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The Importance of Coarse Organic Matter and Depositional Environment to Carbon Burial Behind Dams in Mountainous Environments

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Key Points:
- Carbon burial rates in reservoir sediments are spatially and temporally heterogeneous
- Allochthonous, coarse-grained organic matter accumulation in reservoir sediments is a significant component of carbon burial in reservoirs
- Estimates that do not account for reservoir heterogeneity may significantly underestimate or overestimate carbon burial in reservoir sediments

Supporting Information:
- Supporting Information S1

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Abstract The relationship between carbon burial and sedimentation in reservoirs is unknown, contributing to uncertainty in our understanding of the net impact of dams to the global carbon budget and exposing gaps in our fundamental understanding of the transport, processing, and deposition of organic matter in fluvial and lacustrine systems. Taking opportunistic advantage of the removal of two high-head dams, we investigate this relationship by developing a stratigraphic, process-based framework to estimate total carbon accumulation as a function of depositional environment in the sediments of two former ~1-km^2 reservoirs on the Elwha River, Washington, USA. Former Lake Mills (upstream; completed 1927) accumulated ~330 Gg, with depositional zone average accumulation rates from 229 to 9,262 gCm^2/year, while Former Lake Aldwell (downstream; completed 1913) accumulated ~91 Gg (263 to 2,414 gCm^2/year). Carbon storage in both reservoirs was dominated by heterogeneous, coarse organic matter and woody debris in the coarse-grained delta slope and relatively coarse-grained prodelta regions of the reservoirs, with little in the gravel-dominated, subaerial delta plains. Carbon accumulation in fine-grained lacustrine and prodelta sediments was relatively homogeneous, but turbidity flows from the Gilbert-style delta slope in former Lake Mills delivered significantly more carbon to the prodelta than the mouth bar-style delta of former Lake Aldwell. C:N ratios support interpretation of most organic matter in both reservoirs as allochthonous. Sampling schemes based only on lacustrine and/or prodelta would underestimate total carbon accumulation by up to 30% in former Lake Aldwell but overestimate carbon by up to 47% in former Lake Mills.

Plain Language Summary By storing, processing, and emitting carbon to the atmosphere, dams and reservoirs disrupt the global carbon cycle. However, the net impact of impoundments to the global carbon cycle is poorly understood, in part because the relationship between sediment accumulation and the long-term storage of organic material behind dams is unknown. To develop a better understanding of the movement and burial of organic material in reservoirs, this study uses differences in the composition, morphology, and position of unique sedimentary units to estimate the accumulation of carbon in two former reservoirs on the Elwha River, Washington, USA. Both the type of organic matter and the total accumulated volume of carbon varied significantly across different *depositional zones* in each reservoir, indicating that heterogeneity in sedimentation type and volume matters to the accumulation of carbon and that coarse-grained, terrestrially derived organic carbon can represent a significant sink of carbon in lakes and reservoirs in mountainous, forested environments. This stands in contrast to previous studies that have suggested that organic carbon is concentrated in the fine-grained, lacustrine sediments of a reservoir. Estimates of carbon accumulation in reservoirs that do not account for spatial variation in accumulation rates may underestimate (by up to 30% in former Lake Aldwell) or overestimate (by up to 47% in former Lake Mills) the total accumulation of carbon in reservoir sediments.

1. Introduction: Carbon Accumulation in Reservoirs

The widespread construction of large (>15-m) dams over the last century has altered the fluvial connections between terrestrial and oceanic environments on a global scale. Conservatively, dams and reservoirs now affect ~50% of large rivers (Lehner et al., 2011; Nilsson et al., 2005), intercept >40% of global discharge (Vörösmarty et al., 2003), and have increased the global terrestrial water surface by >7% and the lacustrine

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freshwater storage by ~10% (Gleick, 2000). As a result, as much as 25% of global annual sediment discharge is now impounded (Vörösmarty et al., 2003), resulting in a 1,400 Tg/year *decrease* in global sediment delivery to oceans despite an estimated 2,300 Tg/year anthropogenic *increase* in global sediment transport (Syvitski et al., 2005). Indeed, a provocative recent paper argues that sediment retention behind dams is a fundamental marker of the stratigraphic and functional distinctiveness of the Anthropocene (Waters et al., 2016).

Reservoirs appear to be hot spots of biogeochemical activity when compared to natural lakes, with intensified rates of nutrient cycling, including primary production, mineralization, and sedimentation (Cole et al., 2007; Maavara et al., 2017). High rates of terrestrial carbon input, as well as high aquatic productivity due to large nutrient inputs, appear to create environments that promote the mineralization and off-gassing of large volumes of greenhouse gases (Abril et al., 2005; Clow et al., 2015; Jacinthe et al., 2012; Guérin et al., 2006; St. Louis et al., 2000; Tranvik et al., 2009). Following decades of intense study and debate, the most recent estimate of greenhouse gas emissions from reservoirs suggests that annual global emissions are 0.8 (0.5–1.2) Pg carbon dioxide (CO_2) equivalent per year, primarily due to methane (CH_4; Deemer et al., 2016). Reservoirs also appear to intensify the burial of carbon, however (Mendonça et al., 2017). Most CH_4 (and much CO_2) production occurs in the shallow sediments of aquatic environments, where heterotrophic microbes mineralize organic matter that is supplied as a fraction of the sediment supply or as rain-out from in-reservoir production (cf. Burdige, 2006; Wetzel, 2001). As sediment builds up, any particulate organic matter that escapes mineralization is buried and typically considered to have been removed from the *active* pool of carbon cycling.

Despite the importance of carbon burial in sediments on the net impact of dams to the global carbon cycle, however, studies of carbon burial in reservoir systems remain relatively scarce and estimates of carbon burial rates vary widely. The most commonly cited estimate of a global, area-weighted carbon burial rate in reservoirs is about 400 $gC \cdot m^2 \cdot year$ (e.g., Dean & Gorham, 1998; Mulholland & Elwood, 1982; Stallard, 1998), but recent studies suggest that the true value may be as high as 1,000 $gC \cdot m^2 \cdot year$ (Downing et al., 2008) or as low as 80 $gC \cdot m^2/year$ (Maavara et al., 2017). This disparity may be due in part to the estimation of carbon burial in lakes and reservoirs from limited data sets; as noted by Clow et al. (2015) in their recent, comprehensive effort to estimate total carbon burial in lakes and reservoirs of the conterminous United States, the databases from which their data are drawn represent less than 1% of reservoirs in the conterminous United States (Clow et al., 2015; p. 7,615).

The uncertainty in global burial estimates is compounded by the difficulty of estimating accurate carbon burial rates from individual reservoirs. In the past, many studies of reservoir carbon burial have relied on limited grab sample of coring-based data points to extrapolate across the reservoir area (e.g., Downing et al., 2008). However, this approach, while in keeping with the *depocenter* paradigm of homogeneous deposition in lakes, is limiting in larger reservoir systems where complex processes influence sediment transport and deposition (cf.Mendonça et al., 2016 ; Shotbolt et al., 2005). For example, using a longitudinal core transect of the reservoir axis, Vanni et al. (2011) found that average organic carbon concentration increased downstream in two hard-water reservoirs in Ohio. In contrast, Mendonça et al. (2016) found that organic carbon concentration decreased *downstream* in a subtropical reservoir in Brazil. Additional studies in Zimbabwe and northern California have shown variable patterns of carbon burial that appear to be influenced by complex sedimentation dynamics (Kunz et al., 2011; Pondell & Canuel, 2017).

Despite these indications of significant heterogeneity in the patterns and rates of carbon burial in reservoir sediments, however, relatively few studies have investigated spatial and/or temporal variability in carbon burial behind dams in a systematic way, and the relationship between carbon burial and complex patterns of sedimentation remains poorly understood. This gap creates uncertainty in our estimates and understanding of the net impact of impoundments on the global carbon budget and reveals deficiencies in our fundamental understanding of the transport, processing, and deposition of organic matter in fluvial and lacustrine environments.

This study capitalizes on the unique opportunity created by the 2011–2014 removal of two large dams on the Elwha River, Washington, USA (Figure 1) to investigate the relationship between sedimentation dynamics and carbon burial in reservoir environments. Due to the large-scale and pioneering nature of the project (cf. Duda et al., 2008), extensive data sets on sediment volume and grain size (Bountry et al., 2011; Gilbert & Link, 1995; Randle et al., 2015), sediment stratigraphy (Stratton & Grant, 2019), and sediment carbon (Wing, 2014) were collected. By synthesizing these data with additional field-based observations of detrital

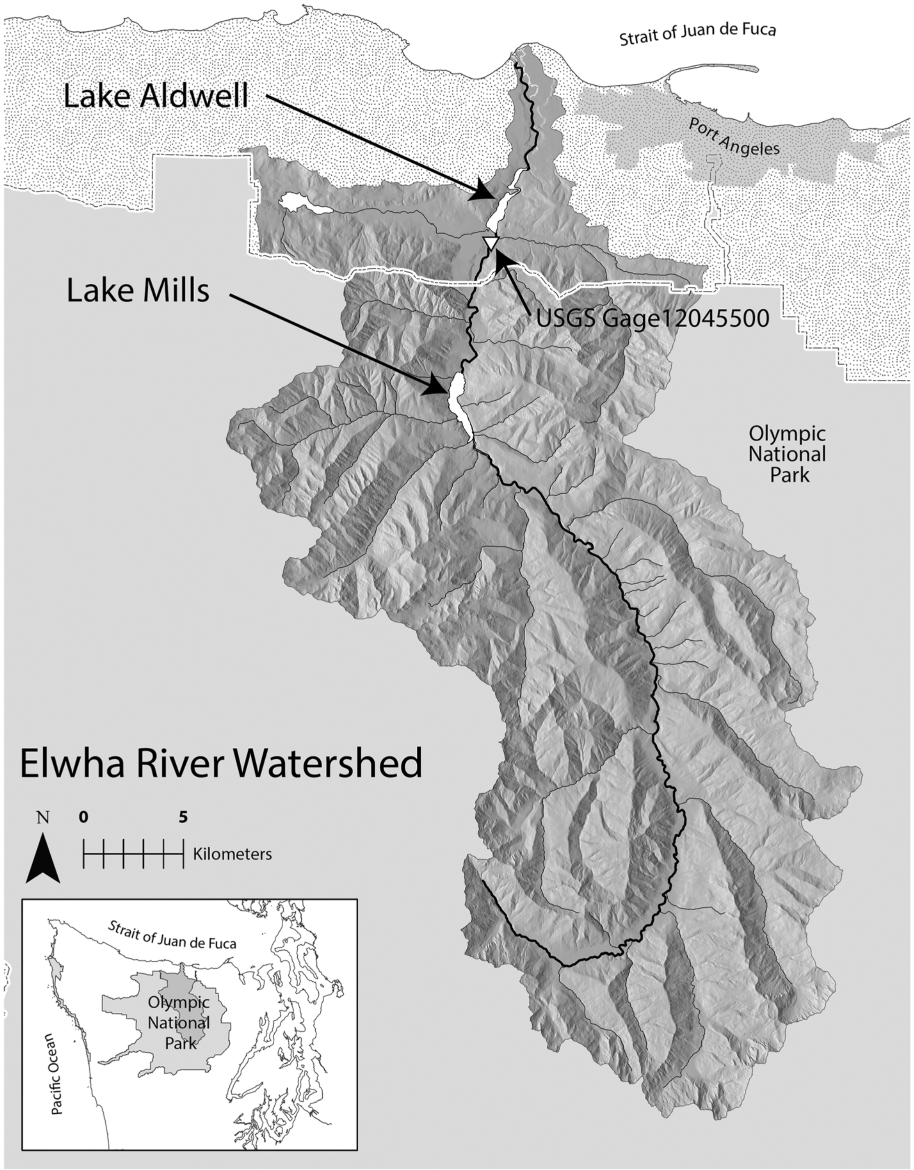


Figure 1. Location of former Lakes Aldwell and Mills in the Elwha River watershed, Clallam County, Washington. Discharge and water quality data discussed in text were collected from U.S. Geological Survey (USGS) gage 12045500, Elwha River at McDonald Bridge near Port Angeles, Washington. Inset shows location of Elwha watershed within Olympic National Park, relative to the Pacific Ocean and Strait of Juan de Fuca.

carbon accumulation, we investigate three questions necessary to understanding the deposition of carbon in reservoir sediments: First, where is carbon stored in reservoirs and what processes contributed to its deposition? Second, what is the primary source of carbon in reservoir sediments and how does it vary between and within individual reservoirs? And third, what can these insights tell us about the total volume of carbon accumulation in reservoirs?

While stratigraphy and sediment analysis have long provided a paradigm to recognize patterns and interpret the processes responsible for carbon storage in both terrestrial and aquatic environments (cf. Huc, 1990), this work is unique in its application of stratigraphic tools to better understand carbon burial in the sediments of artificial reservoirs. By treating detrital organic matter as an *organic sediment* subject to similar transport and depositional processes as mineral-based sediment, our framework allows stratigraphic tools to inform the development of a process-based understanding of the processes influencing carbon storage in reservoir sediments.

2. Study Area

2.1. Elwha Watershed

The Elwha River watershed comprises 833 km^2 on the northernmost Olympic Peninsula (Figure 1), draining the glaciated Olympic Mountains north to the Strait of Juan de Fuca. Precipitation is strongly seasonal and shows a sharp orographic gradient over the watershed; annual peak discharges on the Elwha River occur in winter with a secondary peak during spring melt out. Average daily discharge is ~43 m^3/s, and the flood of record (recorded in 1897) is 1,180 m^3/s, with seven measured annual peak discharges greater than 800 m^3/s since 1897 (Duda et al., 2008).

Sediment sources in the Elwha drainage are abundant due to the steep gradient, highly erodible bedrock, and history of glaciation (Acker et al., 2008; Batt et al., 2001; Brandon et al., 1998; Draut et al., 2011; McNulty, 2009; Schuster, 2005; Tabor, 1987; Tabor & Cady, 1978). However, sediment delivery to channels is moderated by thick forest and other vegetative cover and very limited land use development as the result of long-standing federal protection of most of the watershed. Studies on plant communities completed in the vicinities of Lakes Aldwell and Mills found that 90% of land area was vegetated; of the remaining 10% land area, 80% was composed of the river itself and associated gravel bars (National Park Service, 1996). Plant communities are dominated by conifer forest (43%; predominantly western hemlock and Douglas fir), mixed forest (18%), hardwood forest (17%), and palustrine forest (6%), with minor areas of grassland, deciduous shrubs, and low wetland communities (National Park Service, 1996).

The Elwha is classified by the Washington State Department of Ecology as Class AA waters, a designation indicating *extraordinary* water quality (Federal Energy Regulatory Commission, 1991). As measured at U. S. Geological Survey Gage 12045500 (Elwha River at McDonald Bridge), located immediately upstream of former Lake Aldwell (Figure 1), dissolved oxygen, nitrogen, and phosphorous values in Elwha River water are consistent with waters typically classified as oligotrophic (bimonthly mean values collected from October 1985 to 1986: dissolved oxygen 11.8 mg/L; percent saturation 98; pH 7.7, hardness 41 mg/L as $CaCO_3$; alkalinity 37 mg/L as $CaCO_3$; nitrate 0.1 mg/L as N; ammonia nitrogen 0.02 mg/L as N; total phosphorus 0.01 mg/L as P; and orthophosphorous 0.01 mg/L as P;Federal Energy Regulatory Commission, 1991 ; Wetzel, 2001). Additionally, water quality data collected from Lakes Aldwell and Mills in the summer and early fall of 1987 indicated pH and alkalinity values typically associated with oligotrophic systems, and dissolved oxygen and secchi depth readings typically considered oligotrophic to mesotrophic (Federal Energy Regulatory Commission, 1991; Wetzel, 2001). No direct measurements of in-reservoir productivity were, to our knowledge, ever collected; however, low nutrient values are typically associated with limitations on algae growth (Wetzel, 2001).

2.2. Elwha Reservoirs

Elwha Dam was completed in 1913 and impounded Lake Aldwell until 2011. Glines Canyon Dam, located approximately 18 km upstream, was completed in 1927 and impounded Lake Mills until 2012. Elwha Dam was 33 m tall and impounded a reservoir 1.3 km^2. Former Lake Aldwell had an initial water capacity of approximately 1.0×10^7 m^3, an average depth of 7.6 m, a maximum depth of 29 m, and maximum fetch of 2,000 m (Stratton & Grant, 2019). Glines Canyon Dam was 64 m tall and impounded a reservoir with similar area but 5 times the capacity of former Lake Aldwell. During the decades the dams impounded the Elwha, the river built substantial subaerial deltas into both former reservoirs, significantly reducing their capacity, area, and average depth while increasing the shoreline complexity in the deltaic regions of the reservoirs (Stratton & Grant, 2019).

The dams were operated primarily as *run of the river*, that is, constant head, facilities from at least 1975 onward (Duda et al., 2008; National Park Service, 1996). To restore native fish populations reduced by 90% from their predam abundance, both dams were removed from 2011 to 2014 in the largest dam removal yet undertaken globally (Duda et al., 2008; Pess et al., 2008; Randle et al., 2015). Removal occurred in stages, during which each reservoir was drawn down by a depth of 3 to 5 m and held at that elevation for a period of time before proceeding to the next step (Randle et al., 2015). This process allowed time for the Elwha River to erode significant portions of the deltaic deposits through incision and lateral migration at each step, creating terraces with extensive cutbank exposures and the opportunity for detailed stratigraphic study.

3. Methods

This study expands a previously developed physical stratigraphic framework for former Lakes Aldwell and Mills (Stratton & Grant, 2019) to include rigorous classifications of facies influenced or dominated by detrital organics visible at the section scale, allowing the assignment of samples analyzed for total organic carbon (TOC) and carbon-to-nitrogen ratios (C:N) to characteristic facies that comprise a framework of *depositional zones* within each reservoir. These zones then provide a process-based framework to develop whole-lake estimates of carbon burial and source for each reservoir.

The stratigraphic framework for former Lakes Aldwell and Mills is based on stratigraphic description of 100+ surface and cross-sectional exposures in the former reservoirs (Stratton & Grant, 2019). These stratigraphic sections were used to develop depositional zones defined by characteristic depositional processes, as shown in Figure 2. Facies definitions (Table 1) are coded by dominant grain size (G = gravel; S = sand; HS = heterogeneous [sand dominated]; F = fines [a field-scale determination including silt and clay]; O = predominantly organic; OF = heterogeneous unit composed of organics in fine-grained units or with a fine-grained matrix) and grain size within the group, from coarse to fine (e.g., G1 is coarser than G2, but both are gravel-dominated). *Organic* facies (those designated O or OF) consist of units that, at the facies scale, are 50% or greater organic matter by visual estimation of area or for which organic components provide the clastic framework. Additional criteria and examples of organic-dominated facies are provided in the supporting information.

Using the reported location and photographs of individual samples, sample plots, and adjacent stratigraphic features, combined with facies descriptions and photographs from stratigraphic sections completed by Stratton and Grant (2019), we classified individual analytical samples according to (1) depositional era, (2) depositional zone (Figure 2), and, where possible, (3) facies. Depositional era includes (1) predam (i.e., soils deposited prior to the establishment of the reservoirs), (2) primary (i.e., sediments deposited during the normal operating lifespan of the former reservoirs), and (3) secondary (i.e., sediments deposited during dam removal-related drawdown events. Depositional zones and facies are discussed below. Statistical analysis of analytical samples was completed using R version 3.0.3. Standard error was measured using a one-sample t test (p values reported below) and comparison of means using a two-sample t test (p values reported below).

TOC and C:N data were collected as part of an separate study (Wing, 2014). As described therein, samples were collected by defining 390-m north-south transect intervals and selecting three to five plot locations along each transect (Figure 2). At each plot, samples were collected at intervals from 0 to 20 cm, 20 to 50 cm, 50 to 100 cm, and at subsequent 1-m intervals as deep as feasibly possible to the total depth of sediment accumulation. Maximum sampling depth was 600 cm below ground surface or from the top of a terrace. Samples were collected using a variety of soil coring probes and with sharp-pointed trowels, depending on conditions. Samples were analyzed to determine TOC, carbon to nitrogen (C:N) ratios, bulk density, and coarse (>2 mm) versus fine fraction (≤2 mm) according to the methodology detailed in Wing (2014). C:N ratios are reported as weight ratio and can be converted to molar ratio by multiplying by the molecular weight ratio (14/12 or 1.67).

Volume and area calculations were completed using ArcMap 10.3.1 Spatial Analyst functions on 3.048-m^2 horizontal resolution digital elevation models (DEMs) of the predam removal (ca. 2010) and predam surfaces provided by the U.S. Bureau of Reclamation (Bountry et al., 2011). DEMs representing predam surface elevations in former Lake Mills are based on 1.52-m (5-ft) topographic maps completed prior to dam construction. No such map was completed for former Lake Aldwell; as a result, the predam river thalweg was estimated using contemporaneous photographs and large-scale maps. DEMs representing the reservoir bathymetry at the time of dam removal were surveyed and interpolated according to the methods documented in Bountry et al. (2011), who estimated uncertainty in volumetric calculations as 13% for former Lake Mills and 26% for former Lake Aldwell. We digitized the approximate reservoir outlines in the earliest available maps or aerial photographs of each reservoir and subdivided the reservoir into depositional areas as shown in Figure 2 then performed simple raster subtraction to determine the volume of sediment accumulated in each depositional zone. Estimates of total carbon accumulation are based on the best estimate of sediment volume and do not account for error within sediment volume estimates.

Grain size distributions are from Gilbert and Link (1995), who utilized a depositional zone-based approach to quantify sediments and sediment grain size in both former reservoirs as part of early dam removal

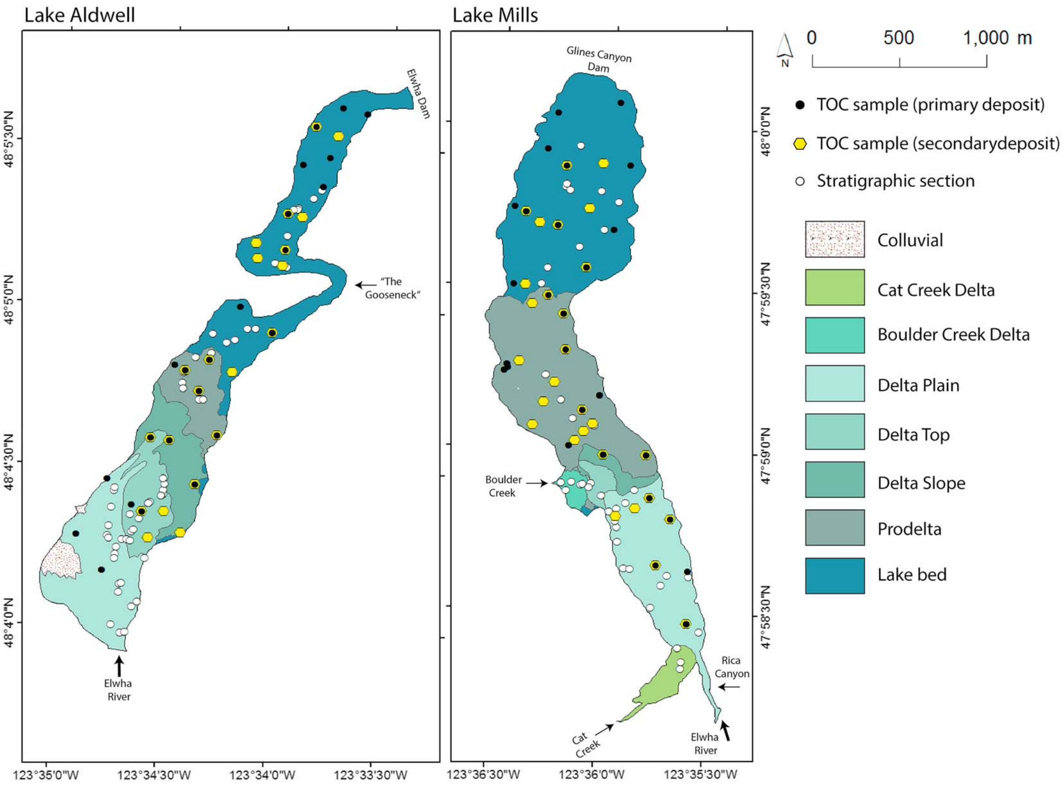


Figure 2. Location of TOC samples collected by Wing (2014) and stratigraphic sections described by Stratton and Grant (2019) overlain on the surface expression of depositional zones at the time of dam removal. *Primary deposit* refers to sediments deposited during normal operations of the reservoir, while *secondary deposit* refers to sediments emplaced during the dam removal process.

planning (see supporting information). These areas were based on average sampled grain size and are thus not directly comparable to the depositional zones in this study but provide estimates of grain size and simple facies architecture from a similar environment-based perspective.

4. Results

4.1. A Stratigraphic Approach to the Deposition of Organic Matter

4.1.1. Lake Mills

Former Lake Mills was characterized by a classic Gilbert-style delta (Gilbert, 1885; Stratton & Grant, 2019), which is typically defined by a tripartite structure consisting of coarse-grained, low-angle topset beds, coarse-grained, steeply dipping foreset beds, and low-angle, fine-grained bottomset beds, beyond which are lacustrine-style deposits. As the delta progrades into the water body, the coarse-grained deltaic deposits override the fine-grained, more distal lacustrine deposits, creating a coarsening-upward stratigraphic section characteristic of a Gilbert-style delta (Figure 3a). The resulting deposits can be grouped into characteristic depositional zones, including the alluvially dominated *delta plain* near the reservoir head, which may grade into a sandy *delta top* where mouth bar sands are deposited, followed by the steeply dipping *delta slope*, *prodelta*, and fine-grained *lakebed* deposit near the dam (Figure 2). As discussed here, the accumulation of detrital organic matter appears to vary systematically from zone to zone.

4.1.2. Delta Plain and Delta Top

By 2010, when a detailed survey of reservoir sediments was conducted (Bountry et al., 2011), the Elwha River had built a subaerial or nearly subaerial delta nearly 1 km into the reservoir from the mouth of Rica Canyon (Figure 2). The delta plain and delta top depositional zones of former Lake Mills (Figure 2) represent a large number of complex environments but are probably volumetrically dominated by gravel topset beds. Complete exposures near Boulder Creek, Cat Creek, and the mouth of Rica Canyon (Figure 2) show multistory accumulations of the coarse-grained G1, G5, and O1 facies (Table 1 and Figure 3a), while fluvial gravels

Table 1
Facies Designations, Former Lakes Aldwell and Mills

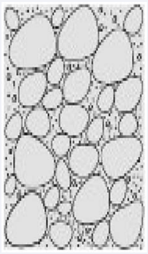
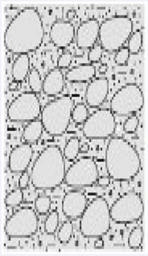
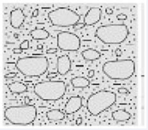
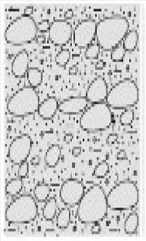
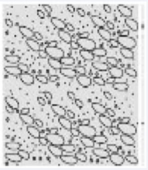
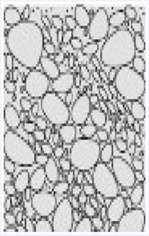
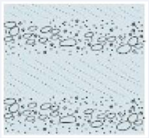
Facies	Description	Bedding	Visible organic detritus
G1 	Unchannelized cobble-boulder gravels; massive to crudely stratified. Clast- to matrix-supported; matrix sandy to pebbly. Little silt.	Sheet-like, laterally extensive beds to 5-m thickness	Isolated, intact to well preserved fine (average diameter ~2–5 cm and coarse (tree with intact root balls) woody debris. <5% surface exposure.
G2 	Unchannelized, poorly sorted large pebble to cobble gravels; similar to G1 but finer-grained and consistently matrix-supported; some silt in matrix.	Sheet-like, laterally extensive beds to 2-m thickness	Isolated, intact to well preserved fine (average diameter ~2–5 cm and coarse (tree with intact root balls) woody debris. <5% surface exposure.
G3 	Matrix-supported, very poorly sorted angular gravels; inverse grading and elevated clasts common.	Subhorizontal to 20° dip, maximum 0.5 m, local unit pinches out downstream	None observed
G4 	Weakly graded, weakly channelized silty sandy gravel with lag. Lag shows imbrication, occasional weak channel form.	As multistory ~0.5-m bed; laterally extensive, pinches out over hundreds of meters	Isolated, intact to well preserved fine (average diameter ~2–5 cm and coarse (tree with intact root balls) woody debris. <5% surface exposure.
G5 	Cross-stratified, well-imbricated pebble to cobble gravels. Open framework to clast-supported.	Steeply dipping cross beds 20–30 cm thick; laterally extensive.	Isolated, intact to well-preserved fine (average diameter ~2–5 cm) woody debris. <5% surface exposure.
G6 	Interbedded pebble, small cobble, and coarse sand to granule conglomerate. Individual beds moderately to well sorted; may be open framework	Steeply dipping (25–30°) beds to 0.5-m thickness, uniform geometry	Intact to well-preserved fine woody debris and general \litter interbedded as lenses within conglomerate and granule beds. <5% surface exposure.
G7 	Crudely stratified, gently dipping pebble to cobble gravels. Matrix- to clast-supported; little silt.	Forms sigmoidal foreset on scale of 2–3 m; individual beds ~10 cm	Isolated, intact to well preserved fine (average diameter ~2–5 cm and coarse (tree with intact root balls) woody debris. <5% surface exposure.

Table 1
(continued)

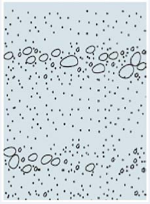
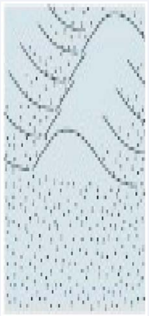
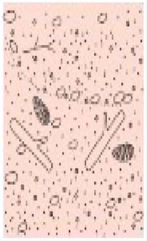
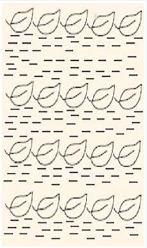
Facies		Description	Bedding	Visible organic detritus
G8		Weakly channelized, well-sorted sandy gravel with prominent lag; little silt. Clast-supported, weakly imbricated to massive. Finer and less silty than G4.	Subhorizontal to broadly undulating; beds 10 cm to 0.5 m thick	Frequently interbedded with organic units but absent to very rare in G8.
G9		Tabular to channelized pebble gravels and pebbly sand. Clast-supported, rarely open-framework. Little to no silt.	Complexly bedded; sheet-like tabular beds cut by channel forms with migration lag	Frequently interbedded with organic units but absent to rare in G9.
G10		Low-angle, tabular pebbly gravel beds interbedded with sigmoidally cross-bedded coarse and very coarse sands. Individual beds to ~1-m thick but pinch out.	Gently dipping to broadly undulatory, laterally extensive but variable.	Absent to very rare.
S1		Well-sorted medium to coarse sand with granules forming well-developed cross beds and planar-laminated beds.	Multiple cosets of sheet-like units, pinch out downstream. Maximum thickness ~0.5 m.	Trace; as <1-mm thick lamina
S2		Medium to coarse or very coarse sand and fine pebbles; moderately to well sorted with little internal structure. No silt.	Laterally extensive, gently dipping; beds typically 10–20 cm.	Well-bedded, intact to well-preserved needles, leaves, and general litter; organic beds to 4 cm thick or as clasts in sand to 10 cm thick.
S3		Well-sorted medium to fine sand with interbedded organics. Planar to sigmoidal cross-lamina, climbing ripples common. Beds typically ~10 to 50 cm.	Subhorizontal to undulating; extensive, relatively uniform.	Intact to well-preserved needles, general litter, and fine woody debris individually cross stratified with sand or as beds to 4–10 cm thick separating ripple cosets. Where occur as beds, clast-supported to open framework. ~15% surface exposure.

Table 1
(continued)

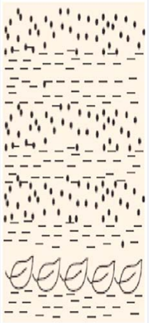
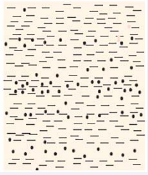
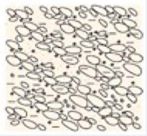
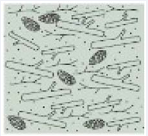
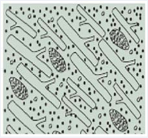
Facies		Description	Bedding	Visible organic detritus
S4		Very thick beds of massive to cross-laminated sand and silty sand with climbing ripples and load structures; gravel absent.	Beds to several meters thick; upper contact frequently channelized	Intact to well-preserved leaves, needles with subordinate general litter and rare fine woody debris. Interlaminated with climbing ripples and cross-lamina; Absent to ~15% surface exposure.
HS1		Variable, chaotic to channelized or weakly bedded, poorly sorted sand with medium to coarse organics and rare pebbles.	Sheet-like. Extensive, bottom contact erosive. Grades finer laterally, typically little fabric.	Intact to well-preserved general litter, fine and rare coarse woody debris; chaotically interbedded with sand units. Variable; to 15% surface exposure.
HS2		Fine to medium cross-laminated sand regularly interbedded with wave rippled or wavy-bedded muds to ~5 cm thick. Silt subordinate to sand beds.	Subhorizontal to gently dipping; silt interbeds pinch out but laterally extensive	Intact needles and leaves (less common) in lee of cross-lamina and ripples; also as imbricated, densely packed leaf beds in lenses to 5 cm thick. Intact fine woody debris occasionally imbricated in sandy beds. <10% total surface exposure.
HS3		Well-sorted, interbedded sand and pebbles separated by thin silt beds. Beds laminated with pebbles imbricated along dip.	Steeply dipping (25–30°) beds to 0.5-m thickness, uniform geometry	Intact needles and leaves (less common) in lee of cross-lamina and ripples; also as imbricated, densely packed leaf beds in lenses to 5 cm thick. Intact fine woody debris occasionally imbricated in sandy beds. <10% total surface exposure.
F1		Striped mud and sand lamina and beds, frequently with needles. Sand beds to 5 cm, cross-laminated, increase up-section relative to silt beds.	Subhorizontal; laterally extensive. Thickness from 0.5 m to many meters	Intact to well-preserved general litter and needles as lamina or lenses to 1 cm thick; also individually in lee of ripples. ~10% of total surface exposure.
F2		Interlaminated mud and silty sand with organics. Parallel to weakly wavy, rare ripple formsets or climbing ripples.	Subhorizontal, laterally extensive. Thick bedded (to several meters).	Irregular, 1 mm to 1-cm lamina of well-preserved to poorly preserved general litter; also well-preserved needles in lee of rare ripples, well-preserved general litter in lee of isolated coarse woody debris and whole trees.

Table 1
(continued)

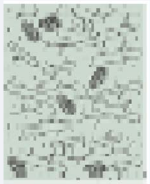
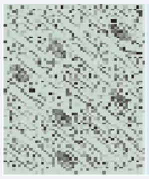
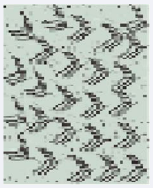
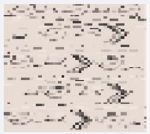
Facies		Description	Bedding	Visible organic detritus
F3		Laminated to massive very fine mud beds, typically blue-gray. Maximum bed thickness 10 cm, often representing single current ripple formset.	Subhorizontal, laterally continuous. Interbedded with organics, gravels.	Absent to trace (well-preserved needles)
F4		Thick, massive to weakly laminated blue-gray clayey mud and brown silty mud. Beds to several meters thick.	Subhorizontal, laterally extensive; drapes pre-existing topography.	Visible rare; as rare, poorly preserved, millimeter-scale lamina or isolated fine woody debris
F5		Striped mudstone with fine organics. Silt beds with interlaminated organic mats (mostly leaves). Interbeds 1 to 3 cm, weakly wavy to planar	To 2-m total thickness, subhorizontal, laterally extensive	Beds of intact to well-preserved, well-sorted leaves to 3 cm thick. Little matrix; leaves form cohesive mat separating wave-rippled silt. To 30% total surface exposure.
F6		Thinly graded fine organic and silt interbeds with fine sand. Sticks, cones, and bark fragments constitute minor total area of unit but are not uncommon.	Subhorizontal; laterally extensive	Needles and well-preserved general litter and (uncommon) intact to well-preserved fine woody debris. As *clasts* om sandy matrix forming beds to ~10 cm thick or as caps to graded beds. <15% total surface exposure.
F7		Poorly sorted, thick-bedded silty sand to sandy silt capped by silt bed. Chaotic fabric with occasional climbing ripples and organics.	Variable, frequently erosive. Laterally extensive.	Variable; similar to S3 or as lag in composed of well-preserved needles and general forest litter in drawdown channels.
F8		Laterally migrating, channelized mud-clast conglomerate interbedded with pebbles, sands.	Laterally migrating channel form directly overlying forest floor	Absent to rare
O1		Interlocked, randomly oriented branches to 2–3-cm diameter forming open-framework lenses or beds. Sticks typically bark-denuded but angular.	Channelized lenses or planar beds pinching out within several meters	Organic unit. Intact, well-preserved fine woody debris typically 0.5 to 1 m long.
O2		Steeply dipping, well-bedded organics including branches, cones. Clast- to matrix-supported, matrix medium sand and granules.	Steeply dipping (25–30°), to 1 m thick	Organic unit. Well-preserved general litter and fine and coarse woody debris; rounding greater than O1, average diameter ~5 cm.

Table 1
(continued)

Facies		Description	Bedding	Visible organic detritus
O3		Clast-supported medium to coarse organics in a sandy matrix with common muddy interbeds. Fabric typically chaotic; organics may occur as lag.	Undulating channel form or as lenses; bottom contact typically erosional.	Organic unit. Densely packed general litter, fine and coarse woody debris with little matrix. Well preserved. Beds to 30 cm thick; surface exposure >75% organics.
O4		Cross stratified to cross-bedded channelized organic units in sandy matrix. Clast to matrix supported; organics are needles, bark fragments, cones.	Gently dipping or subhorizontal, channel cuts common	Major organic unit. Beds to 1 m thick consisting of >75% organics; well-preserved needles, general litter, rare fine woody debris.
OF1		Weakly bedded silt and organic unit. Organic units matrix supported, densely packed, silty matrix to open framework	Beds 1 cm to 10 cm thick, subhorizontal to undulating.	Well-rounded bark fragments, general litter, some fine woody debris, imbricated leaves
OF2		Coarse organics (branches to 10-cm diameter, sticks, root balls) in mud matrix. Tightly packed, clast-supported.	Irregular; often in lee of stranded root ball	Organic unit; variable from well-preserved leaves to fine woody debris. General litter most common; forms beds to 20 cm thick (>90% surface exposure).

Note. Facies coded by dominant grain size (G = gravel; S = sand; HS = heterogeneous (sandy); F = fines (a field-scale determination including silt and clay); O = organic; OF = organics in fine-grained units or with a fine-grained matrix). Numeric values indicate field-based description of fining of dominant grainsize within group (e.g., facies G2 is generally coarser grained than facies G3 but both dominated by gravel). Expanded after Stratton and Grant (2019).

and finer-grained facies indicative of alluvial environments appear to be limited to relatively thin veneers at about the former normal operating water surface elevation. This supposition is supported by grain size analysis of topset units, Rica Canyon sediments, and the Cat Creek Fan collected in 1994, which were measured to contain <5% silt and <10% fine sand (Gilbert & Link, 1995). Downstream of the subaerial delta plain, the delta top in former Lake Mills at the time of dam removal was a relatively small area of subaqueous mouth bar sands representing the zone of active deposition at the delta front, which appears to have developed as the result of basin shallowing due to interactions with the Boulder Creek delta but was poorly preserved during dam removal (Stratton & Grant, 2019).

Organic matter deposition in the delta plain and delta slope of former Lake Mills was extremely heterogeneous, making volumetric estimates of total carbon content difficult. As measured by Wing (2014), sediments in the G1 facies in former Lake Mills are negligible, with an average wt% TOC of 0.34 ± 0.08 (Table 2). However, irregularly occurring organic lenses in the delta plain and delta top depositional areas form discrete organic-rich, pockets. These organic-rich units consisted primarily of the O1 facies, characterized by fine woody debris forming open-framework lenses, and the O3 facies, a clast-supported unit composed of needles, general litter, and fine woody debris typically observed in discrete lenses or with an undulating channel form that pinches out downstream (Table 1). Other occurrences of organic matter in topset deposits consisted of stranded coarse woody debris ranging from root balls and single trees to large rafts of interlocked coarse woody debris (for example, at the uppermost head of the delta plain; Stratton & Grant, 2019); these occur both at the surface and interbedded with the G1 and G4 facies (a minor, finer-grained gravel facies).

The importance of coarse organic facies like O1 and O3 and storage of coarse woody debris to the overall carbon storage of the system is difficult to quantify. Wing (2014) did not collect samples representative of the O1 or O3 facies; however, O4, a secondary (i.e., dam removal-related) deposit similar to O3 was measured with a

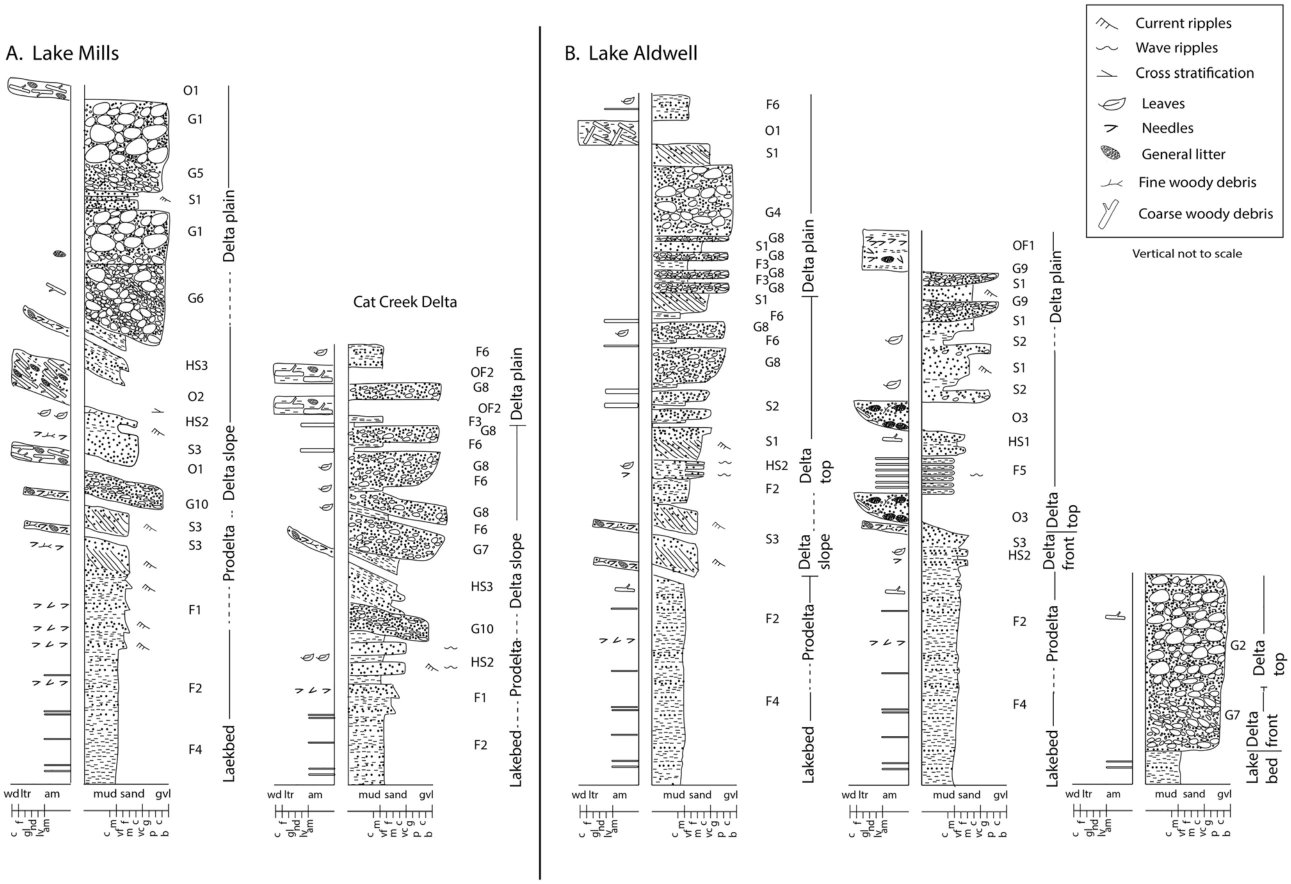


Figure 3. Representative stratigraphic columns, former Lakes Mills (a) and Aldwell (b) indicating typical facies and their assignment to the depositional zones delineated in Figure 1. Left axis represents organic matter-dominated units; right axis represents mineral-dominated sediments. Organic matter classification codes are explained in supporting information data. Facies codes are explained in Table 1. Cat Creek is a minor tributary near the head of former Lake Mills (Figure 2) and represents the only complete section preserved in reservoir sediments by the summer of 2014. Multiple columns in (b) reflect lateral variability in deltaic progradation and upper delta character in former Lake Aldwell.

wt% TOC of 12.77. Additionally, samples of coarse organic matter-dominated sediments collected from other systems have been measured in excess of 30 wt% TOC (e.g., Pondell & Canuel, 2017; Stratton, unpublished data). These concentrations suggest that despite their limited volume and irregular distribution, organic-rich lenses in the coarse-grained topset beds of former Lake Mills store significant volumes of carbon.

4.1.2.1. Delta Slope

While most coarse woody debris appears to have been confined to the delta plain, organic matter preserved downstream in the delta slope (foreset beds) and prodelta regions (Figure 2) contained abundant accumulations of fine woody debris, litter, and even occasional instances of large woody debris. Characteristic facies in the delta slope foreset and toeset beds included S3, O1, O2, G3, G6, G10, HS2, and HS3 (Table 1 and Figure 3), all of which, with the exception of the gravels, tend to be rich in visible detrital organics. The O1 and O2 units are similar, composed of interlocked, randomly oriented branches to 2–3 cm diameter and 50 to 100 cm long, but indicative of different environments. The O1 facies tended to occur as toeset runout and often shows evidence of winnowing (i.e., postdepositional removal of fine-grained material), while the O2 facies occurs as steeply dipping foreset beds as much as 1 m thick. Often, the O2 facies appears to cap a single, well-sorted sand bed, probably representing foreset progradation by flood events. In the O2 facies, clasts of woody debris are typically well imbricated and intact to well preserved, suggesting transport in traction but over relatively short distances; the O2 unit tends to be coarser than the O1 and complexly interbedded with sand and gravels. HS (for *heterogeneous, sand-based*) facies are finer grained and for the most part preserve needles and leaves in the lee of cross lamina. Beds to 5 cm thick of imbricated, well-

Table 2
Analytical carbon content data by facies

	TOC (wt%)				C:N				
Facies	avg	min	max	CI-95	avg	min	max	CI-95	n
G1	0.34	0.24	1.04	0.08	5.67	4.22	13.17	0.93	19
G4[a]	0.17	0.16	0.19	0.04	5.67	5.33	6.33	1.43	3
G8	0.25	0.23	0.26	0.18	7.15	6.34	7.97	10.25	2
G9[a]	0.17	0.13	0.20	0.03	4.33	3.25	5.00	0.70	6
S2	1.23	0.74	1.97	0.40	13.41	8.39	17	3.21	7
S3	2.19	0.36	5.02	3.16	18.9	6.28	31.55	16.97	4
S4[b]	1.3	0.24	4.47	0.29	13.49	4.93	29.22	1.77	45
O4	12.77	-	-	-	40.54	-	-	-	1
F1	1.26	0.87	1.76	0.23	12.61	10.15	16.07	1.45	10
MF2	2.02	0.95	3.88	0.52	16.33	12.54	24.56	2.13	13
AF2	1.83	0.57	3.03	0.34	15.45	10.21	22.11	1.69	16
F2	1.91	0.57	3.88	0.28	15.84	10.21	24.56	1.26	29
MF4	1.03	0.56	3.2	0.14	10.39	7.19	23.4	0.87	48
AF4	1.41	0.39	2.49	0.15	12.88	5.48	20.24	0.84	37
F4	1.2	0.39	3.21	0.1	11.47	5.48	23.4	0.66	85
F7†	2.2	0.83	6.24	0.67	16.98	9.87	25.04	2.53	17

Note. Where individual facies were well represented in samples from each reservoir, they were subset by reservoir: "M" prefix indicates samples from former Lake Mills; "A" prefix indicates samples from former Lake Aldwell; all others not distinguished by reservoir. CI-95 indicates 95% confidence interval. Facies included in Table 1 but not listed here are either minor components of overall deposition or were not sampled for inclusion in analytical data.
"M" prefix indicates samples from former Lake Mills; "A" prefix indicates samples from former Lake Aldwell; all others not distinguished by lake. CI-95 indicates 95% confidence interval. Facies included in Table B but not listed here are either minor components of overall deposition or were not sampled for inclusion in analytical data.
[a] Samples run after long-term storage using high-temperature combustion on a Thermo Quest EA2500 Elemental Analyzer. [b] Facies interpreted to be secondary only (i.e., deposited as part of dam removal drawdown).

preserved leaves occur throughout but represent a minor overall component of the facies (10% surface exposure or less).

With the exception of the Boulder Creek delta, the foreset beds in former Lake Mills were almost entirely excavated during the reservoir drawdown (although their pervasive presence in the delta was noted during a drawdown experiment documented by Childers et al., 2000, and anecdotally by scientists monitoring the early days of the dam removal; Bountry, personal communication, 2014). As a result, no data exist for the average organic content of the delta slope in former Lake Mills; however, data from Englebright Lake, which is defined by a similar Gilbert-style delta front, provide clues to the carbon load in former Lake Mill's delta slope. Core samples collected from the foreset beds of Englebright Lake appear to be strongly influenced by event-based sedimentation, with relatively fine-grained, background sedimentation averaging 0.9 ± 0.8 wt% TOC and distinct sandy units capped by organic detritus averaging 15 to 32 wt% TOC (Pondell & Canuel, 2017). This event-based interpretation is in keeping with data from the toeset/proximal prodelta beds of Lake Billy Chinook, a Gilbert delta-dominated reservoir on the Deschutes River, Oregon (USA) discussed further below (Stratton, unpublished data), and with the stratigraphic heterogeneity visible in exposures in former Lake Mills. Pondell and Canuel (2017) measured the average wt% TOC in Englebright Lake, including both background and event-based deposition, as 2.64 ± 5.95.

4.1.2.2. Prodelta

Downstream of the delta slope, Lake Mills was characterized by thick accumulations of organic-rich prodelta sands, designated the S3 facies (Figure 3). These sands were frequently interbedded with the F1 facies (discussed below) and with organic-rich facies O1 and HS2. The S3 facies is typically characterized by multistory, 10- to 50-cm beds of well-sorted fine to medium sand, typically showing planar to sigmoidal cross lamina and climbing ripples. Detrital organics may be absent or occur in two forms: (1) as dispersed clasts (typically intact to well-preserved conifer needles; more rarely, as centimeter-scale leaf fragments) trapped in the lee of current and climbing ripples or as interlamina within sigmoidal cross bedding and (2) as ≤4-cm interbeds composed of intact to well-preserved general litter and fine woody debris. These beds appear to cap the underlying individual sand beds and are frequently clast-supported to open framework. Closer to the delta toeset, the organic interbeds may reach 10-cm thickness and extend for tens of meters.

In samples collected from the Elwha reservoirs, the S3 facies has an average TOC of 2.19 ± 3.16 wt%. The large variance, while possibly reflective of the small sample number ($n = 4$), is more probably reflective of real heterogeneity within the unit at a scale difficult to capture in analytical samples, as in Englebright Lake, discussed above. Of the S3 samples collected from the former Elwha reservoirs, the reported TOC content ranges from 0.36 wt% to 5.02 wt%, reflecting the difference in carbon content between clean sand interbeds and those characterized by conifer needles and other detrital carbon. In organic-dominated beds, 5 wt% TOC is probably an underestimate. Samples collected from the proximal prodelta in Lake Billy Chinook have similar stratigraphy to the Elwha dams' transition from F1 to S3 facies and report average TOC of 2.81 ± 1.64 wt% and 4.51 ± 1.18 on two major arms (Stratton, unpublished data).

With increasing distance from the delta, prodelta sands were more frequently interbedded with the F1 and F2 facies (Figure 3). Occupying the longitudinal axis of the prodelta, the F1 facies was composed of ≥50% fine sand interbeds (to 15 cm thick) that formed a distinctive *striped mudstone* appearance and were extensive across the proximal prodelta area. Organics in the fine-grained lamina of the F1 facies tend to occur as 1 mm to 1 cm lamina of well-preserved to poorly preserved general litter and well-preserved needles in the lee of ripples. The sandy interbeds tend to be devoid of visible detrital carbon with the exception of discontinuous lenses of intact needles stranded in the lee and trough of current ripples, which, while visually prominent, do not appear to constitute a significant fraction of the sediment accumulation. This concentration of needles in ripple troughs is consistent with descriptions by Gastaldo (1994), who note that the mesodetrital fraction of organic matter often "behaves sedimentologically in a manner similar to that of mica ... dispersed across the bedding surface or concentrated in ripple troughs." (p. 115). TOC content for the F1 facies is 1.26 ± 0.23 wt%.

Occurring distally and marginally, the F2 facies represents the transition from purely suspended-sediment deposition in the basin to zones within the reservoir occasionally influenced by distal turbidity current outflow (Stratton & Grant, submitted). Within the F2 facies, organic interlamina are increasingly common with proximity to the delta, occurring as 1 mm to 1 cm lamina of well-preserved to poorly preserved general litter and well-preserved needles in the lee of ripples. In addition, F2 deposits in the prodelta are occasionally interrupted by lenses or channelized units of chaotically bedded needles, general litter, and fine woody debris in a matrix of poorly sorted silty sands. Where observed, these lenses were frequently associated with isolated coarse woody debris (roots, root balls, and trunks) and tended to have erosional bases. The F2 facies averages 2.02 ± 1.78 wt% TOC.

4.1.2.3. Lake Bed Sediments

Deposits in the distal basin (closest to the dam) in former Lake Mills were relatively homogeneous, consisting predominantly of the F4 facies (Table 1). Field observations of the F4 facies define it as mud, which appears to be relatively clay-dominated at the base and to coarsen upward to become silt-dominated. These observations are confirmed by Gilbert and Link (1995), who found that 100% of sediments in the former Lake Mills basin were <0.075 mm. The F4 facies typically has few visible organics; where present, organic deposits occur as irregularly spaced, millimeter-scale lamina. These lamina are recognizably organic in color only, consisting of poorly preserved, amorphous organic detritus. In addition to organic lamina, organics in the basin of former Lake Mills occasionally include isolated fine and coarse woody debris. Visible lamina appear to increase in frequency closer to the delta and to contain larger fragments of identifiable leaves and needles. Despite the relative paucity of visible organics in former Lake Mills, samples of the F4 facies average 1.03 ± 0.13 wt% TOC.

4.1.3. Lake Aldwell

Compared to the simple, Gilbert-style depositional model of Lake Mills, former Lake Aldwell, was considerably more complex (Figure 3b). For the first decade and a half of Lake Aldwell's impoundment, abundant sediment supply and a relatively shallow upper basin appear to have caused the rapid progradation of a Gilbert-style delta into the upper reservoir. However, with the impoundment of Lake Mills upstream, the bed load supply to former Lake Aldwell was essentially cut off, causing delta progradation to slow and shift in character. Deposited as an overprint on the distinct topset, foreset, and bottomset facies, the low-sediment

Aldwell delta was characterized by a stable, extensively vegetated *delta plain* (Figure 2) composed of interbedded sand, gravel, and silty facies and an extensive *delta top* with a low-angle *delta slope* formed by the progradation of sandy mouth bars. Toeset facies and prodelta sands were essentially absent, with the *prodelta* considerably finer-grained than former Lake Mills, beyond which extensive *lake bed* sediments were deposited.

4.1.3.1. Delta Plain

Quantification of carbon storage in the upper environments of former Lake Aldwell lacks adequate data. The prominence of organic-rich facies like O3 and F5 in the delta top and delta slope suggests that carbon concentration is high in these depositional zones. One sample of Facies O4, a secondary deposit analogous to, but finer-grained than Facies O3, is 12.77 wt% TOC. Similarly, the F5 facies, with its fine-grained proximity to inflowing organic material and its leaf beds, probably has relatively high TOC, but analogous systems report widely varying carbon content. Floodplain sediments from *partly confined younger forest* and *unconfined old-growth multithread* headwater streams in Colorado have been reported to contain as much as 12% TOC (Wohl et al., 2012); however, samples from floodplain sediments on the Middle Fork Snoqualmie, Washington, report median values of approximately 2.5% or less (Scott & Wohl, 2018), while samples from frequently inundated, low-lying floodplains in Quebec report average TOC of 1.74 ± 0.17 wt% (Saint-Laurent et al., 2016) and overbank sediments in rivers from the United Kingdom range from 2.17 to 5.07% (Walling et al., 2006). In contrast, samples from Facies G4, G8, and G9 in former Lake Aldwell average between 0.17 and 0.25 wt% TOC. Gravel-dominated areas of former Lake Aldwell thus appear to be extremely low in carbon.

4.1.3.2. Delta Slope and Delta Top

The active delta top and delta slope in former Lake Aldwell were more complex than in former Lake Mills. The delta slope prograded as subaerial mouth bars, grading from fine-grained gravels (G7) to finer-grained HS2 and S3 deposits with depth in the reservoir. As in former Lake Mills, the S3 facies showed significant accumulation of organic detritus. In former Lake Aldwell, organic accumulation frequently included fragmented leaves and general litter, as well as the needles characteristic of former Lake Mills. No analytical samples from mouth bar deposits in former Lake Aldwell were collected; however, estimates from the S3 facies of former Lake Mills (Table 2) provide a reasonable estimate and suggest that significant carbon is stored in the mouth bar deposits of former Lake Aldwell.

The delta top in former Lake Aldwell was characterized by deposits associated with both proximal active-channel mouth bar and quiescent interdistributary areas. Proximal mouth bar deposits were characterized by fine channel lag gravels interbedded with well-sorted sands capped by thin-bedded leaves, needles, and general litter (G8, S2). Channel scour into in the more distal delta mouth bar deposits were frequently infilled with Facies O3, which appears to have been deposited as lag (Spicer, 1989). Inactive portions of the delta top were characterized by heterogeneous sand facies with variable, coarse-grained coarse woody debris (HS1 and S1). In addition, the F5 facies, which consists of varve-like wave-rippled silt beds interbedded with horizons of mostly intact leaves several centimeters thick, was prominent in former Lake Aldwell. This facies was not observed in former Lake Mills.

4.1.3.3. Prodelta and Lake Bed Sediments

Downstream of the delta slope, the prodelta in former Lake Aldwell differed from former Lake Mills. While much of the former Lake Mills prodelta was dominated by the F1 facies, the F1 facies was essentially absent in former Lake Aldwell. Instead, the prodelta was dominated by the F2 facies. The mean wt% TOC in the F2 facies of former Lake Aldwell is 1.83 ± 0.34. In contrast to the F4 facies, this is not significantly different from the mean wt% TOC in F2 deposits in former Lake Mills.

As in former Lake Mills, the lakebed deposits in former Lake Aldwell consisted of the F4 facies. However, in contrast to former Lake Mills, where the lakebed facies were deposited in a single elongate basin, the basin area of former Lake Aldwell consisted of two subbasins separated by a submerged canyon known colloquially as *the gooseneck* (Figure 2a). The lower subbasin of former Lake Aldwell was the site of extensive deposition during the dam removal drawdown, with several meters of accumulated sediment in areas. We group these sediments as F7 (fine-grained) and S4 (coarse-grained) and note that they tend to be fairly rich in carbon (Table 1). However, because they do not represent operating conditions during the life of the reservoir, we do not consider them in detail. F4 facies deposited in each subbasin of former Lake Aldwell show no statistically significant difference in wt% TOC or C:N ratio and no longitudinal trend along the length of the reservoir ($R^2 = 0.0009$). However, both the mean wt% TOC and the mean C:N ratio of the F4 facies in former Lake Aldwell are significantly higher than in former Lake Mills ($p < 0.01$).

4.2. Organic Matter Provenance

Where is detrital carbon in reservoir sediments coming from? The stratigraphic prominence of detrital organics and correlation between visually organic-rich facies and higher concentrations of TOC, as discussed above, suggests that the former Lake Mills and Aldwell reservoirs were sinks for refractory pools of terrestrially derived carbon. While a detailed investigation would require a multiproxy approach utilizing biomarkers, isotopic analysis, and other methods, we can address this hypothesis at a broad scale by examining the ratio of carbon to nitrogen in samples collected from reservoir sediments by Wing (2014).

C:N ratios have long been utilized to infer trends in the source of sediment organic matter, predicated on the premise that terrestrial plant matter has a significantly higher C:N ratio than aquatic plants and phytoplankton (cf.Gordon & Goñi, 2003 ; Tyson, 1995). In general, the C:N ratio of fresh terrestrial plant material is typically between 20 and 200, although woody detritus in headwater streams may have C:N ratios as high as 250 to 1,340 (Tyson, 1995). On Vancouver Island, located directly north of the Elwha River watershed across the Strait of Juan de Fuca, Nuwer and Keil (2005) reported that fresh alder, maple, and fern leaves and hemlock needles to have C:N ratios between 36 and 46. After degradative processing, Tyson (1995) reports typical C:N ratios in terrestrial detritus as between 12 and 40, while recent sediments tend to range from the ones to teens. C:N ratios of >10–12 in estuarine or marine sediments are typically interpreted as indicative of terrestrial organic matter (Hyne, 1978; Tyson, 1995), while at the low end of the spectrum, phytoplankton, and other aquatic plants tend to have C:N ratios between 6 and 8 (Gordon & Goñi, 2003; Redfield et al., 1963).

The C:N ratios in former Lake Mills vary from 5 to 32, with a mean of 12 ± 1, while former Lake Aldwell varies from 3 to 22, with a mean of 13 ± 1 (Table 2). These values suggest that organic matter in both reservoirs is primarily derived from terrestrial input as opposed to autochthonous production. Spatial variation in C:N ratios, however, reveal intrareservoir trends in allochthonous input. Assuming that C:N ratio of ~19 measured in the S3 facies in former Lake Mills is applicable to former Lake Aldwell, the C:N ratio in the lower reservoir, as grouped according to characteristic facies, appears to decrease with distance from the river input. The F2 facies in former Lake Aldwell has a C:N ratio of 16, while the F4 facies has a C:N ratio of 13. We interpret this trend as evidence of the settling out of allochthonous material with distance from the delta. Former Lake Mills shows a similar trend, with the exception of the F1 facies (Figure 4b). Mean C:N ratios in the F1, F2, and F4 facies are all significantly different at the 95% level or better.

The strong relationship and positive slope between TOC and C:N in basin sediments of both reservoirs and the former Lake Mills prodelta sediments (Figure 5a) further suggest that higher TOC concentrations in these depositional zones are primarily the result of terrestrially derived carbon influx, as opposed to primary production. Similarly, the positive slope of the regression suggests that variations in TOC are the result of real changes in organic matter supply to basin and prodelta sediments, as opposed to *concentration* (or dilution) of the TOC signal with variation in sediment supply (which would tend to maintain a constant C:N ratio across a range of TOC concentrations). Although conclusive differentiation from soil carbon is not possible without additional proxies, the high overall C:N ratios suggest that this terrestrial influx is due to vascular plant debris, as opposed to soil matter. However, nonzero intercepts in the relationship between wt% TOC and total nitrogen (Figure 5b) also suggest the presence of inorganic nitrogen (probably ammonia, NH_4), which implies in-reservoir degradation products or a soil carbon influence.

However, former Lake Aldwell appears to have a more complicated relationship between wt% TOC and organic matter sources. Total nitrogen increases with wt% TOC more steeply in former Lake Aldwell than former Lake Mills, suggesting that higher TOC preservation may be the result of higher primary production (Figure 5b). The relationship between wt% TOC and C:N (Figure 5a) in former Lake Aldwell is more poorly defined than in the former Lake Aldwell basin or in former Lake Mills ($R^2 = 0.30$); relatively uniform, relatively high C:N ratios appear to contradict the relationship between wt% TOC and total N but probably actually reflect selective processing of proteins in phytoplankton during early diagenesis, increasing the C:N ratio (Tyson, 1995).

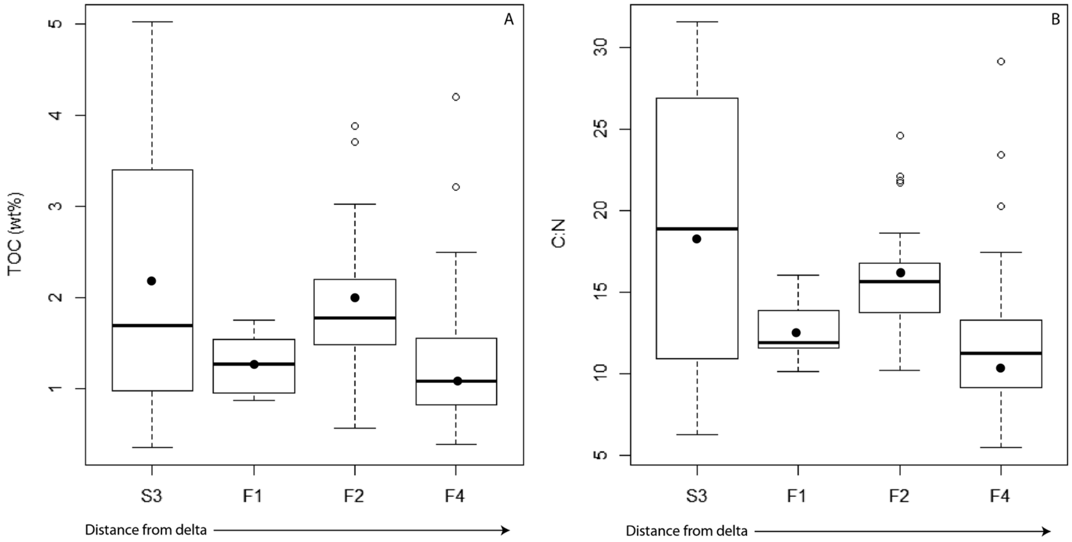


Figure 4. Whisker plot of prodelta and basin facies wt% TOC (a) and C:N ratio (b) in former Lake Mills. Black dots represent mean values; white dots represent outliers.

4.3. Carbon Accumulation by Depositional Zone: Toward Quantification of Carbon Storage

The depositional zones in each reservoir (Figure 2) are characterized by a set of typical facies, as discussed in section 4.1, above (Figure 3). Here, we estimate the average carbon content in each reservoir depositional zone and apply it to the sediment volume of that area as calculated from preremoval and predam DEMs (Bountry et al., 2011) to derive a zone-based estimate of total carbon accumulation in each reservoir (Table 3). Carbon content of facies without adequate sampling are estimated from literature.

Carbon storage in both former Lakes Aldwell and Mills appears to be concentrated in the delta slope/foreset depositional areas of the reservoirs, while the coarse-grained delta plain accounts for little storage (Table 3). While estimated foreset beds (including within the delta plain) in former Lake Mills represent only 14% of sediment deposition in the former reservoir, they account for ~30% of carbon storage (in contrast, lakebed deposits in former Lake Mills represent approximately 17% of total sediment volume but account for only 8% of carbon storage). This relationship also holds in former Lake Aldwell; however, former Lakes

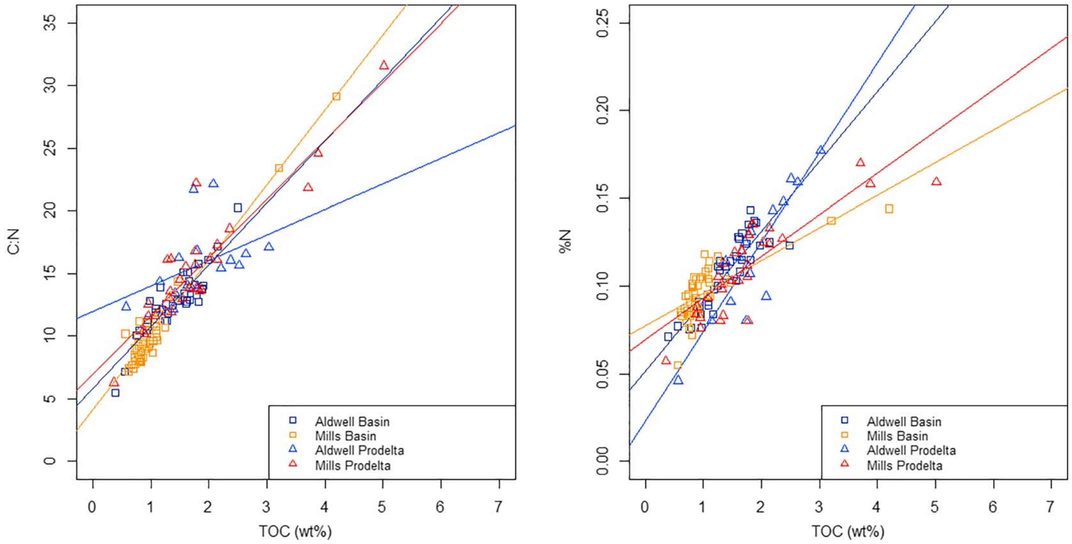


Figure 5. (a) Relationship between TOC and C:N by depositional zone. Former Lake Mills basin $r^2 = 0.9413$, prodelta $r^2 = 0.839$; former Lake Aldwell basin $r^2 = 0.7827$, prodelta $r^2 = 0.2953$. (b) Relationship between TOC and N by depositional zone. Note nonzero intercepts.

Table 3
Depositional Volumes and Estimated Area-Weighted Carbon Accumulation Rates

Depositional zone	Volume (m^3)	Volume (%)	Total mass (g)[d]	Avg TOC (weight %)	TOC (Gg)	% Carbon stored	TOC accumulation rate (gC · m^2 · year)
Lake Aldwell[a]	4.57E+06		6.73E+12		90.7		742
Lakebed	1.34E+06	28%	1.47E+12	1.41%	20.7	23%	415
Prodelta	3.87E+05	8%	4.26E+11	1.84%	7.8	9%	577
Delta slope	5.86E+05	12%	9.97E+11	2.19%[b]	21.8	24%	1,402
Delta top	8.63E+05	18%	1.47E+12	2.19%[b]	32.1	35%	2,414
Delta plain	1.40E+06	29%	2.37E+12	0.35%[c]	8.3	9%	263
Lake Mills[f]	1.51E+07		2.03E+13		320		*2,098*
Lakebed	2.51E+06	17%	2.77E+12	0.98%	27.1	8%	*416*
Prodelta	3.82E+06	25%	4.20E+12	1.76%	73.9	23%	*1,636*
Boulder Creek bottomset	*9.07E+04*	1%	9.97E+10	1.76%	1.76	1%	746
Delta plain bottomset	*2.17E+06*	*14%*	2.39E+12	1.76%	42.0	13%	*1,474*
Delta slope	7.08E+05	5%	1.20E+12	2.64%	31.8	10%	*9,262*
Delta top	6.80E+05	4%	1.16E+12	2.19%	25.3	8%	*8,880*
Delta plain foreset	*2.17E+06*	*14%*	3.69E+12	2.64%[e]	97.4	30%	*3,417*
Boulder Creek foreset	*9.07E+04*	1%	1.54E+11	2.64%[e]	4.1	1%	1,729
Delta plain topset	*2.17E+06*	*14%*	3.69E+12	0.35%[c]	12.9	4%	*453*
Boulder Creek topset	*9.07E+04*	1%	1.54E+11	0.35%[c]	0.5	0%	229
Cat Creek	6.02E+05	4%	8.43E+11	0.35%[c]	3.0	1%	590

Note. Average TOC as estimated from samples collected from depositional zones; where sampling was inadequate, literature values applied (as indicated in table).
[a] Lake Aldwell excludes landslide volume in delta plain. [b] Estimated from Facies S3, this study. [c] Estimated from Facies G1, this study. [d] Calculated using dry bulk density from Wing (2014). [e] Pondell and Canuel (2017). [f] Calculated by dividing thickness of Boulder Creek wedge and main stem delta plain into thirds representing topset, foreset, and bottomset beds, after Stratton and Grant (2019) and Gilbert and Link (1995)

Aldwell and Mills show different patterns of carbon storage in their lakebed and prodelta zones. While the prodelta sediments in both reservoirs are proportionally richer in TOC than the lakebed sediments, in former Lake Aldwell, the lakebed sediments are estimated as 1.41 wt% TOC and store an estimated 22% of the total carbon in the reservoir, while the prodelta sediments are estimated as 1.84 wt% carbon but store only 9% total carbon accumulation. In contrast, the prodelta sediments in former Lake Mills are similar in carbon content (1.76 wt%) but, due to the volume of prodelta sediment accumulation, store approximately 23% of the total carbon in the reservoir while the lakebed sediments store approximately 8%. As estimated, the coarse-grained delta plain accounts for disproportionately little carbon storage relative to its accumulation rate; these values, however, are almost certainly underestimates, as they do not account for fine-grained deposition in the heterogeneous facies discussed above.

Based on the depositional zone-weighted calculations discussed above, we estimate that approximately 91 Gg of carbon was stored in former Lake Aldwell prior to its removal, with TOC accumulation rates per depositional zone ranging from 263 to 2,414 gCm^2/year (Table 3). Former Lake Mills is estimated to have stored approximately 330 Gg of carbon, with TOC accumulation rates per depositional zone ranging from 229 to 9,262 gCm^2/year. Given the necessary assumptions for this estimate, a numerical estimate of error is difficult to determine. However, we discuss potential sources of error, as well as the merits of this approach, below.

5. Discussion

Most previous studies of carbon burial in lake and reservoir sediments have assumed that storage is concentrated in relatively homogeneous, fine-grained portions of the reservoir and excluded deltaic regions (explicitly or implicitly) from sampling coverage (e.g., Mendonça et al., 2014; Sobek et al., 2009; Sobek et al., 2012). This approach is based on the well-established negative correlation between grain size and TOC (Hedges & Keil, 1995; Tyson, 1995), and the assumption that sand and gravel units are essentially devoid of carbon, as "larger [organic] material (>100 um) may be conspicuous … [but] its contribution to the transported load is generally insignificant" (Tyson, 1995). However, our characterization of carbon storage in former Lakes

Mills and Aldwell shows that while fine-grained sediment deposited as the result of suspended sediment fallout is important to carbon burial in reservoirs, it is moderate in comparison to storage in the complex, coarse sediment-dominated deltaic and delta-adjacent portions (Figure 3 and Table 3).

The deposition of coarse organic matter appears to be associated with event sedimentation, leading to complex patterns of organic matter burial, in both deltaic and prodelta regions, which vary between reservoirs. Gilbert and Link (1995) show that grain size in former Lake Mills progressively decreased downstream of the delta, with toeset/bottomset (proximal prodelta) sediments composed of as little as 33% undifferentiated silt and clay, while samples designated prodelta consisted of 88% undifferentiated clay and silt and 100% of basin sediments were composed of silt and clay. The typical negative correlation between grain size and average TOC would thus predict that TOC increases downstream in former Lake Mills. However, the prodelta sands (characterized by the S3 facies) average 2.19 ± 3.16 wt% TOC, while the F1 facies (characteristic of the proximal prodelta) averages 1.26 ± 0.23 wt% TOC, significantly less than the F2 facies (2.02 ± 0.52; $p = 0.011$) characteristic of the distal prodelta, and the F2 facies and the F4 facies is significantly greater than the average wt% TOC of the F4 facies characteristic of the lacustrine basin (1.03 ± 0.14; $p = 0.0027$; see stratigraphic column in Figure 3). We interpret this pattern to represent the importance of turbidity currents and deltaic slope failure, probably triggered by high-flow events. In former Lake Mills, deltaic processes appear to concentrate coarse organic matter in the toeset facies, while turbidity currents moving downslope carry organic matter beyond the proximal prodelta, which is characterized by interbedded fine-sand-and-silt F1 facies, to be deposited with the finer-grained F2 facies deposited as the distal runout of turbidity currents. However, the F1 facies is absent in former Lake Aldwell, probably as the result of less influence from turbidity currents associated with steep delta slope failure, as appears common in former Lake Mills. This interpretation is supported by the C:N relationships shown in Figures 4b and 5, which suggest a strong terrestrial signal that decreases with distance from the delta.

While few studies have assessed coarse organic matter in reservoirs, the limited evidence suggests that former Lakes Aldwell and Mills are not unique in their accumulations of coarse organic matter. In a study of six Gilbert-style tributary deltas exposed during a severe drought at Trinity (Clair Engle) Lake on the Trinity River in California (USA), Spicer and Wolfe (1987) described continuous beds of organic material composed of large pieces of twigs and cones and other plant material in the toeset beds and along the contours of sandy foreset beds. Additionally, a coring-based study at Englebright Lake, a multi-use, medium-sized reservoir on the Yuba River in northern California (USA), reported sandy deposits of *wood and leaf matter* in foreset/toeset deposits of the Gilbert-style deltas (Pondell & Canuel, 2017; Snyder et al., 2006). Our study, one of few to sample from coarse-grained reservoir, calculated an annual burial rate of 6,600 $\mathrm{gC \cdot m^2 \cdot year}$ (as compared to the commonly cited global estimate of ~400 $\mathrm{gC \cdot m^2 \cdot year}$ burial in reservoir sediments; Cole et al., 2007). Further, evidence suggests that thick accumulations of organic material are not limited to depositional environments associated only with small, low-order streams. For example, a study of TOC distribution in two large reservoirs in Texas found that higher carbon concentrations were associated with deltaic areas than the distal, lacustrine portions of the reservoirs (Hyne, 1978). In contrast, Spicer (1989) found significant plant matter accumulation in the delta of a small (0.013 $\mathrm{km^2}$), ca. 1815 reservoir in England, while Gastaldo et al. (1987) reported bedded leaf-litter horizons as much as 3 cm thick in delta mouth bar sands and active crevasse channels (morphologically similar to former Lake Aldwell) in the Mississippi River delta offshore of Mobile Alabama and interpreted them as the result of event deposition, which, when saturated, serve to baffle against the transport of sand and encourage burial of organic beds.

The location of reservoirs like former Lakes Mills and Aldwell in forested mountainous regions on a sixth-order stream suggests that coarse particulate organic matter and woody debris are likely to comprise a significant portion of the riverine organic load. In a detailed study in the western Oregon Cascades (a climate similar to that of the Elwha watershed) Naiman and Sedell (1979) found that coarse organic matter (>1 mm) represented a mean of 50.0% of the benthic organic matter load in Lookout Creek, a fifth-order stream, and 40.4% of the benthic organic matter load in the McKenzie River, a seventh-order stream. These numbers, which excluded large wood >10 cm in diameter, were shown to be highly seasonally dependent, with coarse particulate organic matter present in concentrations up to 69.2% during the spring freshet. Similarly, Goñi et al. (2013) found that particulate organic matter export from two small, mountainous rivers in the Pacific Norwest was dominated by winter high-flow events, while Turowski et al. (2016) found that carbon discharge from mountain streams was dominated by coarse organic matter; when floods were included, coarse organic matter accounted for 80% of organic carbon discharge. Large woody debris also appears to comprise a significant portion of export from mountainous watersheds. Seo et al. (2008) found that large woody debris averaged 15% of total particulate organic carbon export from 121 dammed watersheds in Japan, while Rathburn et al. (2017) found that a large log raft, similar to that removed from the head of former Lake Mills prior to drawdown, accounted for approximately 20% of the long-term carbon storage rate in a small reservoir on a fourth-order stream in the Colorado (USA) Front Range.

We believe our estimates of carbon burial to be the most methodologically robust yet completed for reservoirs globally, but they should be viewed with several caveats. First, because Glines Canyon and Elwha dams were removed in stages, sediments remaining in the reservoir basins after dam removal were heavily biased toward basin and prodelta facies. As a result, the basin and prodelta facies of former Lakes Aldwell and Mills are well represented in the analytical sampling results and we have a high degree of confidence in estimates from these regions. However, the more heterogeneous upper facies are poorly represented in the available data and rely on literature estimates from similar systems. Additionally, woody debris is not explicitly accounted for our estimates of carbon burial, suggesting that actual values may be significantly higher (cf., Rathburn et al., 2017). Our estimates of deposition in heterogeneous regions are thus subject to a great deal of uncertainty; however, we believe our literature-based carbon concentrations to represent relatively conservative values.

Additionally, quantification of carbon in these coarse-grained sediments represents a significant challenge. Because transport and deposition of coarse-grained material (both sediment and detrital organic material) are typically event-based, organic delivery may be seasonally controlled (Ambers, 2001; Naiman & Sedell, 1979; Senter et al., 2017; Snyder et al., 2006; Turowski et al., 2016). Additionally, because organic material is both (1) irregularly shaped and (2) variably dense depending on its relative saturation (Gastaldo, 1989), the transport and accumulation of coarse-grained organic matter in sediments are uniquely difficult to predict. Further, the scale of coarse organic matter, combined with the scale of heterogeneity in the facies architecture of reservoir sediments, makes the determination of a representative sediment volume problematic, and, once collected, most analytical methods are not equipped to measure coarse-grained material. Additionally, coring-based studies are unlikely to collect the full scale of woody debris stored in reservoir sediments due to of its irregular shape and large diameter relative to the core barrel.

Previous efforts to determine predictive factors of carbon burial rates in reservoir sediments have relied on characteristics such as impoundment size, average temperature, catchment runoff, watershed cultivation, operations, longitude, or average slope. These efforts have had limited success, however, with results showing contradictory or weak explanatory relationships (cf.Clow et al., 2015 ; Downing et al., 2008 ; Mendonça et al., 2017 ; Ritchie, 1989). The work in former Lakes Mills and Aldwell suggests that while external factors such as watershed setting are indeed critical to understanding the supply of organic matter, carbon storage and spatial distribution in reservoirs cannot be assessed without an understanding of the dominant depositional processes operating in that system, including an understanding of the influence of an upstream impoundment on carbon accumulations. As discussed above, organic matter storage in former Lake Mills appears to be concentrated in the foreset beds and prodelta regions of the reservoir. Neglecting organic matter storage in these regions and estimating total carbon storage in former Lake Mills based only on fine-grained, lacustrine zone samples (average wt% TOC 0.98%), as is common in many reservoir studies, would result in an ~47% underestimate of total carbon storage in former Lake Mills. In contrast, while organic matter storage in former Lake Aldwell is also delta-associated, as compared to former Lake Mills, the deltaic volume (both relative and absolute) in former Lake Aldwell is much lower. As a result, a similar, lacustrine-based sampling scheme would differ from our depositional zone-based estimates by only about 5% (based on average wt% TOC of 1.41%). However, if that sampling location were to instead represent the large prodelta region (average wt% TOC = 1.84%), the resulting carbon estimate would yield a 30% (33 Gg C) *overestimate* of total carbon storage.

6. Conclusions and Implications

While the estimates of total carbon burial in former Lakes Aldwell and Mills developed here are inevitably case-specific, the stratigraphy-based estimates of organic matter accumulation in former Lakes Mills and

Aldwell illustrate both the importance of deltaic sedimentation and the importance of coarse organic matter to carbon storage in artificial reservoirs and other lacustrine environments. Studies of reservoirs dominated by Gilbert-style deltas that fail to account for the importance of the foreset beds and prodelta regions to the storage of coarse organic matter stand to underestimate total carbon burial by up to 50%. While probably an oversimplification, Gilbert-style sedimentation remains the accepted *typical* paradigm in deep lakes and artificial reservoirs (e.g., Morris & Fan, 1998). Given the importance of particulate organic matter and woody debris to carbon storage in former Lake Mills and its location damming a mountainous, forested watershed, we suggest that (1) coarse organic matter deposition is probably underappreciated across a wide range of lacustrine environments, (2) dams in mountainous environments may represent a greater disruption to the global carbon budget than previously appreciated, and (3) the underestimation of organic matter storage in the coarse sediments of reservoirs is probably significant at a global scale.

Because organic matter stored in reservoirs constitutes a fraction of the sediment itself, it cannot be characterized in isolation from sedimentation processes and the exogenic and endogenic factors that influence them. Additionally, the added complexities of variable density (i.e., varying saturation), complex shapes, seasonal fluctuations in organic matter supply, and subsequent biogeochemical processing, further complicate the dynamics of organic matter sedimentation and long-term storage in reservoirs. However, by using stratigraphic characterization as a tool to understand the processes influencing sediment and organic matter transport and deposition, this work provides a framework to tease out the controls on carbon storage in reservoir sediments and other lacustrine environments, to better understand the fundamental role of rivers and lakes in the global carbon cycle, and to investigate the global impact of dam construction on global biogeochemical cycles.

While the opportunity to investigate reservoir sediments exposed in cross section is limited to dam removals or deep reservoir drawdowns, coring-based stratigraphic interpretation can be used to develop well-supported stratigraphic frameworks for a variety of depositional environments (c.f. Huc, 1990), particularly when utilized in concert with seismic and other remote sensing methods (cf. Mendonça et al., 2014). However, extensive coring campaigns and the collection of seismic data may be prohibitively expensive. As such, the development of robust stratigraphic frameworks for a broad range of reservoir sizes (both area and volume), operational regimes, and geographic settings could help identify the complete suite of anticipated depositional zones in a reservoir or lake setting and effectively target sampling campaigns in individual reservoirs.

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