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Evaluating carbon storage on subalpine lake deltas

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ABSTRACT: 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. We quantified OC storage in subalpine lake deltas in the Washington Central Cascades and Colorado Front Range with the objectives of determining the magnitude of transient carbon storage and understanding the differences in storage between the two ranges. We used field, laboratory, and GIS techniques to determine the magnitude of and controls on the subalpine lake delta OC pool in 26 subalpine lake deltas. Soil moisture, soil texture, mean basin slope, and delta valley confinement are significantly correlated with soil carbon on deltas. Average soil OC concentration on subalpine lake deltas ranges from 3 to 41%, and stocks range from 140 to 1256 Mg C/ha. Surprisingly, the carbon content of subalpine lake deltas is not significantly different between the two regions, despite stark contrasts in their climate, vegetation, and total ecosystem carbon stocks. We present a conceptual model that invokes geomorphic and biogeochemical processes to suggest that carbon is more likely to reach subalpine lake deltas from the upstream basin in the Colorado Front Range compared with the Washington Central Cascades, thus accounting for the similarity in OC storage between the two regions despite differences in total ecosystem carbon stocks and climate. This points to a complex interaction among carbon production, transport, and stability in each region, and supports the idea that geomorphic and biogeochemical processes determine the magnitude of transient OC storage more strongly than primary productivity or climate. Copyright © 2017 John Wiley & Sons, Ltd.

KEYWORDS: organic; carbon; subalpine; delta; storage

Introduction

Terrestrial organic carbon (OC) entering freshwaters is either transported to the oceans, stored in sediment or living tissue, or respired to the atmosphere, where it may act as a greenhouse gas, affecting global climate (Houghton, 2007; Aufdenkampe *et al.,* 2011). Fluvial systems act as carbon reactors that store, process, and emit OC (Butman *et al.,* 2016; Hotchkiss *et al.,* 2015; Sutfin *et al.,* 2015). Recent management paradigms and conceptual models of CO_2 emissions from rivers highlight the need for a better understanding of where OC is located on the landscape in order to better constrain potential carbon emissions from fluvial systems (US Forest Service, 2012; Hotchkiss *et al.,* 2015). Modeling of the global carbon cycle relies on an understanding of the distribution of carbon on the landscape and the processes that control carbon storage and processing. Unfortunately, such modeling is highly uncertain, potentially due to its reliance on broad-scale climatic variables to explain carbon distributions (Doetterl *et al.,* 2015). Recent investigations of the controls on soil OC storage indicate that local soil and geomorphic factors may play a stronger role than climatic factors in determining the magnitude of OC storage in terrestrial and riverine environments (Doetterl *et al.,* 2015; Sutfin, 2016). Correspondingly, Galy *et al.* (2015) have recently identified erosion as more dominant than climatic variation or primary production in determining carbon export from the land. This motivates our investigation of whether climatic and ecosystem-scale variation between regions is more important than local geomorphic processes in controlling OC storage.

Mountainous regions in the western USA exhibit high gross primary productivity (Schimel *et al.,* 2002). Rivers in these regions receive OC from the input of detrital organic matter, wood, and fossil-derived kerogen (Sutfin *et al.,* 2015). 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 sediment yield (Leithold *et al.,* 2006). This means that mountain rivers have the potential to act as neutral pipes for carbon (Schlesinger and Melack, 1981), transporting carbon through the headwaters to lower in the basin without significantly processing or storing that carbon. However, recent work has shown that mountain river basins are indeed not neutral pipes, but actually store, transport, and emit carbon in different parts of the network (Sutfin *et al.,* 2015).

Recent work has also suggested the importance of small, depositional components of the fluvial network in acting as temporary storage zones for OC on timescales of 10^1–10^3 years (Wohl *et al.,* 2012; Sutfin, 2016). Such temporary storage zones are disproportionately important to the fluvial carbon reactor because they have the potential to release large quantities of stored OC either to the atmosphere or downstream if disturbed (Sutfin *et al.,* 2015).

We focus on subalpine lake deltas as a riparian wetland environment that may store high concentrations of OC and as a previously unrecognized component of OC storage near the head of river networks in mountainous regions where gross primary productivity and terrestrial input of OC to rivers are maximized (Schimel and Braswell, 2005; Hotchkiss *et al.,* 2015). We present an examination of these deltas to determine their OC content and the geomorphic controls on that OC content.

Subalpine lake deltas form at the heads of subalpine lakes, likely as Gilbert-type deltas (Smith and Jol, 1997). However, unlike lake deltas lower in the river network, subalpine lake deltas are typically confined by their valley walls to varying degrees, forming riparian wetland complexes, commonly with multiple channels. Deltas observed in this study display similar forms to low-gradient headwater floodplains, with single or multi-thread meandering channels. Subalpine lake deltas may be the first components in a mountain river network that effectively trap fine sediment and segment a river network (Arp *et al.,* 2007; Carvalho and Schulte, 2013). They commonly form the first low gradient, depositional wetlands in headwater catchments. Thus, they likely integrate OC production, transport, and storage in headwater basins and may have a significant impact on OC dynamics downstream. This allows us to use subalpine lake deltas as representatives of basin-scale carbon dynamics and investigate the variation in those carbon dynamics.

As potential depositional sites high in river basins, subalpine lake deltas probably play an important role in ecosystem processing of nutrients, including organic matter and OC (Sutfin *et al.,* 2015) and may be one of the first major reactive sites for OC in riverine systems. Although OC storage in subalpine lake deltas is likely transient, such short-term storage that interrupts the continuum of downstream OC transport and processing in a basin can have important effects on microbiology and the behavior, age, and signature of OC lower in the basin. OC storage zones act as metabolically reactive hotspots that support microbial growth and, as potential OC storage hot spots relative to uplands, they may encourage microbial diversity (Battin *et al.,* 2008). Studies of the fate of OC transported through riverine landscapes highlight the impact of riverine processing and storage of OC on the age, chemical signature, and behavior of that OC lower in the basin as well as in oceanic environments (Blair and Leithold, 2014; Leithold *et al.,* 2015). No studies have yet determined whether subalpine lake deltas are capable of storing elevated amounts of OC relative to the upland landscape. We provide such a characterization to motivate future examinations of the role of these landforms in determining the biogeochemistry of riverine systems.

Similarly to other montane wetlands, subalpine lake deltas may be capable of storing OC for time spans of 10^2–10^3 years or longer (Chimner and Karberg, 2008; Norton *et al.,* 2014). We examine OC storage in subalpine lake deltas of the Washington Central Cascades and the Colorado Front Range (hereafter referred to as the Cascades and Front Range, respectively) to compare OC dynamics between two regions with differing tectonic history, climate, and biota (the Cascades being more tectonically active, wetter, and exhibiting different and denser vegetation than the Front Range). This provides a robust characterization of the role of subalpine lake deltas in transient OC storage in riverine landscapes and allows for a comparison of that role between two very disparate environments.

OC storage in soil is controlled by a balance of stabilizing processes that reduce microbial respiration and increase adsorption of OC to mineral soil and destabilizing processes that prevent adsorption and increase respiration (Pinay *et al.,* 1992; Jobbágy and Jackson, 2000; Doetterl *et al.,* 2015). OC storage is generally maximized in wetter, colder environments with higher net primary production and resulting higher total ecosystem carbon stocks (Howard and Howard, 1993; Yuste *et al.,* 2007; Appling *et al.,* 2014; Sutfin *et al.,* 2015). We hypothesize that the differences in environmental conditions between the Cascades and the Front Range will be reflected in the OC content of their subalpine lake deltas: deltas in the Cascades are expected to have higher concentrations of OC than those in the Front Range due to a wetter climate, higher primary productivity, and higher total ecosystem carbon stocks (Smithwick *et al.,* 2002; Bradford *et al.,* 2008; Sutfin *et al.,* 2015). However, we hypothesize that subalpine lake deltas will be strongly enriched in OC compared with their surrounding uplands in both environments, giving them the potential to act as OC reactive zones.

Field areas

To test our hypothesis, we examined carbon storage in subalpine lake deltas of the Front Range and Cascades (Figure 1). The Cascades are wetter (2.54 m mean annual precipitation), warmer (mean of 36.3 days entirely below freezing annually) (Western Regional Climate Center, 2009), and have a higher exhumation rate (0.33 m yr^{-1}) (Reiners *et al.,* 2003) and steeper, more confined topography. The Front Range is drier (1.13 m mean annual precipitation), slightly colder (mean of 50 days entirely below freezing annually) (Natural Resources Conservation Service, 2015), and has a much lower exhumation rate (0.026 m yr^{-1}) (Garber, 2013), with lower gradient, less confined subalpine valleys. Vegetation tends to be much more expansive and denser in the Cascades (subalpine live biomass estimates range from 278 to 528 Mg/ha) (Gholz, 1982) than the Front Range (subalpine live biomass estimates range from 202 to 321 Mg/ha) (Bradford *et al.,* 2008). The lithology of the Cascades consists of dominantly granitic rocks (Frizzell *et al.*, 1993; Tabor *et al.,* 2000) producing very little carbon from bedrock. Similarly, the lithology in the Front Range consists of gneiss, schist, and migmatite (Braddock and Cole, 1978), none of which produce significant amounts of carbon when weathered.

Deltas in these areas are characterized by a complex patchwork of vegetation, ranging from sedges and grasses to mature

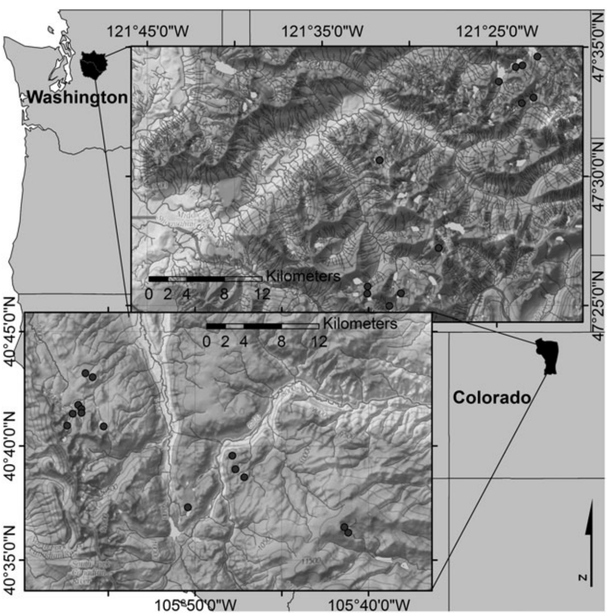

Figure 1. Map of study areas in Colorado and Washington. Insets focus on the portion of the study areas containing field sites. Studied subalpine lake deltas are represented by dark gray dots.

forests (Figures 2 and 3). We observed many relatively immobile features on deltas, such as bedrock outcrops, hard-points created by large conifers, and large boulders that increase the complexity of the delta by preventing soil deposition in certain areas and altering the course of channels on the deltas. Deltas also exhibited features normally associated with meandering rivers such as recently vegetated point bars and abandoned channels. This suggests a gradual deposition of sediment across the delta surface due to the migration of channels and overbank flows, similar to a low-gradient floodplain surface. Vegetation succession on newly formed surfaces likely provides inputs of OC from autochthonous production on the delta, in addition to the OC delivered in sediments from upstream. These two sources of OC supply the total OC storage of subalpine lake deltas.

Methods

We define a subalpine lake delta as the low-gradient, vegetated surface at the head of a subalpine lake. We characterized carbon storage on subalpine lake deltas by sampling 14 deltas in the Front Range and 12 deltas in the Cascades. We used visual aerial imagery analysis to select deltas that would be sufficiently large to likely have soil development and would be reasonably accessible. Although subalpine lake deltas may form similarly to Gilbert-type deltas (Smith and Jol, 1997), we observed substantial complexity in the study deltas in the form of bedrock islands and uneven valley walls. Thus, we concluded that there was too much spatial heterogeneity at the surface of the delta to justify any assumptions regarding the subsurface stratigraphy of the delta. Therefore, we used a random sampling method to select three coring locations on each delta. At each location, we used a soil auger to retrieve a soil core from the surface to the depth of refusal (material impenetrable by the auger, usually cobbles or bedrock) in approximately 30 cm depth increments. Samples were sealed in bags and stored in a cooler or freezer until laboratory analysis.

Each soil sample was tested using either loss-on-ignition (relative standard deviation of estimates up to 10%; LOI) (De Vos *et al.,* 2005b) or a CHN furnace (relative standard deviation of estimates up to 5%) (Sparks, 1996; J. Self, Colorado State University, pers. comm., 2016) for OC concentration and moisture. To convert from LOI mass to OC concentration, we used a texture-based linear regression with a non-zero intercept as suggested by De Vos *et al.* (2005b, Table VII); texture was obtained through a texture-by-feel technique (Thien, 1979). Because samples were collected in a disturbed fashion from the soil auger, we were unable to directly measure bulk density in the field. We used a regression calibrated on forest soils based on soil organic matter content to estimate bulk density for each sample (De Vos *et al.,* 2005a). This regression likely underestimates actual bulk density (De Vos *et al.,* 2005a), providing a conservative estimate on the actual OC stock for each sample. OC values for entire cores and for whole deltas were calculated using depth-weighted averages of OC concentration or stock.

To determine the volume of soil in each delta, we modeled deltas as tilted cones, using the surface area of the delta (calculated in Google Earth using delta-margin coordinates mapped with a GPS) and the height of the delta (measured with a laser rangefinder in the field). The tilted cone model, while likely approximating the general shape of a Gilbert-type delta in a small lake (Smith and Jol, 1997), does not take into account any large-scale undulations in bed topography beneath the delta, or changes in the shape of the downstream side of the delta that may occur due to long-timescale fluctuations in lake level or upstream delivery of sediment. We also

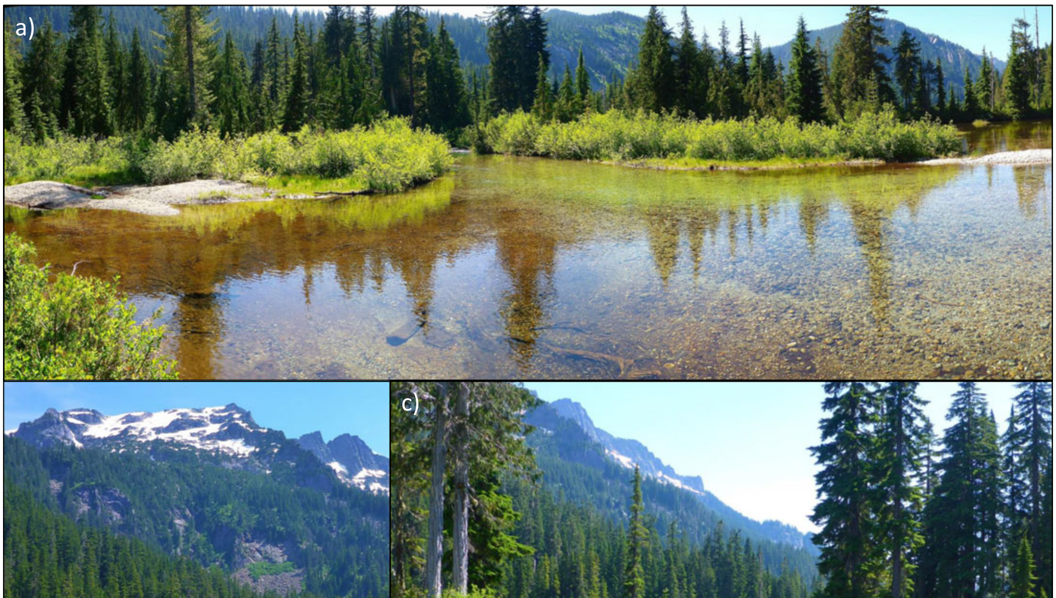

Figure 2. Subalpine lake deltas in the Central Cascades, WA. (a) Dorothy Lake delta. Notice variation in vegetation, newly created surfaces (gravel), and a heterogeneous mix of forest canopy height. (b) and (c) Myrtle Lake delta. Notice the high relief of the surrounding landscape, the patchiness of vegetation, and the conifer hard-points that create complexity on the delta. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 3. Subalpine Lake Deltas in the Front Range, CO. (a) Upper Sandbar Lake delta, looking upstream from across the lake. Notice the low relief landscape surrounding the delta. (b) Upper Sandbar Lake delta, looking upstream from the middle of the delta. Notice the meandering channel, patchy vegetation, and variable forest canopy height. Lines show approximate location of (b) within frame of (a). [Colour figure can be viewed at wileyonlinelibrary.com]

measured valley confinement around each delta: the ratio of the width of the valley around the delta to the width of the delta. Higher values of this ratio indicate a less confined valley. Using Google Earth, we measured the dominant aspect of each delta and assigned a cardinal direction. Using USGS StreamStats, we measured the mean basin slope and drainage area above each delta (United States Geological Survey, 2012).

To characterize the size of the subalpine lake delta OC sink in each region, we performed a census of subalpine lake and delta abundance using Google Earth and USGS topographic maps. We limited our census in the Cascades to the Snoqualmie and Skykomish watersheds, which exhibit similarly high exhumation rate (Reiners *et al.,* 2003), similar topographic variation compared with basins farther north or south in the range (Mitchell *et al.,* 2009), and similar climate. We limited our census in the Front Range to the east flank of the range in order to minimize variability in post-glacial topography (Anderson *et al.,* 2006) and climate.

To evaluate trends in OC by depth, we first grouped all samples from all deltas in each region and normalized the average depth of each sample by the total depth of the core to which that sample belongs. This allowed for an evaluation of trends in OC concentration (% OC) and stock (Mg C/ha) with normalized depth. Cores with only one sample were excluded from this analysis. This resulted in one delta (Upper Melakwa Lake in the Cascades) being entirely excluded from this analysis, due to all three of the cores taken from that delta being comprised of only one sample. We performed a Spearman correlation test on these samples normalized by depth for each region to test for the presence of a significant monotonic trend in OC with depth. We also grouped both regions and analyzed trends in depth by delta, using a depth-weighted average of the topsoil and buried (all samples below the topmost sample in each core) samples separately for each delta. Comparing the topsoil and buried samples allows for a comparison of soil layers that are probably currently being affected by modern processes (topsoil samples) and those that are buried and are probably less affected by modern OC deposition (buried samples). We compared the OC concentration and stock in both topsoil samples and buried samples between regions, as well as between topsoil samples and buried samples across both regions.

Statistical analyses were performed using the R statistical package (R Core Team, 2015). All reported statistics use a 95% confidence level, and all uncertainties reported represent the corresponding 95% confidence interval (CI). We utilized all subsets multiple linear regression modeling and the corrected Akaike Information Criterion (AICc) to perform model selection (Wagenmakers and Farrell, 2004) to examine aspect, mean basin slope, drainage area, valley confinement, and soil moisture as potential predictors of OC storage on subalpine lake deltas. To satisfy the assumptions of multiple linear regression, we square root transformed the response variable (OC content), then back transformed after a best model was selected in order to interpret the model. Because of the categorical nature of our soil texture measurements, we grouped samples into sands (including sands, loamy sands, sandy loams, loams, and silt loams) and fines (sandy clay loams, silty clay loams, clay loams, sandy clays, silty clays, and clays), then used a Kruskal-Wallis Rank Sum test (Kruskal and Wallis, 1952) to compare the OC concentration between sands and fines. We performed comparisons between each study region in terms of OC stock and concentration, as well as comparisons to evaluate trends with depth, using a t-test when sample distributions were normal and a Kruskal–Wallis Rank Sum test when sample distributions were non-normal (Kruskal and Wallis, 1952).

Results and discussion

Estimating subalpine lake delta organic carbon stocks

Subalpine lake deltas in the Cascades exhibit a median carbon concentration and stock of 13.2% and 539 Mg C/ha (95% confidence intervals between 11.6 and 18.9%, 377 and 694 Mg C/ha), insignificantly different from those in the Front Range, which exhibited a median carbon concentration and stock of 8.6% and 384 Mg C/ha (95% confidence intervals between 4.1 and 21.1%, 221 and 860 Mg C/ha) (Figure 4). This result contradicts the hypothesis that differences in climate, vegetation community, primary productivity, and total ecosystem carbon stocks between the Cascades and the Front Range (Smithwick *et al.,* 2002; Bradford *et al.,* 2008) will result in different magnitudes of OC storage.

Examining the areal extent of subalpine lake delta soils in addition to their OC content is necessary to rigorously test for a difference in OC storage between the two regions. Our census of the number of lakes and deltas in each study region indicates a total density of delta-bearing lakes of 8.36×10^{-4} lakes per ha in the Front Range (373 deltas in 718 lakes in an area of 446 400 ha) and 8.34×10^{-4} lakes per ha in the Cascades (228 deltas in 624 lakes in an area of 273 300 ha). Average delta area is 0.58 ± 0.39 ha for the 14 deltas surveyed in the Front Range and 1.47 ± 1.33 ha for the 12 deltas surveyed in the Cascades. The proportion of mountainous land area in our census comprised of delta soil is 0.048 ±0.033% in the Front Range, which is insignificantly different from the 0.12 ± 0.11% found in the Cascades. Our estimates indicate that the OC contents in subalpine lake deltas in the Cascades and Front Range are insignificantly different.

These estimates have significant error stemming from the high variability in delta area, making this only a first-order estimate of the total contribution of subalpine lake deltas across both study regions to the total fluvial OC pool. We emphasize, however, that despite their large uncertainty, these estimates of carbon stock in subalpine/e lake deltas suggest that deltas are hot spots for OC storage on the landscape.

Median topsoil OC concentration and stock were 18.9% and 320.4 Mg C/ha (95% confidence intervals between 14.0 and 34.4%, 298.0 and 493.9 Mg C/ha) in deltas in the Cascades compared with 14.5% and 293.4 Mg C/ha (95% confidence intervals between 4.2 and 26.4%, 104.1 and 531.4 Mg C/ha) in the Front Range. Median buried soil OC concentration and stock were 6.2% and 139.8 Mg C/ha (95% confidence intervals between 3.0 and 23.5%, 61.3 and 267.3 Mg C/ha) in deltas in the Cascades compared with 4.1% and 88.4 Mg C/ha (95% confidence intervals between 1.8 and 16.9%, 33.5 and 245.3 Mg C/ha) in the Front Range (Figure 4). Median sampling depth in deltas of the Cascades was 55 cm (95% confidence interval between 40 and 65 cm, range between 15 and 206 cm) compared with 53 cm (95% confidence interval between 42 and 77 cm, range between 10 and 154 cm) in the Front Range.

Spearman correlation tests to examine OC by depth in both the Cascades and the Front Range show significantly monotonic decreases in OC concentration (P = –0.28, P = 0.01 for the Cascades and P = –0.33, P = 0.001 for the Front Range) and stock (P = –0.39, P = 0.0003 for the Cascades and P = –0.42, $P < 0.0001$ for the Front Range) with normalized depth. This is substantiated by nonparametric comparisons of all topsoil samples with all buried samples across both regions, which shows that buried samples exhibit significantly less OC by both concentration (P = 0.002) and stock ($P < 0.0001$). This result is similar to previous findings of OC concentration decreasing

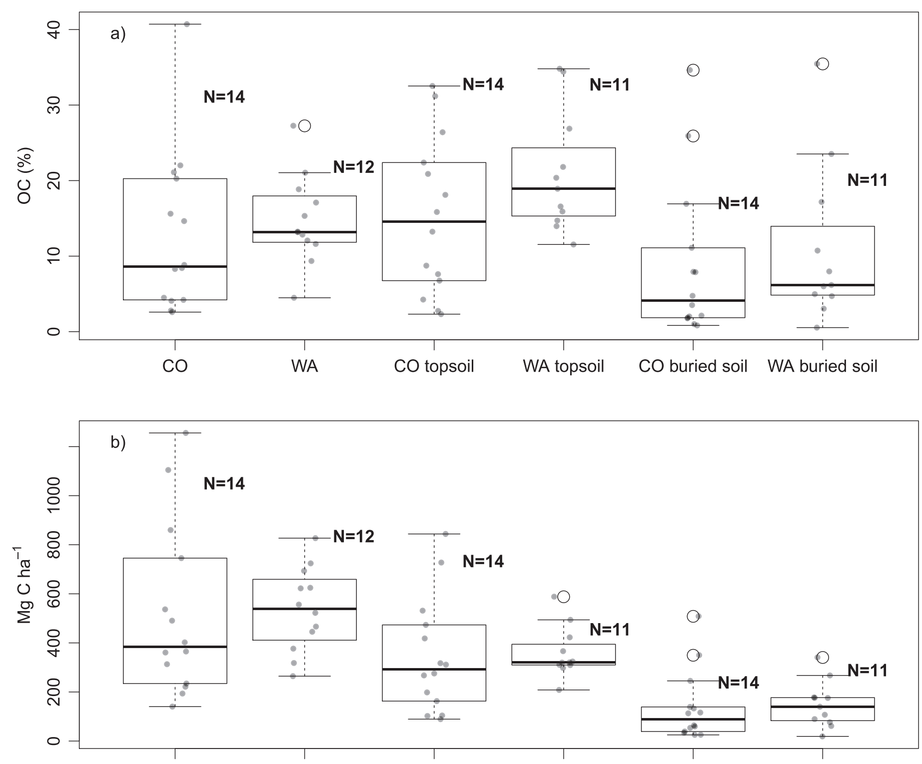

Figure 4. Boxplot showing organic carbon (OC) (a) concentration (%) and (b) stock (Mg C/ha) in subalpine lake deltas of the Front Range (CO) and Cascades (WA) for entire cores, topsoil, and buried soil. Sample sizes are given for each plot (N). Whiskers represent range of data. Ends of box represent 25th and 75th quartiles. Bold line within box represents median of data. Actual data points are shown as grey filled circles scattered along each box. Outliers are represented by circles.

with depth (Jobbágy and Jackson, 2000; Schaetzl and Anderson, 2005) and indicates that OC is likely being enriched near the surface by active, autochthonous deposition from plants.

Comparing deltas in each region in terms of their topsoil using nonparametric methods shows that there is no significant difference between regions in terms of OC concentration (P = 0.13) or stock (P = 0.32). Similarly, parametric comparisons of buried soil show no significant differences in concentration (P = 0.82) or stock (P = 0.32) between regions. This suggests that OC in deltaic soils in both regions experiences similar rates of surface enrichment by modern plants and subsequent decomposition through time and depth increases.

Controls on subalpine lake delta organic carbon storage

Mean basin slope (direct correlation, P = 0.03), valley confinement (direct correlation, P = 0.009), soil moisture (direct correlation, $P < 0.0001$), and soil texture (P = 0.01) significantly correlate with OC concentration on subalpine lake deltas. Deltas with steeper upstream basins, in more confined valleys, exhibiting lower soil moisture and/or coarser soil texture, generally store less OC than wetter, finer-textured, less confined deltas in less steep basins. The significance of these correlations indicates that geomorphic factors play a strong role in determining OC inputs to and storage on subalpine lake deltas, potentially more so than differences between regions such as climate and primary production. This substantiates recent work that has shown that OC storage and export in other landforms is also more dominantly controlled by local geomorphic and biogeochemical processes, rather than climate or primary production alone (Doetterl *et al.,* 2015; Galy *et al.,* 2015).

Deltas in the Cascades are significantly more confined (P = 0.04) and reside in significantly steeper basins (P = 0.001) than those in the Front Range, despite exhibiting statistically similar soil moisture. Specifically, mean basin slopes in the Cascades (averaging 28°) are approaching and in many cases exceeding threshold slope, suggesting that they may have higher rates of landslide-mediated hillslope material transport to the headwater river network (Larsen and Montgomery, 2012) than the Front Range, where slopes average 17°. Such landslide-mediated transport of material is proposed to dominate the signal of range-scale denudation in the Cascades (Moon *et al.,* 2011). With regard to our specific study sites, we observed some landslide and avalanche scars on hillsides upstream and coarse colluvium on delta surfaces in the Cascades, but only rarely in the Front Range, where upstream basins were generally of lower relief.

Morphologic metrics such as mean basin slope and valley confinement are analogs for physical processes that influence OC dynamics in mountain basins. Mean basin slope and the attainment of threshold slope is likely directly proportional to the rate at which hillslope material such as OC-laden organic material and mineral soils (Yoo *et al.,* 2006) enters the headwaters of the river network (Larsen and Montgomery, 2012), which likely transport such material efficiently (Goldsmith *et al.,* 2008; Blair and Leithold, 2014) to subalpine lake deltas. The potential attainment of threshold slopes in the Cascades may mean that fluvial OC is dominated by landslide-mediated input, as opposed to bank and riparian inputs (Leithold *et al.,* 2006). Delta valley confinement likely directly impacts the rate of soil turnover on deltas, whereby wider deltas take longer to turn over and hence have longer periods of time to accumulate sedimentary OC, analogous to unconfined reaches of rivers that have lower turnover times than more confined reaches (Beechie *et al.,* 2006).

The Cascades are wetter and have much higher total ecosystem carbon stocks than the Front Range. Even though the Cascades have much more OC that could potentially be deposited in subalpine lake deltas and climatic conditions that would seem to favor OC preservation in deltaic soil, our results indicate no significant difference between the Front Range and Cascades in terms of the size or density of OC storage in subalpine lake deltas. These data reject our hypothesis regarding the differences in OC storage between regions and support the idea that physical geomorphic processes dominantly control the transient storage of OC in subalpine lake deltas high in the mountain river network, as opposed to primary productivity, climate, or total ecosystem carbon stocks.

One notable difference in the OC storage 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 content in that region compared with the Cascades.

Conceptual model of subalpine lake delta organic carbon storage

We present a conceptual model (Figure 5) that utilizes our observations in conjunction with data regarding the upstream factors that influence carbon transport and deposition of these two regions to explain how two disparate regions could exhibit such similar OC storage in subalpine lake deltas. Although the signal of OC input to deltaic soils from autochthonous vegetation may obscure the signal of OC input from upstream, our multiple linear regression modeling suggests that the upstream OC signal is clear enough to develop such a conceptual model and to use OC storage on subalpine lake deltas to make inferences about processes occurring upstream. This conceptual model utilizes a likelihood approach by examining the effect of environmental conditions on the relative likelihood of OC reaching the subalpine lake delta from the upstream basin.

The magnitude of OC storage in a landform can be controlled by a variety of environmental conditions. On the scale of particles of mineral soil storing OC, soil moisture and texture (Pinay *et al.,* 1992; Howard and Howard, 1993; Jobbágy and Jackson, 2000; Appling *et al.,* 2014) control the decomposition rate of and storage capacity for OC. Wetter soils prevent microbial respiration of OC, and finer textured soils provide more surface area for OC to bond to the mineral grains in the soil. In the context of our study sites, temperature and moisture are controlled not only by climate but also by the hydrology of the lake bordering each delta. Lake level fluctuations likely impact moisture and, consequently, temperature on the delta.

Conditions in the upstream basin affect the amount of OC that may be delivered to river systems and the mode by which OC is transported to depositional landforms. The total ecosystem carbon stock approximates the total amount of carbon upstream of a landform that can be transported and potentially deposited and stored on the landform. Processes which control the respiration of OC during transport regulate how much of the total ecosystem carbon stock can reach a subalpine lake delta. Dissolved OC (DOC) generally does not precipitate in flowing water. In contrast, particulate OC (POC) has a substantial

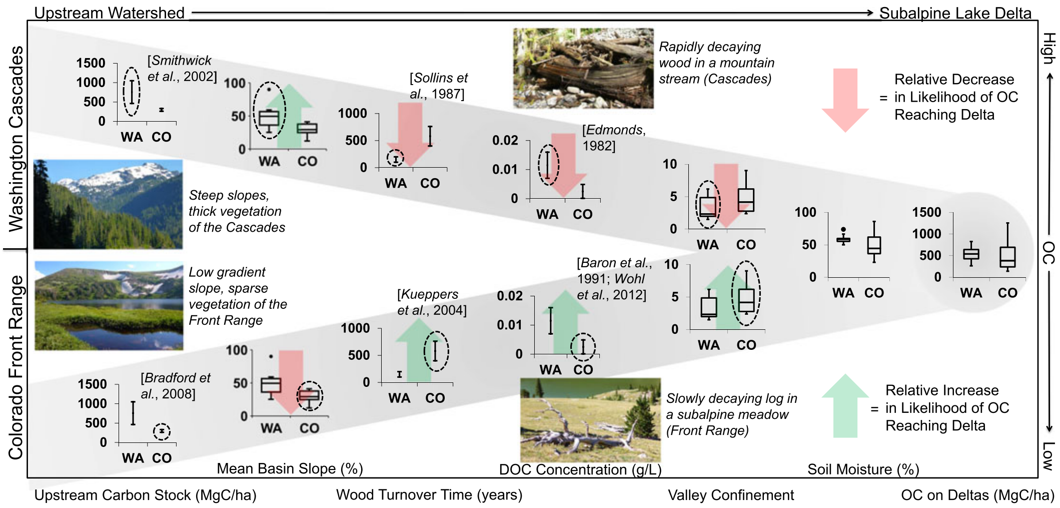

Figure 5. Conceptual model of carbon dynamics for the Washington Central Cascades (top branch) and Colorado Front Range (bottom branch). Each branch shows how the likelihood of organic carbon (OC) reaching the delta changes from the upstream watershed to the delta. Each factor influencing the potential OC storage on a subalpine lake delta is labeled on the bottom horizontal axis. Each label on the horizontal axis corresponds to the vertical axis of the plots above it. The upstream carbon stock, wood turnover time, and DOC concentration for each region are shown by range plots. The mean basin slope, valley confinement, soil moisture, and OC storage on subalpine lake deltas are shown as box plots, and come from data presented here. The Cascades and the Front Range have significantly different mean basin slopes and valley confinement ratios, but insignificantly different moisture in deltaic soils. Arrows are shown on some plots to illustrate whether the magnitude of the process in each region relative to the other increases or decreases the likelihood of OC reaching the delta. [Colour figure can be viewed at wileyonlinelibrary.com]

likelihood of settling in low velocity floodplain or deltaic environments. Thus, the proportion of the total OC load transported by a river system in the form of DOC is less likely to settle in a deltaic environment that experiences flowing water. The proportion of the total OC load being transported as POC, which includes pieces of wood, is more likely to be deposited in a deltaic wetland environment and may be stored for long periods of time. The ratio of DOC to POC controls the proportion of OC in transport that may be deposited within a landform as opposed to being transported through it. However, limited research suggests that OC transport in mountain streams may be dominated by POC (Turowski *et al.*, 2016), which would reduce the importance of variations in the ratio of POC to DOC. Wood turnover time controls the time available for OC stored in wood and POC to reach a stable storage zone from higher in the basin and the proportion of OC being transported as POC. Higher wood turnover times may lead to longer potential transport durations for wood before it decomposes and respires, allowing more of the OC stored in wood and POC to reach the subalpine lake delta, thus increasing OC storage.

The geomorphic characteristics of the basin above a subalpine lake delta and on the delta itself may influence the rate of OC transport to the delta and the length of time that sediment and soil OC persist on the delta. Increasing valley confinement tends to correlate with lower OC storage, as we have found on deltas and Wohl *et al.* (2012) found in mountain streams. We interpret this as reflecting the fact that a more confined valley provides less lateral room for the streams moving across a delta to migrate, as well as a greater probability of extensive erosion during high-magnitude flows. Soil turnover time in a floodplain or delta is controlled by how fast a stream can migrate laterally across the entire surface (Richards *et al.*, 2002). Soil turnover time should therefore decrease as valleys become more confined, if other factors are comparable between sites. Faster soil turnover times in a confined valley would likely lead to decreased time available for OC to accumulate and faster transport of OC to the lake, thus decreasing the total OC storage on the delta. Mean basin slope serves as an estimator of the erosive potential of the hillsides in the basin upstream of a delta. Higher mean basin slopes, especially those that exceed threshold slope (Larsen and Montgomery, 2012), should result in high rates of transport of soil and wood containing OC downslope into the river network, where that OC can be rapidly delivered to a subalpine lake delta.

The total basin carbon stock in the Cascades, including soil and living biomass, ranges from 463 to 1050 Mg C/ha (Smithwick *et al.*, 2002), compared with a range of 261 to 333 Mg C/ha (Bradford *et al.*, 2008) in the Front Range. Thus, the potential quantity of OC that could reach subalpine lake deltas is higher in the Cascades than in the Front Range. The mean basin slope is similarly higher in the Cascades (averaging 28°) compared with the Front Range (averaging 17°) (P = 0.001), probably resulting in faster transport of hillside OC to river systems and subalpine lake deltas. However, the wood turnover rate in the Cascades ranges from 100 to 200 years (Sollins *et al.*, 1987), compared with a range of 400 to 760 years (Kueppers *et al.*, 2004) in the Front Range. Rapid wood decay in the Cascades increases the likelihood of coarse OC being respired prior to reaching the delta, decreasing the likelihood of coarse OC being transiently stored on the delta. The DOC concentration in subalpine waters in the Cascades ranges from 7 to 16 mg L^{-1} (Edmonds, 1982), compared with a range of 0.1 to 4.9 mg L^{-1} (Baron *et al.*, 1991; Wohl *et al.*, 2012) in the Front Range, which may further decrease the likelihood of OC being stored on a Cascades delta relative to the Front Range by increasing the proportion of OC that may pass through the deltaic system. Subalpine lake delta valleys in the Cascades have a significantly higher (P=0.04) median confinement ratio of 2.32 compared with a value of 4.17 in the Front Range. The more confined deltas of the Cascades likely experience a higher turnover rate than those in the Front Range, limiting the time available for OC to accumulate in deltaic soils. The two regions are not significantly different in terms of soil moisture. Although soil moisture is likely related to climatic conditions, lake level may be a more dominant control on soil moisture in deltas. Seasonal fluctuation in lake level likely provides a much stronger control on soil moisture than does the difference in precipitation between the two regions.

Figure 5 summarizes the above information and shows how the Cascades and the Front Range reach a similitude in terms of OC content in subalpine lake deltas, despite having very different total ecosystem carbon stocks. Despite higher total ecosystem carbon stocks and high mean basin slopes in the Cascades, the low wood turnover time, low DOC concentration, and wide, unconfined valleys of the Front Range lead to a higher likelihood of OC reaching and remaining on subalpine lake deltas in the Front Range. This results in similar values of OC storage in subalpine lake deltas between the two regions despite the differences in their environmental conditions and total ecosystem carbon stocks.

Our conceptual model uses the signal of upstream OC inputs to subalpine lake deltas to infer the interactions between processes that regulate carbon dynamics upstream. This signal, especially in topsoil, is complicated by autochthonous inputs of OC from vegetation growing on subalpine lake deltas, which is not controlled by upstream processes. Based on our conceptualization of subalpine lake delta sedimentation as analogous to that of floodplain sedimentation, this autochthonous signal likely permeates much of the soil profile in deltas we examined. This autochthonous vegetation signal is a likely source of variability in our model of controls on OC storage and is largely not considered by our conceptual model. Given the nature of our data and the similarity in plant species composition between deltas and upstream areas, we found it unfeasible to distinguish between autochthonous and allochthonous OC inputs, which would have allowed us to reduce this error in our interpretations.

Conclusion

Our data suggest that subalpine lake deltas provide a transient storage mechanism for OC high in the mountain river network. We present a conceptual model that introduces a novel paradigm for examining the carbon dynamics of a mountain river basin by suggesting that local geomorphic processes, not ecosystem-scale productivity or climate, most strongly control OC storage in headwater depositional landforms. This model provides a way of understanding carbon dynamics in the complex system of a mountain river network. OC storage within a depositional environment such as a subalpine lake delta integrates the processes regulating carbon transport and decomposition within the upstream mountain river network. This result is complementary to recent work indicating that river processes and physical erosion, rather than primary production, are the dominant controls on POC transport in rivers (Galy *et al.,* 2015).

Our conceptual model introduces new, testable hypotheses regarding carbon dynamics in mountain river systems that could guide future investigation. We suggest that a faster rate of delivery of OC to depositional landforms increases the likelihood of that OC avoiding respiration and being stored for long periods of time. This also suggests that geomorphic and biogeochemical processes are more important than broad-scale productivity in predicting the OC storage in stable zones on the landscape, which are likely more important than unstable hillslopes as sites of transient carbon storage in a river basin. Further detailed investigation of the relationship between the geomorphology and biogeochemistry of mountain river systems will be necessary to test these hypotheses.

Understanding how OC-rich depositional basins such as subalpine lake deltas store carbon and regulate the carbon cycle requires a holistic understanding of mountain basin carbon dynamics, not just the total amount of carbon stored in the basin. The length of time for which carbon is stored in the fluvial network is important in understanding the carbon cycle and the biogeochemical fate of carbon on the land. We demonstrate that regional values of OC stored in a stable, depositional, carbon-rich mountain landform do not correspond to regional differences between entire drainage basins. This illustrates why an integrated, process-based view of carbon dynamics must be used in understanding and managing terrestrial carbon cycling, as opposed to the existing paradigm of making inferences from ecosystem carbon stocks. Testing our conceptual model at larger scales and along entire river basins will strengthen the understanding of carbon dynamics in river systems and ability to account for those dynamics in watershed- to regional-scale carbon budgets.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's web site.

Table S1: Measured characteristics summarized by delta. Averaged values are shown with standard deviations. Averages and medians for columns are shown where appropriate. Explanations of variables can be found in the manuscript text.

Table S2: Measured characteristics for each individual sample. Samples are organized by core (sample ID summarizes the lake, core number, and depth). Top and Bottom depths are from the ground surface or standing water. Actual top and bottom depths are from the soil surface, ignoring standing water. 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). OC analysis methods are described in the text and are either Loss-on-ignition (LOI) or Carbon/Hydrogen/Nitrogen furnace (CHN). Further explanation of variables can be found in the manuscript text.