph (taken from Bing Maps) shows the delta and the talus slopes surrounding it.

1.4 Snoqualmie Lake Delta

The Snoqualmie Lake delta vegetation is comprised of mostly grasses and short shrubs (the shrubs on the island in the center-right of the above photograph are ~ 1-1.5 m tall). There are thick forests with mature conifers on the margins of the delta. The inlet channel is cascading, but becomes multi-thread as it enters the delta, producing very wide, very deep channels running across the delta. The banks of these channels are very unstable. The subaerial portion of the delta extends very far into the lake and I could not sample most of the delta (either because it was in one of the channels, which were too deep to stand in, or because it would need to be accessed by swimming through such a channel). The picture on the left shows one of the large channels on the delta, as well as shrubs on a mid-channel bar. The aerial photograph (taken from Bing Maps) on the right shows the delta in its entirety. Note the very deep, multi-thread channel.

1.5 Bear Lake Delta

The Bear Lake delta is dominantly covered by short grasses or small shrubs, with coniferous forests on its margins. The inlet channel is very small, but there are a few small springs on the delta itself, indicating that it is at least partially groundwater fed. At the time of fieldwork (7/10/2014), the entire delta was saturated (stepping on the surface of the delta caused water to drain to the surface). There were a few boulders (on the scale of 0.1 to 2 m in diameter) scattered across the delta. The picture looks downstream from the head of the delta with a person for scale.

1.6 Deer Lake Delta

The Deer Lake delta is dominantly forested with small conifers and shrubs, with patches of mature conifers, and mature conifer forest around its margins. The inlet channel above the delta first runs through a fen with a small pond, then becomes slightly steeper and cascading before reaching the delta. Upon reaching the delta it branches into two channels separated by a mid-channel bar before reaching the lake. The portion of the delta bordering the lake is vegetated with grass and mosses. The pictures above show the delta near the lake.

1.7 Dorothy Lake Delta

Dorothy Lake is the largest of the lakes in this study, and has the largest delta. The delta is approximately half comprised of dense, mature conifer forest (near the inlet), and grassy wetland with patches of conifer (near the lake). The delta grades into a large island that was not counted as part of the delta itself because it appears to be a bedrock outcrop and hence an erosional landform. The inlet is cascading as it enters the delta, then becomes multi-thread as it crosses the delta. The channels on the delta are dominantly very wide and not as deep as those seen on the Snoqualmie Lake Delta. Large wood is abundant on the delta, but evidence of beaver activity was not observed. The two top picture show the portion of the delta nearest the lake. The aerial photograph (taken from Bing Maps) shows the extent of the delta. The delta itself begins just downstream of where the inlet becomes visible in the picture.

1.8 Merlin Lake Delta

The Merlin Lake Delta is grassy with small shrubs and conifers in patches across the delta. The inlet is a step-pool to cascade channel that runs through multiple small fens before reaching the delta, at which point it meanders to the lake. This delta is unique in that it sits atop a pressurized aquifer. Upon coring through the top 20-40 cm of the delta, I reached a large void space with a depth of approximately 20-60 cm. At the base of the void space, my auger was stopped by large wood. Upon removing the auger bucket, the surface of the delta immediately began sinking and water gushed out of the auger hole, indicating pressure beneath the surface of the delta. The two pictures above show the delta from near its head (left) to its mouth (right).

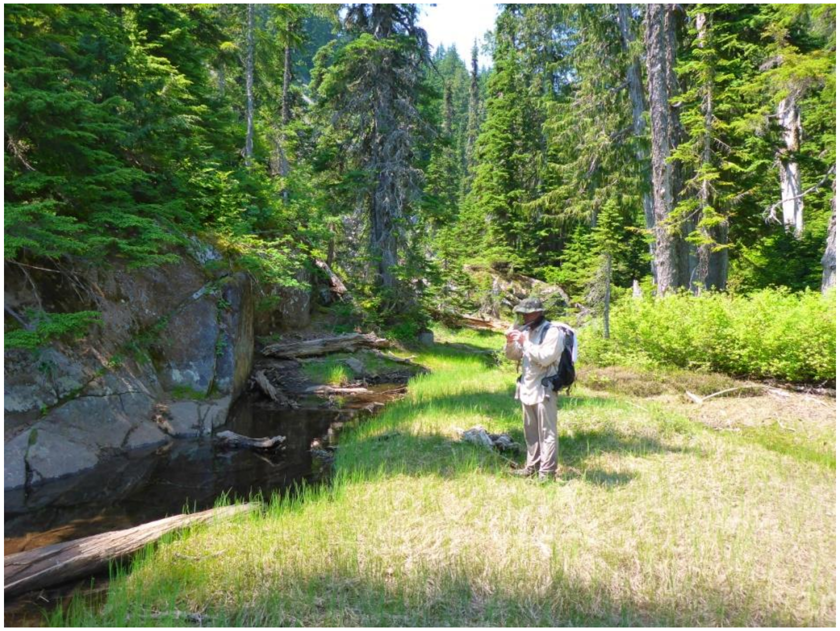
1.9 Myrtle Lake Delta

The Myrtle Lake delta has large patches of mature conifer, shrubs, or grass covering the delta. The inlet channel is steep as it enters the delta, then meanders across the delta to the lake, eventually becoming quite deep (over 2 m) as it nears the lake. There are a few large mounds on the delta with large boulders exposed. The valley surrounding the delta has numerous cliffs and large waterfalls draining into the inlet channel. At the lake, the delta drops off steeply in some places to reach the water surface. The picture on the left shows part of the delta near its mouth and the large inlet channel nearing the lake. The picture on the right shows the upper portion of the delta.

1.10 Rainbow Lake Delta

The Rainbow Lake Delta is confined by a steep, forested hill on its south side, and a talus slope on its north side. The surface of the delta is dominantly vegetated by grasses and a few conifer trees. The inlet is a cascade channel that remains dominantly straight until it reaches the lake The delta slopes gently downward into the lake. The delta is at least partially comprised of large wood and/or boulders. In one instance, I augered through approximately 20 cm of mostly small wood pieces and soil to reach a void space filled with water that was on the order of 50-80 cm deep.The picture on the left shows the head of the delta. The picture on the right shows the talus next to the delta as well as the portion of the delta that extends into the lake.

1.11 Blazer Lake Delta



The Blazer Lake Delta is confined near its head by a steep bedrock wall on its south side and a steep, forested hill on its north side, then quickly spreads out as it nears the lake. The vegetation on the delta itself is almost exclusively comprised of grasses, although there are densely vegetated conifer forests along the delta margins. The inlet channel is steep and cascading as it comes into the delta, then meanders (but remains dominantly straight) through the delta to the lake. There is an abundance of downed wood on the delta, although no signs of beaver activity were observed. The picture on the left shows the inlet channel looking downstream from the head of the delta (person for scale). The picture on the right shows the upper portion of the delta looking upstream (person for scale).

1.12 Upper Melakwa Lake Delta

Upper Melakwa Lake is the highest elevation lake examined in the Washington Central Cascades. It is near treeline, and the forests above the delta are patchy and dispersed through the basin. The delta is surrounded by active talus below massive granite walls that overshadow the delta. The vegetation on the delta is comprised of small shrubs and grasses. The talus slopes feeding the delta deposit boulders across the delta surface. The delta drops off approximately 10-30 cm where it reaches the lake. The picture on the left shows the lower portion of the delta and part of the lake. The picture on the right shows the head of the delta and the upstream basin.

2. Colorado Front Range

2.1 Croaking Lake Delta

The vegetation on the Croaking Lake Delta is comprised of conifer and aspen trees, with groundcover of grasses and moss. The part of the delta nearest the lake is hummocky. The hummocks are interspersed by low-lying regions of grasses. The inlet is low gradient, exhibiting a step-pool morphology upstream of the delta. It meanders slightly across the delta before reaching the lake. The valley walls on either side of the delta are forested with aspen and conifer. Chewed logs imply the past presence of beaver around the lake. The picture on the left shows the delta near the lake and the hummocky topography. The picture on the right shows the upper portion of the delta and inlet channel, taken from the head of the delta looking downstream. Croaking Lake was named by the author.

2.2 Landmark Lake Delta

The Landmark Lake Delta is confined on the west side by a steep, forested hill, and is dominantly unconfined on its right side. The inlet is low gradient, and drains directly into standing water on the delta. The delta begins at the inlet covered by sparse conifer trees, small shrubs, and grasses. Most of the delta is covered only by grasses and downed wood. The grassy area of the delta (near the lake) is hummocky. The outlet of the lake is dammed by at least 3 relict beaver dams. The picture on the left shows the delta looking downstream from its head. The picture on the right shows two beaver-chewed stumps and a relict beaver dam on the outlet of the lake. Landmark Lake was named by the author

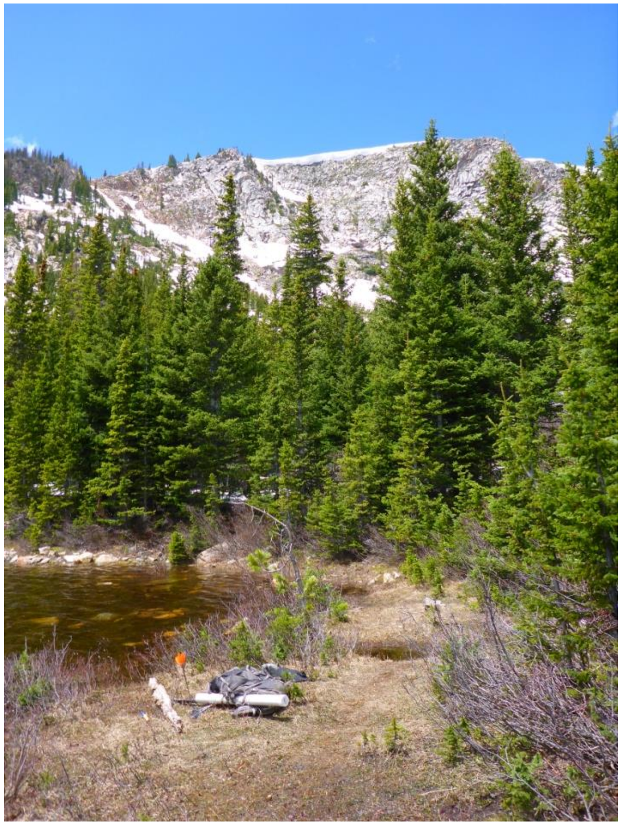
2.2 Jawbone Lake Delta

The Jawbone Lake Delta is very broad and dominantly vegetated by grasses. Near the lake, parts of the delta flex under body weight, indicating that the mouth of the delta may be a floating vegetation mat. The inlet channel is low gradient and slightly stepped as it reaches the delta, then meanders across the delta slightly to the lake. It is very incised on the delta (deeper than wide). The lake is dammed by at least two relict beaver dams on the outlet. The picture on the left shows the lower portion of the delta and part of the lake. The picture on the right is taken looking at the delta from the hill seen on the left side of the left picture. Notice that the picture on the right was taken during snowmelt and that the delta is flooded. Jawbone lake was named by the author.

2.3 Sentinel Lake Delta

The Sentinel Lake Delta is perched approximately .3 to 1 m above the lake. The inlet channel was difficult to identify due to the presence of snow on the delta at the time of data collection (6/17/2014). The delta has sparse conifers distributed nearly evenly across it, with groundcover of grass and few small shrubs. The delta appears to be groundwater fed, although the presence of melting snow obscured that observation during data collection. The delta is very unconfined, with the surrounding topography being of low relief, with the exception of a ridge to the west. The picture on the left looks downstream from near the head of the delta. The picture looks down on the delta from the ridge above it. Sentinel lake was named by the author.

2.4 Browns Lake Delta



The Browns Lake delta is very short (along the axis roughly parallel to the valley) but wide relative to its length. It is mostly covered by dense vegetation such as conifer trees and 1-2 m tall shrubs. The inlet is high gradient and cascading, remaining straight as it runs through the delta to the lake. There are some boulders on the delta surface, and a small, secondary inlet drains into the delta that appears to be groundwater fed. The delta is confined on the west side by a steep hillside that grades into a cliff, and on the east side by a lower gradient, forested slope. The pictures above show the delta as it reaches the lake. Notice the headwall above the lake in the right picture.

2.5 Timberline Lake Delta

The Timberline Lake Delta is located a few tens of meters downstream of Browns Lake. The inlet is cascading and moderately high-gradient, and remains straight as it runs through the delta to the lake. Similar to the Browns Lake Delta, this delta is very short and wide. The head of the delta is covered by short but dense conifers. The vegetation grades towards the lake from conifers to 1-2 m tall, woody shrubs, to grasses as the delta gently grades into the lake. There are a few small boulders on the delta. The pictures above show the portion of the delta nearest the lake.

2.6 Lost Lake Delta

The Lost Lake Delta is mostly covered by grasses and short conifers, although patchy coniferous forests are present near the margins of the delta. The delta is very steep. The inlet channel is cascade to step-pool as it enters the delta, and slowly lowers in gradient as it progresses down the delta to the lake. Downed logs are present across much of the delta. On all sides, the delta is surrounded by steep, densely forested hillsides. The panoramic picture above shows the delta, from just below the head to the lake.

2.7 Laramie Lake Delta

Laramie Lake is the only human-influenced lake in this study. I was unable to locate records of exactly what was done to the lake, but a human-made earthen dam at the outlet of the lake was evident. That dam had been breached by the current outlet channel, which had subsequently been dammed by beaver. The delta is very broad and covered by mostly long grasses. It is slightly hummocky, and has a very incised channel meandering across it. There is some exposed bedrock on the delta. There is a dirt road that intersects with the delta along one of its margins. The delta is surrounded by conifer forest. The left picture above shows the delta as it meets the lake. The picture on the right shows the upper portion of the delta, looking upstream.

2.8 Middle Sandbar Lake

Middle Sandbar Lake lies between Upper and Lower Sandbar Lakes. The inlet is a step-pool channel that begins to meander as it runs across the delta and exhibits mid-channel bars in some areas. The vegetation on the delta is mainly grasses and small shrubs, although there are some patches of small conifer. There are some boulders on the delta, and there are what appear to be small, unvegetated glacial deposits in the proximity of the delta. The panoramic picture above shows most of the delta, taken from the head of the delta.

2.9 Upper Sandbar Lake

Upper Sandbar Lake is located approximately 100 m upstream of Middle Sandbar Lake. The delta is vegetated by mostly tall grasses and dense shrubs, with a single patch of conifers at the head of the delta. The inlet meanders slightly through the delta, but is very incised. I observed breached beaver dams in the inlet, containing beaver-chewed sticks. The west side of the delta is confined by a short, rocky wall comprised of mostly boulders. The east side of the delta is a gently sloping, forested hillslope. The picture on the left shows the delta, taken from the west shore of the lake early in the morning. The picture on the right shows the inlet channel and head of the delta, looking upstream.

2.10 Lower Sandbar Lake

Lower Sandbar Lake is approximately 170 m downstream of Middle Sandbar Lake. The delta is confined by moderately steep, forested hillsides. The inlet channel runs along the left margin of the delta, and is not very incised, remaining of cascade morphology until just before it enters the lake. There is a massive boulder on the right side of the delta. The delta is mostly covered by grasses, with the exception of a few small patches of small conifers. The delta slopes upward near its head, and appears to be groundwater fed from the adjacent hillslope on its right (east) side. The panoramic picture above shows most of the delta, with the lake on the right side of the picture, taken from atop the aforementioned massive boulder.

2.11 Upper Camp Lake

The Upper Camp Lake Delta is dominantly covered by grasses and short shrubs, but is surrounded by conifer forest on its sides. The inlet is very small, cascading, and boulder-bedded as it enters the delta, at which time it becomes very confined and meanders slightly to reach the lake. The mouth of the delta drops off into the lake and is comprised of boulders. The picture on the left looks from the middle of the delta at the upstream basin. The picture on the right shows the mouth of the delta with two people for scale.

2.12 Rawah Lake #2 Delta

The Rawah Lake #2 Delta is longer than it is wide, with the entire delta and lake being in a long, straight valley. The vegetation is dominantly grasses and shrubs with a few patches of conifers. At the time of data collection (8/12/2014), the entire delta was saturated (water drained from the surface under body weight), and it appeared to be fed by groundwater draining from its east valley wall. The inlet is step-pool to cascade as it reaches the delta, then becomes slightly incised and meandering across the delta. The mouth of the delta gently grades to the water surface. The picture on the left looks downstream from the middle of the delta towards the lake. The picture on the right looks upstream and shows two people collecting a soil sample.

2.13 Rawah Lake #3 Delta

Rawah Lake #3 is the highest elevation lake studied in the Colorado Front Range. The inlet as it approaches the delta is very high gradient and cascade morphology. It transitions to step-pool morphology as it crosses the delta and meanders slightly. There is also a noticeable groundwater spring feeding the delta on its east side. The vegetation is dominated by grasses and small shrubs, with a single patch of conifer on the west side of the delta near its mouth. The delta drops off shortly before reaching the lake. The picture on the left is taken from above the delta looking downstream (north) at the lake with a person for scale. The picture on the right looks downstream from the east side of the delta, showing the lake and part of the groundwater spring.

Appendix C: Relationship between Outlet Incision and Delta Height of Subalpine Lakes

I originally hypothesized that changes in the height of the subaerial portion of a subalpine lake delta should be determined by changes in the lake level, which would in turn be controlled by the incision of the lake outlet following deglaciation. I hypothesized that as the lake outlet incises, lake level would drop, which would then allow for the exposure of a low-gradient, depositional area at the head of the lake on which a delta may form. I was motivated to examine this hypothesis because I seek a simple way of understanding how lake basins develop over the course of the development of a mountain range. I would like to better understand how sediment retention in headwaters (which is strongly tied to how much sediment can be stored in lakes and lake deltas) changes as the landscape evolves through glacial cycles. This appendix will detail my method for testing this hypothesis and attempt to explain its failures.

I attempted to test this hypothesis by testing for a correlation between the height of a subalpine lake's delta and the depth to which the lake's outlet had incised after deglaciation. I made all measurements using a laser rangefinder. First, I sought to determine a common datum from which I could measure delta height and outlet incision. I used the water surface of the lake as this datum, as it stretches between the delta and the outlet, and it maintains a level elevation from which to measure. To measure delta height in the context of testing this hypothesis, I measured the vertical distance from the water surface of the lake to the head of the delta. Identifying the delta head is generally straightforward, as the highest point on a delta is usually where the inlet channel meets the delta surface. I planned to identify a near-horizontal, relict surface on the valley walls adjacent to the lake outlet as the lake level at the time of deglaciation. I would then measure the vertical distance from that surface to the lake water level to determine the depth of incision of the outlet since deglaciation. With a measurement of outlet incision depth and delta height, I could then test my hypothesis.

My method was confounded by my inability to reliably identify the lake level at the time of deglaciation. Many lakes had no such relict surface, or had many such surfaces. This made it very difficult to obtain a measurement of outlet incision.

My hypothesis could have been confounded by low-gradient, depositional area existing above the lake level at the time of deglaciation, making the height of the delta greater than the lake outlet incision. Alternatively, if the head of the lake was very steep, lake level could conceivably drop and not expose any low-gradient surface on which a delta could form. In this scenario, the delta, if it formed at all, would have a height less than the incision of the outlet.