Reservoir Sediment Carbon along the Elwha River after Dam Removal

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1. Introduction

The recent removal of two dams from the Elwha River of Washington State's Olympic Peninsula has provided a unique opportunity to assess sediment carbon of two former reservoirs that is now developing into a soil. The removal of these dams was completed by the United States Department of the Interior, Olympic National Park, under the requirements set forth by the Elwha River Ecosystem and Fisheries Restoration Act, Public Law 102-495, passed by congress in 1992. Enacted to restore the Elwha River, specifically the native anadromous fisheries therein, the removal of these two dams has exposed over 18.5 million m^{-3} of sediment between both former Lake Mills and Lake Aldwell (Bountry *et al.*, 2010). The 64 meter tall Glines Canyon Dam on former Lake Mills is the largest dam ever removed in the United States (Gregory & Li, 2002) and no empirical studies on the effects of dam removal at this scale have been completed (Chenoweth, 2007). Few disturbances compare to the removal of the Glines Canyon and Elwha Dams in terms of exposing a landscape empty of vegetation, aside from volcanic or glacial events. The drawdown of Lake Aldwell exposed 107 ha of soil and sediments inundated nearly 100 years, and the Lake Mills drawdown has exposed 167 ha of land after more than 80 years of inundation.

Reservoirs can have dramatically dissimilar characteristics from natural water bodies due to hydrologic, physiochemical, and biologic factors controlled by dam release cycles as well as altered stream flow. This ultimately leads to significant variability in seasonal hydraulic retention time, or the average time a suspended compound remains in a reservoir (Park *et al*., 2009). Many studies have looked at carbon cycling in natural rivers and lakes, however few have considered reservoirs (Kim *et al*., 2000). Given that impoundments like the ones once found on the Elwha River are common in many locations throughout the globe for water supply, flood control, and power generation, it is critical to understand how they influence natural ecosystems, as well as global chemical cycling. Several studies have quantified organic carbon content within sediments of natural freshwater lakes, showing a preservation rate of sequestered carbon to be 50 times higher than that in oceans (Einsele *et al*., 2001). Additionally, small lakes (<500 km^2) similar to that of Lake Mills and Lake Aldwell, commonly bury carbon at higher rates than larger lakes (Einsele *et al*., 2001), and reservoirs are thought to bury carbon at rates three times that of natural impoundments (Dean & Gorham, 1998; Mulholland & Elwood, 1982; Stallard, 1998). Watershed size also contributes to the rate at which organic carbon is buried within these depositional environments (Downing *et al.*, 2008). Given that the Elwha watershed is the largest on the Olympic Peninsula, it likely plays a significant role in local and global ecology and carbon cycling.

The increase of carbon-based greenhouse gases in our atmosphere has led to the need to make direct measurements of Earth's carbon pools for validating global carbon budgets. Direct measurement of these pools has mainly been focused on the major compartments of Earth's carbon, such as the atmosphere, living and dead biomass, and the oceans. However, measurements have been made on other possible pools within the carbon budget. One of these potential sinks of carbon is freshwater lakes and reservoirs (Mulholland & Elwood, 1982; Ritchie, 1989). These freshwater features account for 0.4% of the earth's total surface, a number which is rising as more dams are built globally (Wetzel, 2001). Deposition of soil and organic matter into reservoirs such as Lake Mills and Lake Aldwell, along with primary production within the lakes themselves, provide an abundant source of organic carbon in mineral sediments; a sink of carbon that is often overlooked, that plays a significant role in global carbon dynamics.

Reservoirs are known to affect the global carbon cycle by burying terrestrial carbon in sediments and by emitting greenhouse gases such as carbon dioxide and methane (Battin *et al*., 2009; Cole *et al*., 2007; Dean & Gorham, 1998; Stallard, 1998). Reservoirs have increasingly been acknowledged to sequester sizable amounts of carbon that would otherwise enter oceans (Battin *et al*., 2009; Cole *et al*., 2007). Dams have also altered the transfer of sediment from land to sea, decreasing stream and river particle loads by >50% and decreasing river sediment carbon (Vörösmarty *et al*., 2003). Thus, while reservoirs can store large quantities of carbon in sediments they are also known to release carbon to the atmosphere. Previous estimates indicate emissions from these impoundments reach 321 Tg of carbon per year globally (St. Louis *et al*., 2000). Temperate reservoirs, like former Lake Mills and Lake Aldwell, have been estimated to produce 300 Tg of CO_2, 4 Tg of CH_4, and 70 Tg of carbon total per year (St. Louis *et al*., 2000). With the drawdown of both Lake Mills and Lake Aldwell, anaerobic conditions for a portion of the sediments left behind will likely shift to an aerobic environment, possibly lessening the respiration of CH_4. The introduction of vegetation will also increase above ground carbon to the site and introduce carbon to sediments through roots and litter-fall.

The Elwha River is the fourth largest river of the Olympic Peninsula and provides drainage of its largest watershed. Most of the river lies within the boundaries of Olympic National Park, with the northern terminus and former Elwha dam lying just outside park boundaries. Dam removal on the Elwha River was performed in increments over a three year period starting in 2011. This was done in an effort to minimize sediment erosion in both reservoirs, as the most serious concern with any dam removal is the management of sediment accumulation (Childers *et al*., 2000). Former Lake Aldwell's Elwha Dam was a 32 m tall gravity dam built between 1910 - 1913. Former Lake Mill's Glines Canyon Dam was a 64 m tall concrete arch dam built in 1927. The decision to remove these two dams came in 1994 after two environmental impact statements were completed to better understand alternatives to the restoration of the Elwha River ecosystem as mandated by Congress. These reports made it evident that dam removal was the only viable options for a complete restoration.

Of the sediment trapped behind both the Glines Canyon Dam and the Elwha Dam, about 52% was very fine (≤ 0.075 mm) and 48% was coarse prior to dam removal (USDI Bureau of Reclamation, 1995). It is estimated that 15-35% of coarse sediment, and 50% of fine sediment would be eroded after the dams were removed (USDI Bureau of Reclamation, 1996). This indicates that most sediment will remain within the former reservoirs. Most of the coarse sediments have been deposited into a dynamic complex of deltas where the Elwha River, Cat Creek, and Boulder Creek converge at the southern portion of former Lake Mills, at points reaching depths over 20 m. In former Lake Aldwell the same holds true, with a majority of coarse sediments being deposited in the southern delta region of the lake, with depths of 5 – 7 m expected (USDI Bureau of Reclamation, 1995). Fine sediments generally are found below a layer of coarse mineral material, and exist in greater quantities downstream of the deltas in both former reservoirs. These fine sediments are relatively uniform, with nearly 95% of the fraction being clay and silt-sized and a 5% component of fine sands (USDI Bureau of Reclamation, 1995). The fine sediments of silts and clays are expected to erode faster than the coarser sediment (Mussman *et al*., 2008), and will stay in suspension much longer during transport than coarse materials that move primarily by saltation and surface creep. Once the Elwha River incises through the sediments of former Lake Mills and Lake Aldwell to find an established path, remaining sediment is expected to stay in place as a series of terraces along the margins of both former lakes.

The National Park Service has implemented an extensive restoration initiative to expedite native plant propagation on these recently uncovered sediments. This plan has been initiated to hinder the establishment of invasive species, restore native habitat, and stabilize sediments from erosion. Planting on these new sediments will reduce runoff flow velocities, increase soil stability, and increase water infiltration (Whisenant, 2003). Along with plant propagation, large woody debris can also have a positive influence on revegetation and restoration of riparian habitat. Restoration staff and the Elwha River itself have placed large woody debris in and on sediments. This debris can be very important to limit the erosive process. On the upper slopes of Lake Mills and Lake Aldwell woody debris is expected to slow sediment movement (Mussman *et al*., 2008), provide organic matter and some nutrients to plantings, increase moisture retention, and provide protected spots for natural plant regeneration (Chenoweth *et al.*, 2011). This will accelerate the establishment of native species such as graminoids in fine textured sediments and trees and shrubs elsewhere (Chenoweth, 2007).

The objective of this thesis is to provide detailed information and insight into the location, content, and concentration of sediment carbon of two former reservoirs of the Elwha River: Lake Mills and Lake Aldwell. This information is meant to serve three overarching purposes: the first to serve as a baseline study and account of carbon in these sediments, allowing researchers to reassess carbon in these sediments and quantify change. This will enable a better understanding of how dam removal affects a local and global carbon budget. The second is to provide more detailed information on how much carbon small reservoirs in temperate regions hold. Small reservoirs hold a surprising amount of carbon, yet have had little attention within the scientific research community. This research will help provide insight into the quantity of carbon held in these depositional environments. Lastly, chemical analysis of these sediments will allow for better implementation of revegetation techniques from those working on the Elwha River restoration. Knowing where organic carbon and nitrogen are located, and in what quantities, gives restoration managers information about sediment properties directly affecting plant growth and propagation.

2. Literature Review

The fundamental mechanism of sediment transportation from continents to the ocean is through rivers. Early attempts to quantify total sediment transport by world rivers range between 12.7 Pg yr^{-1} to 58.1 Pg yr^{-1} (Holeman, 1968). More recent research has refined this figure to 19 Pg yr^{-1} with a 95% confidence interval of 11 – 27 Pg yr^{-1} (Beusen *et al.*, 2005). This transport of material and combined aquatic photosynthetic activity has consequently buried a surprisingly high amount of carbon within the Earth's lake basins and reservoirs. The burial of organic carbon in lakes has been estimated within the range of 30 to 70 Tg yr^{-1} (Dean & Gorham, 1998; Einsele *et al.*, 2001; Mulholland & Elwood, 1982), while reservoirs are thought to have burial rates over three times that, accumulating 150 to 220 Tg yr^{-1} of carbon (Dean & Gorham, 1998; Mulholland & Elwood, 1982; Stallard, 1998). One study by Downing *et al.*, (2008) suggests that the annual burial of organic carbon in the impoundments of Earth's farm ponds is similar to the carbon storage of all ocean sediments; which accumulate organic carbon at an estimated rate of 100 Tg yr^{-1} (Dean & Gorham, 1998).

Excluding the Black Sea, lakes account for about 0.4% of the surface area on Earth, with the 20 largest lakes encompassing 51% of this global lake area (Leeden *et al.*, 1990). As of 1982, the total area of reservoirs on earth was about 400,000 km^{-2} (Mulholland & Elwood, 1982) and has been increasing since. Like former Lake Mills and Lake Aldwell, these reservoir areas receive carbon input in three major ways: allochthonous and autochthonous inputs as well as inputs from wind. Allochthonous inputs are those from organic and inorganic materials from inflowing rivers and streams coming from a terrestrial watershed. Autochthonous inputs are produced *in situ*, by phytoplankton and aquatic macrophytes, which are generally the major decomposers of organic carbon and nutrients in these aquatic systems (Kritzberg *et al.*, 2005).

The rate at which organic carbon accumulates in lake and reservoir sediments directly depends on the rate of input from these sources minus the rate at which these carbon sources are oxidized within the aquatic setting. Not surprisingly, it has been shown that aquatic carbon and sediment accumulation is greatest in small reservoirs with high surface area to watershed area ratios (Einsele *et al*., 2001), like that seen in Lake Mills and Aldwell, where the relative size of both reservoirs (< 2 km^{-2}) is small in comparison to their watershed area (831 km^{-2})

Although few studies have quantified carbon sequestration in sediments of small reservoirs of temperate regions, it is clear they bury an exceptional amount of carbon in relation to other aquatic systems. Mulholland & Elwood (1982) estimate through a meta-analysis that organic carbon concentration of reservoir sediments across the United States is relatively constant from 1.5 to 2% which is generally less than lake sediments. Ritchie (1989), states that the carbon concentration of small reservoirs has a wider range than what was found by Mulholland & Elwood (1982), varying from 0.3 to 5.6%, with a mean of 1.9 ± 1.1%.

Dry bulk density for these reservoir sediments within the United States generally fall between 0.7 to 1.3 g cm^{-3} (Dendy & Champion, 1978). Because reservoirs tend to receive higher accumulation rates of sediment per year than do lakes, about 2 cm yr^{-1} on average within the United States (Mulholland & Elwood, 1982), these impoundments have a greater sequestration rate of total organic carbon by volume. This is estimated to be close to 350 to 400 g C m^{-2} yr^{-1} within the United States and 500 g C m^{-2} yr^{-1} within reservoirs globally (Dean & Gorham, 1998; Mulholland & Elwood, 1982). Ritchie (1989) found that small reservoirs within the U.S. have a wide range of sedimentation rates, from 26 to 3,700 g C m^{-2} yr^{-1} with a mean of 675 g C m^{-2} yr^{-1}.

Burial and preservation rates of carbon in the forms of large woody debris, fine particulate organic carbon, and dissolved organic carbon in reservoir settings are usually very high in comparison to large lakes and oceans (Dean & Gorham, 1998). Of these carbon varieties, dissolved organic carbon is generally the largest constituent within a lake, often being 10 times greater in quantity than particulate organic carbon (Wetzel, 2001). Over 75% of particulate organic matter released by phytoplankton decomposes rapidly within the trophogenic zone by the time it reaches the sediment interface (Wetzel, 2001). Though degradation of organic matter increases with water depth, there is generally an increase in the relative accumulation of sediment organic matter at these same deep locations. This is often due to a decrease in available area for sediment to settle as a lake becomes deeper, as well as a decrease in turbulence along the sediment-water interface (Wetzel, 2001). Preservation of this down-falling organic matter has been shown to be 10-25% (Kelts, 1988). This is 50 times higher than in Earth's oceans, which have a mean preservation rate of 0.2-0.4% for organic carbon (Einsele *et al*., 2001).

Beyond sequestering carbon in sediment, reservoirs also serve as a significant source of greenhouse gas emissions. Previous estimates indicate emissions from these impoundments reach 321 Tg of carbon per year globally (St. Louis *et al*., 2000). Temperate reservoirs have been estimated to produce 300 Tg of CO_2, 4 Tg of CH_4, and 70 Tg of carbon total per year (St. Louis *et al*., 2000). Hydroelectric dams, such as the Glines Canyon and Elwha Dams, constitute approximately 20% of all reservoirs and emit about 48 Tg of CO_2, and 3 Tg of CH_4 annually (Barros *et al*., 2011). Reservoirs are thought to contribute 4% of total anthropogenic CO_2 emissions, 18% of CH_4 emissions, and 4% of total carbon emissions (St. Louis *et al*., 2000). Reservoir creation is not greenhouse gas neutral and has a measurable carbon flux on a global scale. Although tropical reservoirs have proven to have higher rates of carbon emissions than temperate reservoirs, small temperate reservoirs like Lake Mills and Lake Aldwell still hold a large amount of carbon that plays a significant role in the global carbon budget.

3. Methods

Study Site Description

The 72 km long Elwha River is the main drainage for the largest watershed on the Olympic Peninsula of Washington State, emptying an area of 831 square kilometers. Eighty three percent of this area is located within Olympic National Park. The river bisects the northern portion of Olympic National Park, eventually emptying into the Strait of Juan de Fuca, and is the fourth largest river by discharge on the Olympic Peninsula (Childers *et al*., 2000). Most of the river lies within National Park boundaries, with the northern terminus lying just outside its extent (Map 3.1).

The Olympic Mountains that feed the Elwha River began during the Eocene as Crescent Formation basalts, erupting close to the North American continent in a marine setting. During the mid-Eocene this formation was deformed due to accretion onto the North American plate, and eventually thrust upwards during the late Miocene (15 to 20 million years ago). The northern section of the Olympic Peninsula, where the Elwha Watershed presides, was subject to significant erosion by continental ice sheets during the Pleistocene, which ultimately scoured and sculpted much of the Olympic Mountains that are visible today. Upstream from Lake Mills, the Elwha Watershed lays entirely in a formation known as the eastern core, which is comprised largely of Eocene and Oligocene age slate. Visible formations are known informally as the Elwha and Grand Valley assemblages, which consist mainly of phyllite, slate, and sandstone with lesser amounts of basalt, conglomerate, and other rock types (Tabor & Cady, 1978). The Olympic Mountain’s geologic transformation continues today, as alpine glaciers continue to alter the landscape in the upper reaches of this watershed.

The headwaters of the Elwha River are found in the highly glaciated peaks east of Mount Olympus (2,432m). From these peaks, this river and its tributaries flow through glaciated U-shaped valleys, often cutting into thick glacial alluvium (Childers *et al*., 2000). The Elwha River watershed's surficial geology is composed of alluvium (2.3%), alpine glacial till (0.08%), basalt flow (13%), continental sedimentary deposits (~0.01%), continental glacial till and outwash (2.51%), glaciolacustrine deposits (1.5%), marine sedimentary deposits (77%), mass-wasting deposits (1.4%), and volcanic rock (0.07%), with water bodies making up 2.4% of the Elwha Watershed area (Washington State Department of Natural Resources, 2010) . Soil characteristics for the majority of the Elwha River watershed are still largely unknown, as much of it lies within Olympic National Park which has had no formal soil survey completed to date.

Due to the effects of atmospheric orographic lifting over the Olympic Mountains, the precipitation gradient across the Elwha River watershed is significant. At the headwaters of the Elwha River, Mount Olympus has an average precipitation rate of over 500 cm yr^{-1}. Below the summit of this mountain, the rate drops to about 355 cm yr^{-1}. As the river moves north, precipitation continues to drop; former Lake Mills normally receives 180 cm yr^{-1} of precipitation, and former Lake Aldwell's northern shore receives less than 130 cm yr^{-1} on average. At the furthest point north on the Elwha River, precipitation declines further, where 75-100 cm are received annually (Daly, 2010). With the Elwha's change in elevation comes a change in snow accumulation from south to north. Below 300 m in elevation, winter precipitation is mostly rain, between 300 and 750 m there is a mix of snow and rain, and above 750 m snow is most common. At low elevation stations in this region, the lowest recorded temperatures are -16 to -19°C, while the highest have been 34 to 40°C. The average temperature during January is close to 0°C, while the average for august is 21°C (Houston *et al*., 1994).

The average flow rate of the Elwha River, as measured from the McDonald Bridge, for the 80 year period between 1914 and 1994 was 42 m^{-3} s^{-1} (Federal Energy Regulatory Commission, 1991). Maximum flow rates generally occur from November to February from rain and snow fall, as well as from May to June from snowmelt. Minimum flows generally occur during late summer and early fall, which usually range from 9 to 14 m^{-3} s^{-1} (Childers *et al*., 2000). The largest flood event on record since the building of the Glines Canyon dam was in 2007, where water flow of 1,000 m^{-3} s^{-1} was recorded at McDonald Bridge (Bountry *et al*., 2010)

During 1910 to 1913 the 33 m Elwha Dam was constructed at river kilometer 7.9, forming Lake Aldwell, which impounded approximately 9,990,000 m^{-3} of water and inundated 107 ha of land (Federal Energy Regulatory Commission, 1991). This reservoir is 4.5 km in length and is 0.4 km across at its widest point, with a maximum depth just under 30 m (Chenoweth *et al*., 2011). Former Lake Aldwell has two distinctive sections: a moderately confined valley adjacent to the dam and a wider, unconstrained alluvial valley constituting the upstream portion. These two sections are separated by a relatively narrow, meandering valley composed of bedrock, often referred to as the Goose Neck.

During 1925 to 1927 the 64 m high Glines Canyon Dam was constructed upstream at river kilometer 21.6, forming Lake Mills, which impounded approximately 49,300,000 m^{-3} of water, inundated 167 ha of land, and had a maximum depth just under 60 m. Lake Mills was almost 4 km in length and 0.8 km wide (Chenoweth *et al*., 2011). Both reservoirs were used as sources of hydroelectric power, water, and for recreation. Dam removal along the Elwha River began in September, 2011 with the removal of Lake Aldwell's Elwha Dam. This removal was completed in March, 2012. Removal of Lake Mill's Glines Canyon Dam began in October 2011, and is expected to be completed by late 2014.

Sediment volume in former Lake Mills has been estimated at 15.6 million m^{-3} with an uncertainty of ± 2 million m^{-3}. Of that sediment, approximately 40% is located in the main reservoir body, 54% is located at the southern end of the reservoir in the Elwha Delta, and the remaining 6% is located in Rica Canyon (Bountry *et al*., 2010). Prior to 2010, the last study to assess alluvium distribution was performed in 1989/1994. At that time sediment volume was estimated as 10.6 million m^{-3} (USDI Bureau of Reclamation, 1995). This means there has been a 47% increase in sediment during the 16 year period between 1994 and 2010.

Sediment volume in Lake Aldwell has been more difficult to quantify, as there was no pre-dam survey performed (prior to 1913), as there was for Lake Mills. However, the Bureau of Reclamation has attempted to quantify sediment volume using drill hole data obtained during a 1989/1994 drawdown experiment. This sediment volume estimate is based on a very limited Bureau of Reclamation drill exploration of Lake Aldwell's delta, and limited drill penetration of lake basin sediments explored by Hosey (1990), combined with survey data taken by the Bureau of Reclamation during 2010, and LiDAR data from 2009 (TerraPoint, 2009). The current estimate of total sedimentation volume for Lake Aldwell is 3 million m^{-3} with an uncertainty of ±765,000 m^{-3} (Bountry *et al*., 2010). It is thought that the majority of sediment captured by the Elwha Dam in Lake Aldwell occurred between the years 1913 and 1927, prior to the completion of the Glines Canyon Dam upstream (Bountry *et al*., 2010).

Field Methods

A total of 314 sediment samples were taken at 73 separate plots across both former Lake Mills and Lake Aldwell. Former Lake Mills had a total of 41 plots, while Former Lake Aldwell had a total of 32 plots (Map 3.2). Sample plots were chosen by defining approximate transects across both former Lake Mills and Lake Aldwell at an interval of 390 m, from north to south.

Along each transect, generally 3 to 5 sampling locations were chosen. Actual sampling sites were made as close to predetermined locations as safety allowed. If possible, a river-cut sediment face would be utilized for sampling, as much deeper samples could be collected than if sampling from a surface location. When a sampling location was chosen, its coordinates were taken using a Garmin, 72 series, GPS device; allowing for at least 10 separate readings to be made, and averaged, obtaining the most precise measurement possible. The datum used for GPS readings was WGS84.

Once a sample location was found, a 3.6 x 3.6 m (12ft x 12ft) square plot was defined around a center point using metal stakes and a measuring tape. All woody debris measuring over 7.5 cm in diameter within the plot boundaries were measured to calculate total volume of large woody debris for each plot. To measure small woody debris, a 20 cm x 20 cm square frame was randomly thrown into the plot area and all woody debris that was found within it was collected for weighing and put in a marked plastic bag.

Sediment sample collection was done for the following depths: 0-20 cm, 20-50 cm, 50-100 cm, 1-2 m, and every meter below this until the maximum accessible depth was reached. If sampling from the surface, this depth was no more than 1 m as material was often unaggregated and easily slumped. If sampling from a river-cut bank, this could be as deep as 6 m. When sampling from the surface, a coring probe with a 1.9 cm (0.75 in) inner diameter was used to extract fine sediment samples. If the sediment was too coarse for probe use, then a standard steel blade round point shovel was used to reach a depth of 1 m. In holes that were manually dug, samples were taken from the sidewall of the hole at prescribed depths using a hand trowel. Cut-bank faces were first scraped clean of any moss or light vegetation along the sampling plane prior to sediment extraction.

Bulk density samples were also collected at all locations and depths where sediment samples were collected, excluding 20 of the 314 samples taken, due to potential hazard from extraction; or in the case of depths below 20 cm when the soil probe was utilized for sediment collection, as bulk density sampling was not feasible. Collection of samples to determine sediment bulk density involved the use of a standard soil bulk density corer of 137.4 cm^{-3}. When sediment samples had mineral material over 2 mm in size, a sample including coarse fragments was collected to allow for carbon concentration corrections in data processing. This sample was collected at all depths where applicable by pushing a hand trowel into the sediment face and extracting a representative volume of material at that particular depth. All samples (sediment, bulk density, coarse fragment, and woody debris) were kept in a cooler on ice once transported off the former reservoir until they could be placed in a refrigerator for longer term storage at 3°C. Additionally, all sampling plots were photographed a minimum of three times at different angles, and all moved natural materials were placed back in their original locations if possible.

Laboratory Methods

Sediment samples taken from both former Lake Mills and Lake Aldwell were air dried at room temperature for a minimum of five days. Once dry, samples were thoroughly mixed and then passed through a sample splitter to reduce material while maintaining a representative fraction of the original sample. Optimum final reduction size was approximately 10 to 12 cm^{-3} of material. Samples were then thoroughly hand ground using a mortar and pestle; the mortar and pestle used for grinding sediment samples was cleaned with a dry cotton rag and compressed air between samples.

To quantify carbon and nitrogen content, sediment samples were run through a Perkin Elmer model 2400 CHN elemental analyzer. This type of analysis utilizes the Pregl-Dumas method, where samples are combusted in a pure oxygen environment and the resultant combustion gases are measured in an automated fashion using a thermal conductivity detector. Sample weights for CHN analysis were between 35 to 45 mg, with an accuracy of a hundredth of a milligram, and were packed in tin capsules. All weighing was performed on a Perkin Elmer AD-4 Autobalance. Samples were run within two days of weighing and kept within a desiccant chamber to avoid weight fluctuation due to moisture gains and losses.

Bulk density sediment samples were placed in metal sample tins and oven dried at 105°C for a minimum of 48 hours then weighed. Coarse fragment samples were air dried at room temperature for a minimum of five days, then separated using a 2 mm sieve and weighed. Woody debris samples were placed in metal sample tins and oven dried at 65°C for a minimum of 72 hours. Once dry, all woody debris samples were weighed.

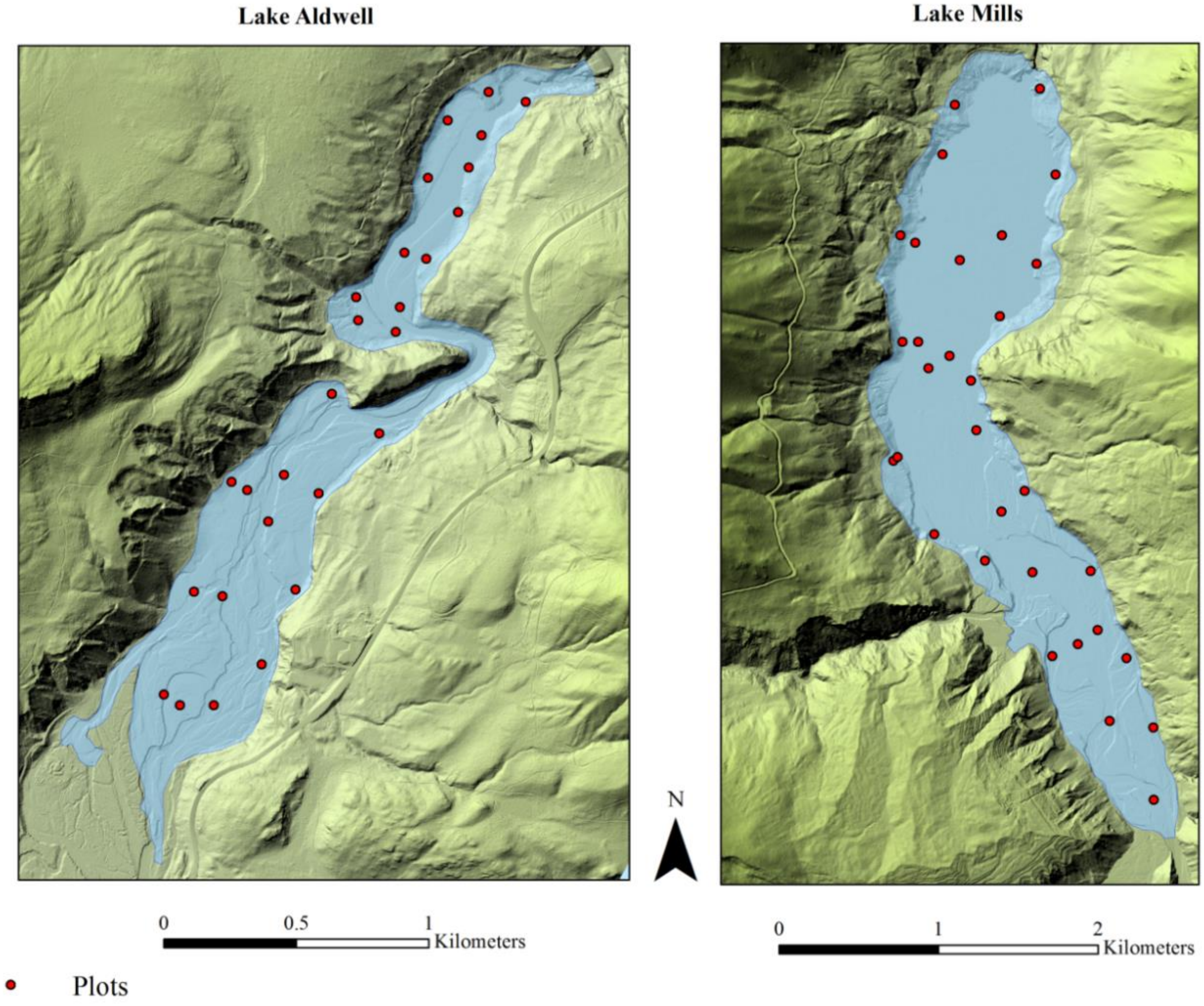
Statistical Analysis

Statistical analysis of the data tabulated from lab and field work included a variety of methods. Simple averaging of bulk density, carbon quantities, particle size, and other known values was used extensively. Generally, standard deviation, minimum and maximum values were also found from datasets. The coefficient of variation was also found for most variables, as it was a useful way to compare variability of one dataset to another. Carbon concentration outliers were identified using the generalized extreme studentized deviate (ESD) test. Geostatistical interpolation modeling of sediment variables was performed using the Geostatistical Analyst of ESRI’s ArcMap 10.2. The modeling method used was ordinary kriging due to its ability to explain variation between points when spatial correlation is assumed.

Figure 3.1. Former Lake Mills sediments, looking south from the north end of the former reservoir (July 2013).

Figure 3.2. Former Lake Aldwell sediments at the south section of the northern portion of the former reservoir (north of the Goose Neck) (September 2013).

Map 3.1. The Elwha River Watershed and location of study.



Map 3.2. Sampling locations at both former Lake Mills and Lake Aldwell; sampling depths vary among plots.

4. Results

Carbon Concentration

Carbon concentration in former Lake Mills' sediment ranges from 0.24% to 5.02% with a mean of 1.13% and a standard deviation of 0.83% (Table 4.1). Similarly, former Lake Aldwell sediments have a carbon concentration range from 0.23% to 12.8% with a mean of 1.65% and a standard deviation of 1.39% carbon (Table 4.2). Changes in former Lake Mills and Lake Aldwell's carbon concentrations by depth are shown in Figure 4.1, where on average, Lake Mills' sediment concentration of carbon is lower than Lake Aldwell's until depths of 3 m are reached. If outliers are not removed, standard deviations for Lake Mills are large, and in many cases have a coefficient of variation over 100%, as is seen in the 20-50 cm layer (Figure 4.1). Therefore, all carbon concentration and content maps have outliers removed at the 1% significance level unless otherwise noted. Sample outliers all had carbon concentrations above 4.4% (see Appendix 1). Three outliers are from former Lake Aldwell at the 0-20 cm (4.47% C), 20-50 cm (12.77% C), and 100-200 cm (6.24% C) depths, and one is from former Lake Mills at the 100-200 cm (5.02% C) depth.

Changes in mean carbon concentration between sediment depths in former Lake Mills is small, only varying from 0.76% in the 0-20 cm layer to 1.46% in the 100-200 cm sampling layer, a difference of 0.70% (Table 4.1). The same is true for former Lake Aldwell sediments, where average concentration by depth varies by 0.68%, from a low of 1.15% in the 300-400 cm sampling layer to 1.83% in the 20-50 cm sampling layer. Overall, former Lake Mills has a lower average concentration of carbon in its top meter of sediment compared to former Lake Aldwell (Figure 4.1).

Sediment carbon concentration of former Lake Aldwell is generally more consistent than in former Lake Mills and does not have the same increase in carbon concentration by depth. The carbon in former Lake Mills' top meter of sediment is effectively diluted by a large fraction of coarse mineral material that has little organic carbon. Former Lake Mills has an average of 33% mineral material >2 mm in its upper meter of sediment, whereas former Lake Aldwell averages 19%.

Spatially, the top meter of former Lake Mills' sediments are generally low in carbon, staying below 1%, with a few exceptions (Map 4.1). Close to the Glines Canyon Dam, on the northeast side of the reservoir, carbon concentrations in the top meter were greater than 3%, with a maximum of 4.20% recorded within this area. Moving upstream from the Glines Canyon Dam site, the 50-100 cm depth had several locations where carbon concentrations reach between 1.8 and 2.2%, higher than the 1.18% mean for that layer. In sediments deeper than 1 m, former Lake Mills is more spatially homogenous; carbon concentration generally is higher for the whole reservoir below 1 m, with a gradual increase into where the Boulder Creek alluvial fan is located (Map 4.1), or about 2.5 km upriver from the Glines Canyon Dam site.

The top 0-20 cm of former Lake Aldwell is spatially the most variable of these sediments, with pockets of higher carbon concentration found both in the southern and northern portion (Map 4.2). Two of these pockets are south of the Goose Neck, reaching >3% carbon, and a third pocket reached 2.82%. Conversely, there are several locations in this top fraction that have very low values (< 0.4%) sometimes nearing zero. These locations generally exist in the delta region in the southern portion of the former lake. North of the Goose Neck within the 0-20 cm depth, carbon concentration varies widely ranging from 0.2 to 3.1%. Below 20 cm, changes in sediment carbon concentration become more gradual spatially. Generally, between 20-200 cm in depth, carbon content is higher in the southern portion of former Lake Aldwell, reaching its highest values close to the Goose Neck, still in the southern half of the reservoir. Below 200 cm, sediment carbon concentration is very homogeneous across the reservoir, with a standard deviation of 0.11% carbon; there was a mean of 1.15% from 200-300 cm and 1.23% from 300-400 cm (Table 4.2).

Surface Woody Debris

Woody debris on the surface of both reservoirs constitutes a small percentage of total carbon contained in former Lake Aldwell and Lake Mills and the values presented in this report should only be considered as estimates. In total, woody debris plots only constituted approximately 0.04% of each reservoir's area and had very high standard deviations. Former Lake Mills' large surface debris data has a coefficient of variation of 206%, while former Lake Aldwell has a coefficient of variation of 309%.

Former Lake Mills' surface debris is estimated to contain a total of 1,600 Mg of carbon, averaging 9,700 kg C ha^{-1} (Table 4.3), with 6.7% of the carbon in debris < 7.5 cm in diameter, and 93.3% from larger debris, ≥ 7.5 cm in diameter. In total, the surface woody debris of former Lake Mills accounts for <1% of all carbon stored in the former reservoir. Former Lake Aldwell's surface debris is estimated to contain a total of 500 Mg of carbon, averaging 4,700 kg C ha^{-1} (Table 4.4). Fine debris < 7.5 cm in diameter constitutes 0.47% of surface carbon, with large woody debris constituting the other 99.5% of surface carbon. In total, surface woody debris accounts for 1.2% of all carbon contained in former Lake Aldwell.

The spatial distribution of surface woody debris carbon in former Lake Mills is varied. Map 4.3 shows higher concentrations close to the western shore of the former reservoir, where carbon reaches an interpolated peak value of 85,000 kg C ha^{-1}; the rest of former Lake Mills is highly variable. Former Lake Aldwell has 52% less surface woody-debris carbon per hectare than former Lake Mills (Map 4.3, Table 4.4). The majority of this surface carbon is located in the northern section of former Lake Aldwell, just east of the Elwha Dam, where interpolated carbon content reaches a value of 41,500 kg C ha^{-1}. As with former Lake Mills, former Lake Aldwell's surface debris is highly variable.

Bulk Density

The average bulk density for all depths of sediment within former Lake Mills was 1.37 g cm^{-3} with a standard deviation of 0.29 g cm^{-3} (Table 4.5, Figure 4.2). The minimum bulk density was 0.88 g cm^{-3} (200-300 cm), with a maximum of 2.01 g cm^{-3} (20-50 cm). Variability in bulk density of all of former Lake Mills' sediments was greatest at 0-20 cm, with a standard deviation of 0.32 g cm^{-3}; the least variability was within sediments 200-300 cm deep (0.14 g cm^{-3}).

Former Lake Aldwell's sediments had a slightly lower bulk density (average of 1.25 g cm^{-3}) than former Lake Mills' sediments (Table 4.6, Figure 4.2). The minimum bulk density was 0.26 g cm^{-3} at the surface between 0-20 cm in depth, with the maximum of 2.01 g cm^{-3} taken at a depth of 20-50 cm. From a depth of 0-400 cm the standard deviation for all bulk density samples was 0.31 g cm^{-3}, a standard deviation of 0.10 g cm^{-3} being the lowest variance of all layers sampled, at the 200-300 cm depth. The upper most layer of former Lake Aldwell, like sediments of former Lake Mills, had the highest variability with a standard deviation of 0.41 g cm^{-3}. Additionally, both former Lake Aldwell and Lake Mills have a similar trend, with higher bulk densities at the surface, reaching a minimum bulk density at 300-400 cm, then either staying constant at greater depths or slightly increasing (Figure 4.2).

The greatest spatial variability in former Lake Mills' sediment bulk density was found in the top layers, mainly the 0-20 cm and 20-50 cm fraction, where measurements range from 1.02 to 2.01 g cm^{-3} (Map 4.4, Table 4.5). The majority of bulk density measurements exceeding 1.9 g cm^{-3} are from the central and northern section of former Lake Mills. All bulk density measurements that were over 1.9 g cm^{-3} were also in locations with >72% coarse mineral material (>2 mm in diameter). With increased depth, bulk density becomes more homogenous. Beneath 1 m, former Lake Mills' sediment bulk density ranged from 1.0 to 1.25 g cm^{-3} except for one plot sampled in the delta region, at the south end of the former reservoir where very coarse sediment is prevalent and bulk density was 1.92 g cm^{-3} (Map 4.4).

Sediments in former Lake Aldwell had spatial variability in bulk density that was more predictable and consistent than former Lake Mills. A smooth gradient can be seen from a high bulk density in the southern delta region of the former lake, to a lower bulk density in the central and northern sections (Map 4.5). The upper layer, 0-50 cm has the largest range, from a minimum of 0.26 g cm^{-3} in the central part of the reservoir to a high of 2.05 g cm^{-3} toward the south. Beyond 50 cm in depth, variability drops and range of values becomes significantly less (Table 4.6). As an example, in the uppermost layer, 0-20 cm, the bulk density standard deviation for former Lake Aldwell is 0.41 g cm^{-3}; by 200-300 cm this variation has dropped to 0.10 g cm^{-3}. This is visible in Map 4.5, where sediments deeper than 1 m produce a kriged map that has very little variability.

Carbon Content

Total carbon content of former Lake Mills and Lake Aldwell sediments was calculated both with and without outliers (at the 1% significance level) using ordinary kriging for each depth sampled. Exclusion of outliers caused a 2% change in the total carbon of Lake Mills as well as Lake Aldwell sediments. Total carbon values both in kilograms per hectare (kg C ha^{-1}) for each sampling depth as well as the total gigagrams of carbon (Gg C) within each reservoir for each sampling depth are in Table 4.7.

The total carbon content of former Lake Mills' sediments, including outliers, is estimated at 161 Gg C, and changes to 159 Gg C without outliers. Of this, 1.6 Gg C is surface woody debris. The majority of carbon within former Lake Mills is contained in sediments deeper than 4 m; this amount is estimated to include over 64% of the total sediment carbon in the former reservoir. Sediments in former Lake Mills reach nearly 28 m in depth where the Elwha River delta and the Boulder Creek delta overlap (see Appendix 7). Carbon content in these deep layers was estimated using a pre-inundation survey for Lake Mills that provided sediment depth data. The top 4 m of sediment contain an estimated 57 Gg C, or 36% of total sediment carbon in former Lake Mills with outliers excluded.

Former Lake Mills has less total carbon content at every sampling depth than does former Lake Aldwell (Figure 4.3). Below the maximum sampling depth of 4 m, former Lake Mills is speculated to have much more carbon buried than former Lake Aldwell (Figure 4.3), due to very deep sediments. However, sediment depth from Lake Aldwell is currently unknown and sampling only went to 4 m deep; if sediment depth is found for Lake Aldwell, it would allow for much greater accuracy in calculating carbon content of these sediments. Though important, woody surface debris accounts for a small percentage of both former Lake Mills and Lake Aldwell's total carbon content (about 1% for both lakes). Lake Aldwell sediments generally have a higher average total carbon content per cubic meter of sediment than former Lake Mills, but Lake Aldwell has a much lower calculated carbon volume for the lake as a whole, mostly due to very deep sediment in Lake Mills. Including outliers, former Lake Aldwell contains a total of 67 Gg C up to 4 m in depth. Excluding outliers, former Lake Aldwell contains 64 Gg C of carbon to the same sampling depth. Total surface debris in former Lake Aldwell is lower than that in former Lake Mills, with a total amount estimated at 0.8 Gg C. This may be an overestimation as actual sediment depth within former Lake Aldwell is unknown. Former Lake Aldwell volume calculations used in this study (4 m in depth for the whole reservoir) are 44% higher than the best known estimate of sediment volume (3 vs. 4.3 million m^{-3}) and 14% higher than the estimated upper limit (3.7 vs. 4.3 million m^{-3}) (Bountry *et al.*, 2010).

When comparing carbon content in kg ha^{-1} between former Lake Mills and Lake Aldwell (Figures 4.4 and 4.5), former Lake Aldwell consistently has higher carbon content per hectare for all depths sampled. Former Lake Aldwell also has lower variability in samples deeper than 1 m (coefficient of variation of 99% compared to 142% for former Lake Mills from 0-400 cm). Specifically within the 0-100 cm fraction, former Lake Aldwell still holds more carbon per hectare than former Lake Mills, and is less variable, with a coefficient of variation of 77%, (Lake Mills sediments having a value of 106%). The total estimated average sediment carbon content of former Lake Mills is 1,340 Mg C ha^{-1} with an average sediment depth of 11.7 m.

When carbon content calculations made in kg C ha^{-1} are standardized to equal a volume of kg C m^{-3}, one can easily compare the average carbon content of all sampling depths in kilograms from both former reservoirs up to 4 m (Figure 4.5). Using this data, Lake Mills' sediments have an average content from 0-20 cm of 4.8 kg C m^{-3}, which is its lowest average value. With increased depth, carbon content rises relatively evenly, peaking at 16 kg C m^{-3} in the 200-300 cm sampling depth and then decreases to 11 kg C m^{-3} at the deepest sampling level of 400-500 cm. Variability within this data set also has a clear trend, with standard deviations of carbon content highest in the most shallow 0-20 cm layer, where the coefficient of variation equals 113%, and decreases to 74% in the 300-400 cm depth.

The total sediment carbon content of former Lake Aldwell to a depth of 4 m averages 600 Mg C ha^{-1}; when comparing former Lake Aldwell to former Lake Mills sediments, carbon content is greater than or equal at all depths for former Lake Aldwell sediments. The greatest differences are within the top meter of sediment; these values steadily approach former Lake Mills' carbon content values with an increase in depth (Figure 4.5). At 0-20 cm former Lake Aldwell has an average carbon content 171% higher than former Lake Mills; at 20-50, 50-100, and 100-200 cm the difference is 64%, 39%, and 21% higher in former Lake Aldwell respectively. At 2-4 m the difference between carbon content for both reservoirs is very close, with former Lake Aldwell averaging 2% more carbon per hectare at 2-3 m, and 3% less at 3-4 m.

Spatial distribution of carbon content in former Lake Mills has a relatively predictable pattern with a few exceptions. In the upper 50 cm of sediment, kriged carbon content ranges from 1-20 kg C m^{-3}, staying below 10 kg C m^{-3} for most sediments that are 0.5 km south of Glines Canyon Dam (Map 4.6). Close to the Glines Canyon Dam, sediments have a higher carbon content than the rest of the reservoir in the upper meter of sediment. In the 50-100 cm sampling depth, kriged values reach over 40 kg C m^{-3}. Additionally, at the 50-100 cm depth there are several spots where carbon content values peak within a small area; these locations are all found south of Windy Arm, or 1.3 km upstream of Glines Canyon Dam. In sediments deeper than 1 m in former Lake Mills, values change more gradually and predictable spatial gradients appear. Overall, carbon content by hectare is highest in former Lake Mills' sediments deeper than 1 m, within the region where Boulder Creek enters into the Lake Mills Reservoir and deposited an abyssal fan of sediment. Here kriged carbon content values of 45 kg C m^{-3} were measured. Additionally, this is the region where sediment is the deepest, in some areas reaching over 28 m. Because of this large amount of material, total carbon content per hectare is highest here, something clearly seen in Map 4.8.

Former Lake Aldwell's 0-20 cm surface layer has a varied content of carbon spatially. In the southern portion of the sediments, kriged values range from 0.8 to 33 kg C m^{-3}, with the southern delta region being lower in carbon than the rest of the reservoir. The northern section of sediments in the 0-20 cm fraction is also quite variable with relatively high and low carbon content values throughout, ranging from 3 to 27 kg C m^{-3}. Below 20 cm, Lake Aldwell sediments have less variability and are more predictable. The southern delta region is generally lower in carbon until 2 m in depth; however the northern end of the southern part of former Lake Aldwell (just south of the Goose Neck) has a consistently higher carbon content than the rest of the reservoir (Map 4.7). Below 2 m in depth, sediment carbon content is relatively stable throughout the reservoir, ranging from 14 – 18.5 kg C m^{-3}, while at a depth of 300-400 cm carbon content ranges from 11 to 16 kg C m^{-3}.

When all depths of Lake Aldwell sediments are combined, unique spatial relationships and patterns of carbon content can be seen (Map 4.8, Figure 4.6). The carbon content of the southern delta region is relatively low, ranging from a kriged value of 430 to 560 Mg C ha^{-1}. Moving north, carbon content increases gradually, reaching a peak of about 780 Mg C ha^{-1} before reaching former Lake Aldwell's Goose Neck. The northern section of former Lake Aldwell has a more even distribution of carbon by content with a kriged range of 570 to 660 Mg C ha^{-1}.

Table 4.1. Mean and variability in carbon concentration of former Lake Mills, from sediment samples by depth.

Depth (cm)	Mean Carbon Concentration (%)	Minimum	Maximum	Standard Deviation	n
0-20	0.76	0.24	2.12	0.51	21
20-50	0.91	0.24	3.21	0.69	21
50-100	1.18	0.26	4.20	0.81	25
100-200	1.46	0.56	5.02	1.10	20
200-300	1.44	0.83	3.71	0.84	11
300-400	1.39	0.76	2.36	0.72	4
400-500	1.34	0.91	1.78	0.61	2
0-500	**1.13**	**0.24**	**5.02**	**0.83**	**104**

Table 4.2. Mean and variability in carbon concentration of former Lake Aldwell, from sediment samples by depth.

Depth (cm)	Mean Carbon Concentration (%)	Minimum	Maximum	Standard Deviation	n
0-20	1.72	0.23	4.47	1.10	23
20-50	1.83	0.24	12.77	2.50	23
50-100	1.61	0.28	3.33	0.84	24
100-200	1.72	0.24	6.24	1.16	23
200-300	1.45	0.55	2.52	0.60	16
300-400	1.15	0.39	1.88	0.60	6
0-400	**1.65**	**0.23**	**12.77**	**1.39**	**115**

Table 4.3. Mean mass and variability of surface woody debris carbon of former Lake Mills.

Debris Size	kg C ha^{-1}	Total Mg C	Minimum	Maximum	Standard Deviation	n
<7.5cm (Fine)	640	100	0	8,655	1,700	41
>7.5cm (Coarse)	9,000	1,500	0	120,274	23,800	41
Total	**9,640**	**1,600**				

Table 4.4. Mean mass and variability of surface woody debris carbon of former Lake Aldwell.

Debris Size	kg C ha^{-1}	Total Mg C	Minimum	Maximum	Standard Deviation	n
<7.5cm (Fine)	20	2	0	598	100	32
>7.5cm (Coarse)	4,700	500	0	100,951	18,500	32
Total	**4,720**	**502**				

Table 4.5. Mean and variability in bulk density of former Lake Mills, from sediments samples by depth.

Depth (cm)	Mean Bulk Density g cm^{-3}	Minimum	Maximum	Standard Deviation	n
0-20	1.50	1.02	1.99	0.32	41
20-50	1.45	1.02	2.01	0.30	41
50-100	1.34	1.02	1.96	0.26	41
100-200	1.18	0.88	1.92	0.19	23
200-300	1.17	0.88	1.44	0.14	14
300-400	1.29	1.13	1.86	0.28	6
400-500	1.28	1.06	1.71	0.29	4
0-500	**1.37**	**0.88**	**2.01**	**0.29**	**170**

Table 4.6. Mean and variability in bulk density of former Lake Aldwell, from sediments samples by depth.

Depth (cm)	Mean Bulk Density g cm^{-3}	Minimum	Maximum	Standard Deviation	n
0-20	1.29	0.26	1.98	0.41	32
20-50	1.33	0.26	2.05	0.37	32
50-100	1.26	0.89	1.97	0.30	31
100-200	1.16	0.85	1.78	0.18	24
200-300	1.15	0.90	1.30	0.10	16
300-400	1.23	1.12	1.43	0.11	6
0-400	**1.25**	**0.26**	**2.05**	**0.31**	**141**

Table 4.7. Total carbon content of both former Lake Mills and Lake Aldwell sediments using interpolation of sampled layers; outliers determined at the 1% significance level. Lake Aldwell data does not take into account lake topography, as no pre-dam survey was conducted.

Including Outliers

Former Lake Mills

Depth (cm)	kg C ha^{-1}	Total Gg C
0-20	6,700	0.79
20-50	14,500	1.70
50-100	41,800	4.89
100-200	150,500	17.62
200-300	152,600	17.87
300-400	134,400	15.75
400-2871	861,900	100.96
0-2871	**1,362,400**	**159.58**
Surface Debris	9,700	1.62
Total Carbon	**1,372,000**	**161**

Former Lake Aldwell

Depth (cm)	kg C ha^{-1}	Total Gg C
0-20	24,900	2.66
20-50	36,200	3.87
50-100	71,200	7.63
100-200	186,400	19.97
200-300	162,100	17.37
300-400	135,800	14.55
0-400	**616,600**	**66.07**
Surface Debris	4,700	0.79
Total Carbon	**621,300**	**66.9**

Excluding Outliers

Former Lake Mills

Depth (cm)	kg C ha^{-1}	Total Gg C
0-20	6,700	0.79
20-50	14,500	1.70
50-100	41,800	4.89
100-200	132,800	15.56
200-300	152,600	17.87
300-400	134,400	15.75
400-2871	861,900	100.96
0-2871	**1,344,600**	**157.51**
Surface Debris	9,700	1.62
Total Carbon	**1,350,000**	**159**

Former Lake Aldwell

Depth (cm)	kg C ha^{-1}	Total Gg C
0-20	26,100	2.79
20-50	34,100	3.65
50-100	71,200	7.63
100-200	165,300	17.68
200-300	162,100	17.37
300-400	135,800	14.55
0-400	**594,800**	**63.68**
Surface Debris	4,700	0.79
Total Carbon	**599,500**	**64.5**

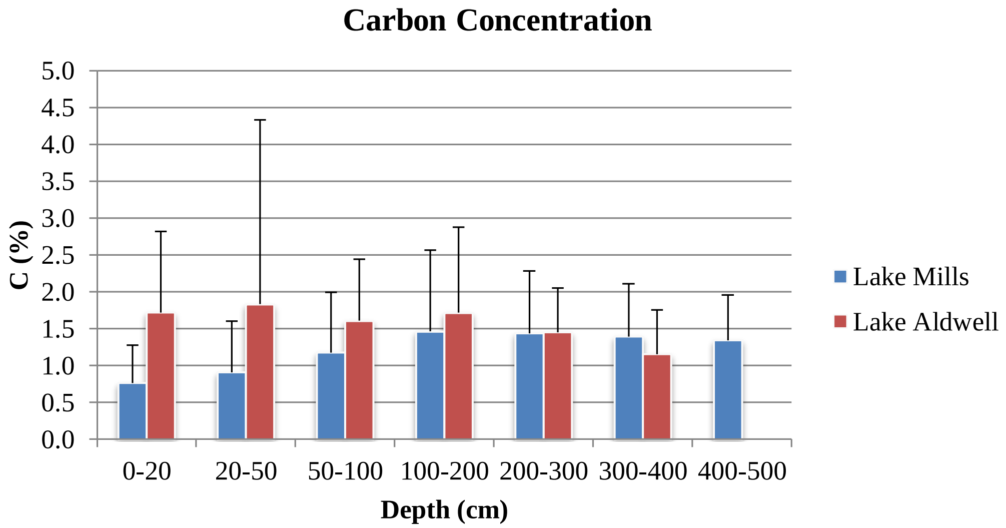


Figure 4.1. Former Lake Mills and Lake Aldwell mean sediment carbon concentration by depth with standard deviation, from sediment samples.

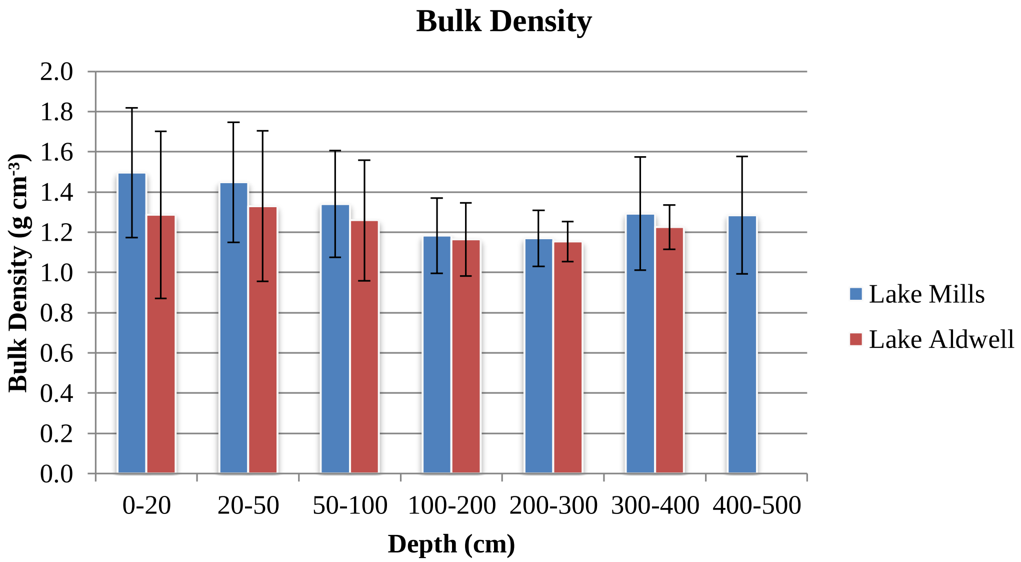


Figure 4.2. Former Lake Mills and Lake Aldwell mean bulk density by depth with standard deviation, from sediment samples.

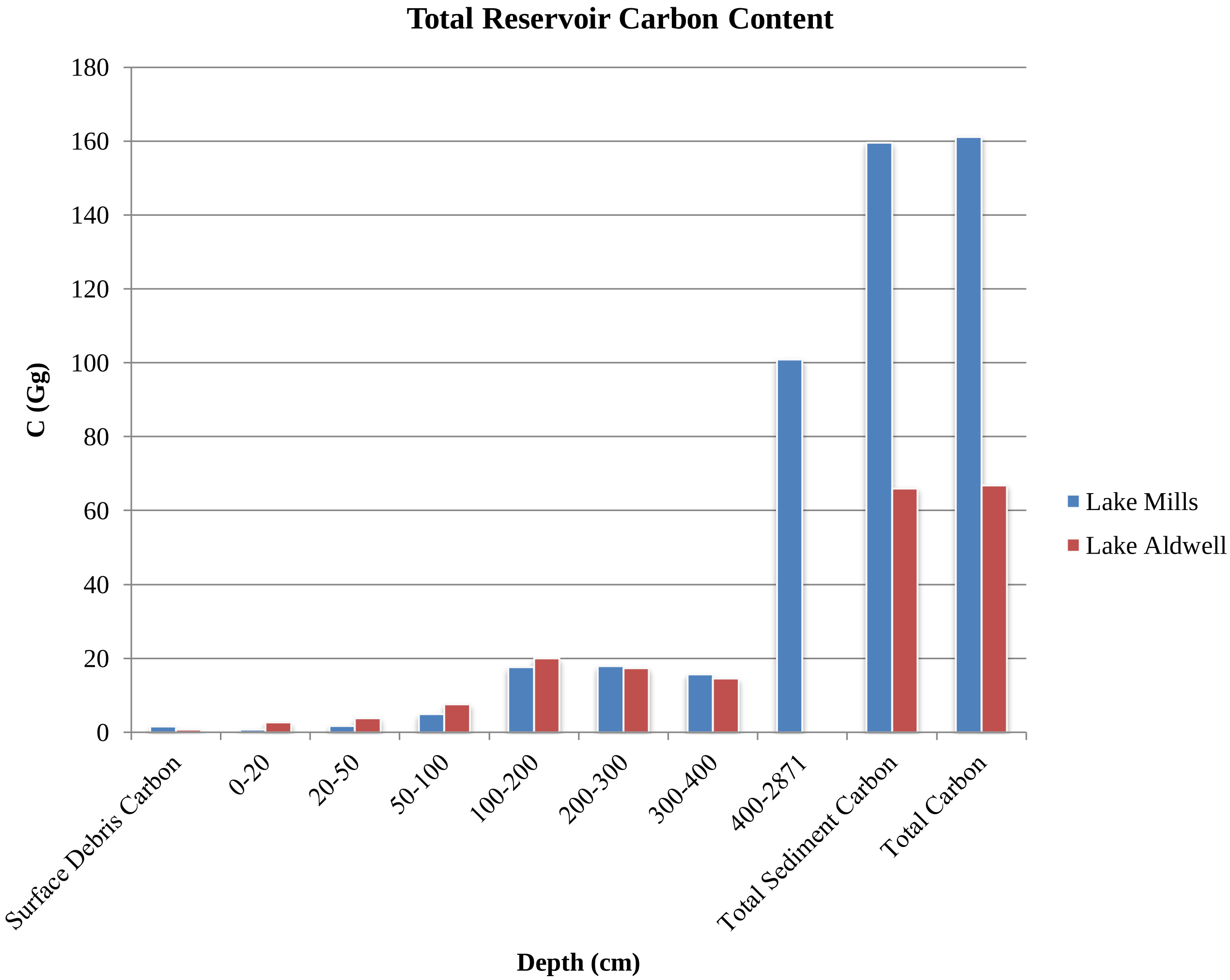


Figure 4.3. Total carbon content of former Lake Mills and Lake Aldwell from interpolation, excluding outliers. Lake Aldwell calculations are made only to a depth of 4 m, as total sediment depth is currently unknown.

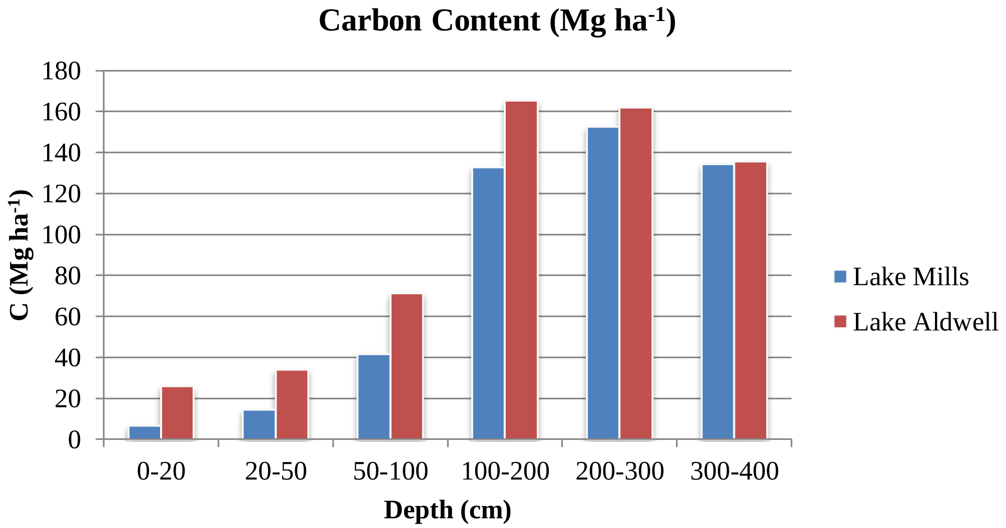


Figure 4.4. Former Lake Mills and Lake Aldwell mean sediment carbon content by hectare from spatial interpolation, excluding outliers at the 1% significance level.

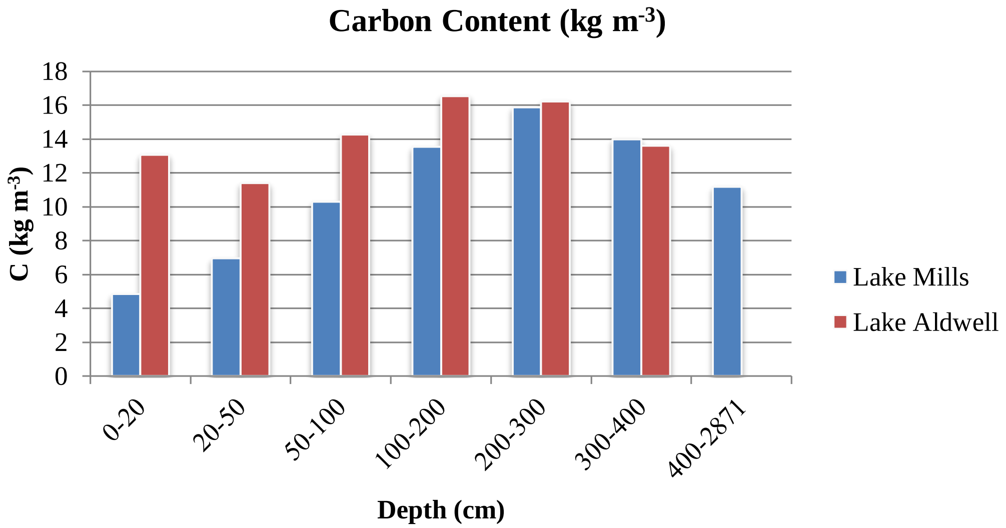


Figure 4.5. Lake Mills and Lake Aldwell mean sediment carbon content measured using a standardized volume of kg C m^{-3} from spatial interpolation. This graph excludes outliers at the 1% significance level.

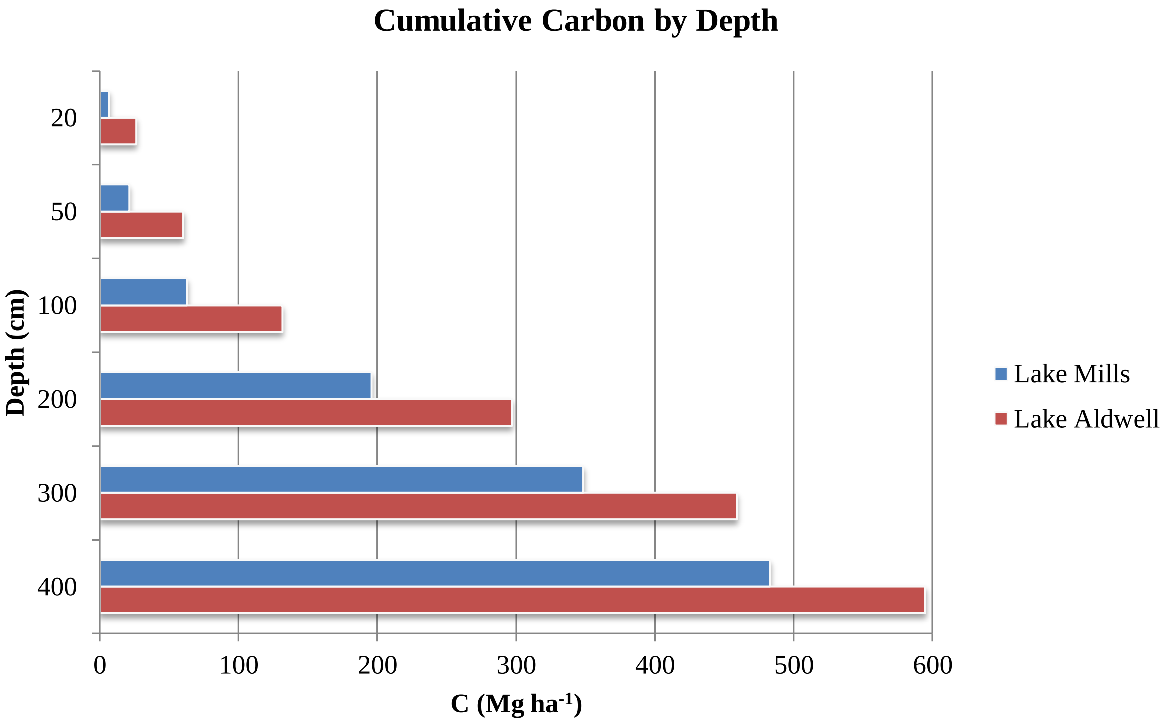
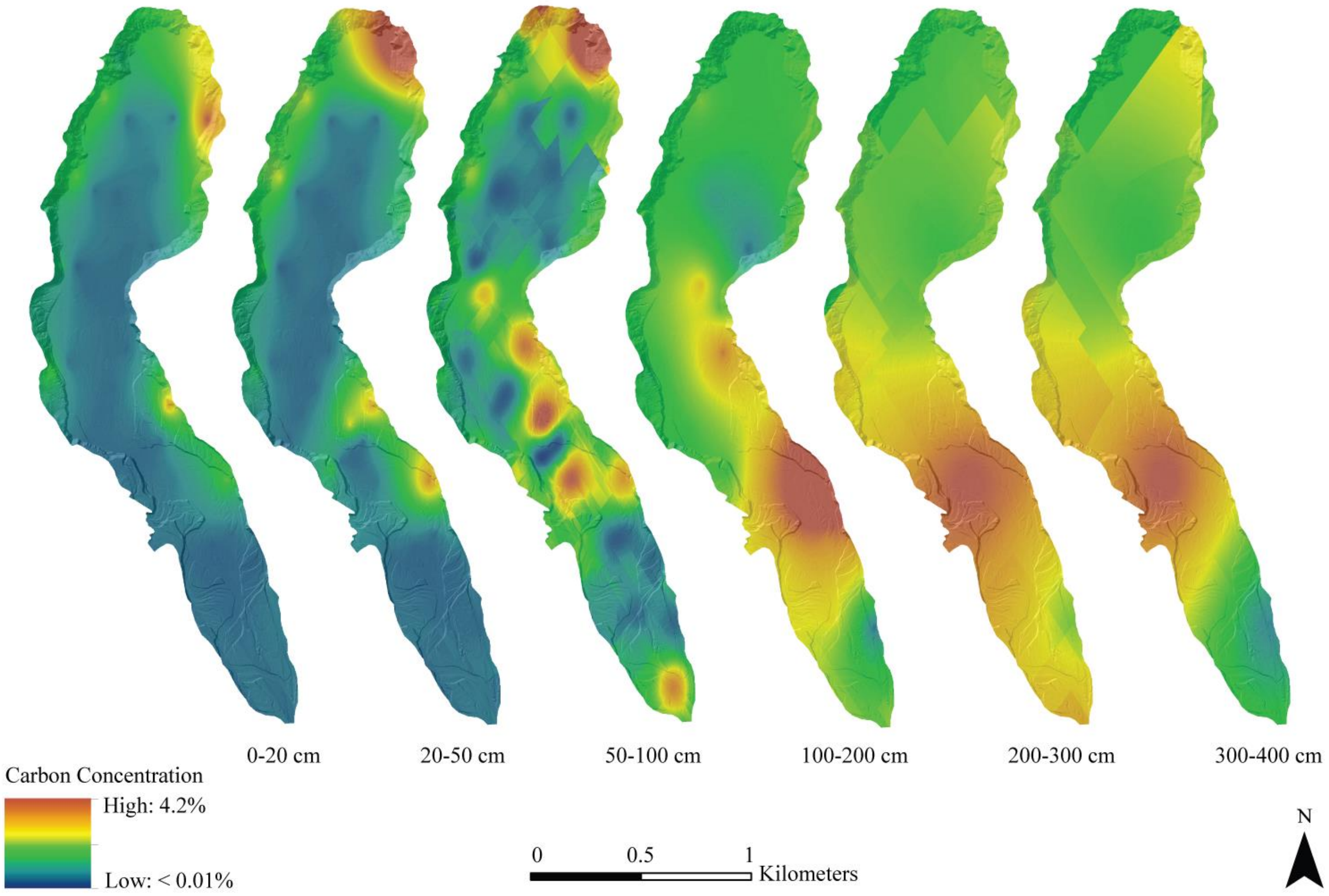


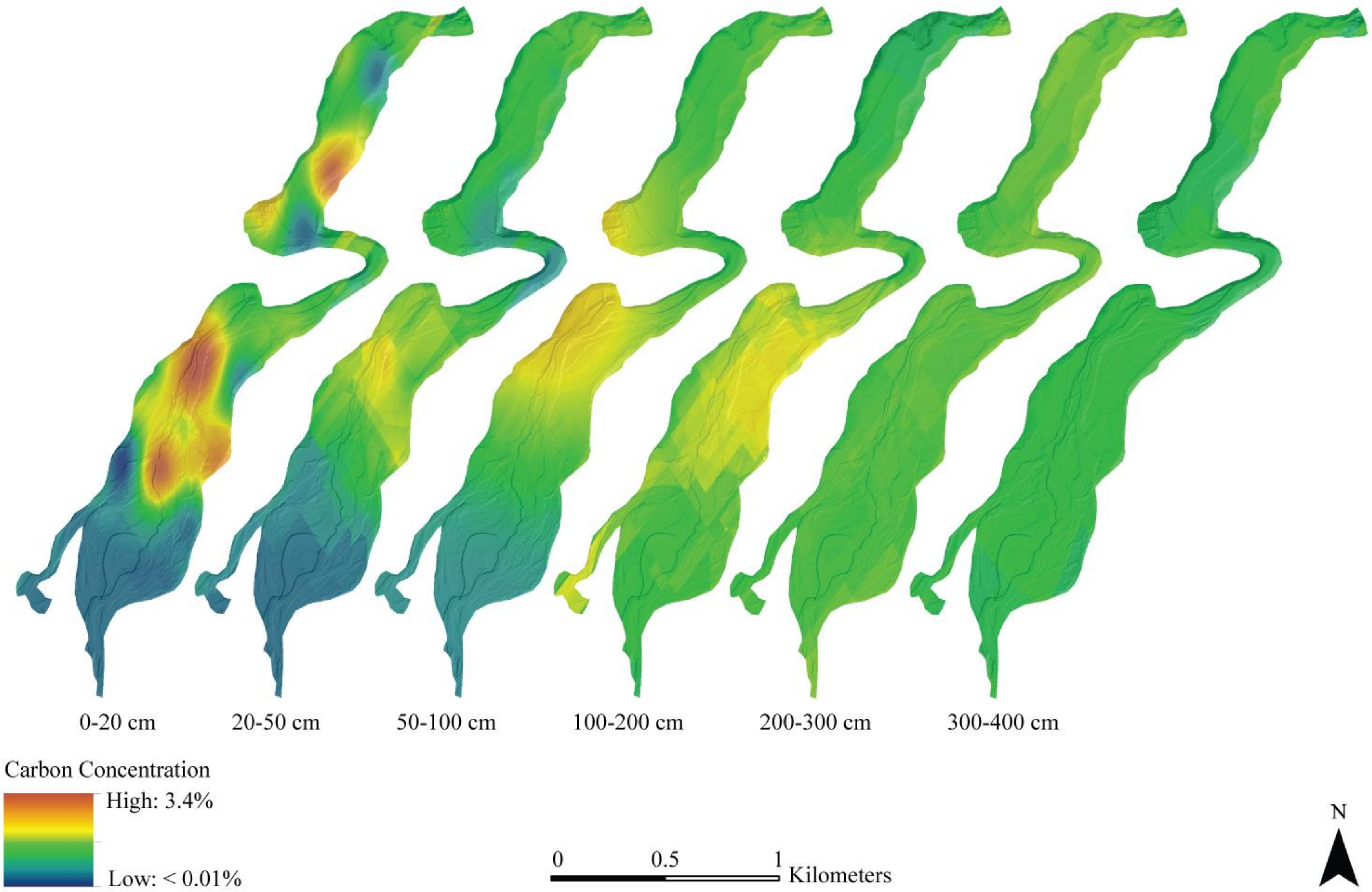
Figure 4.6. Former Lake Mills and Lake Aldwell cumulative sediment carbon content by hectare from spatial interpolation, excluding outliers at the 1% significance level.

Carbon Concentration of Former Lake Mills



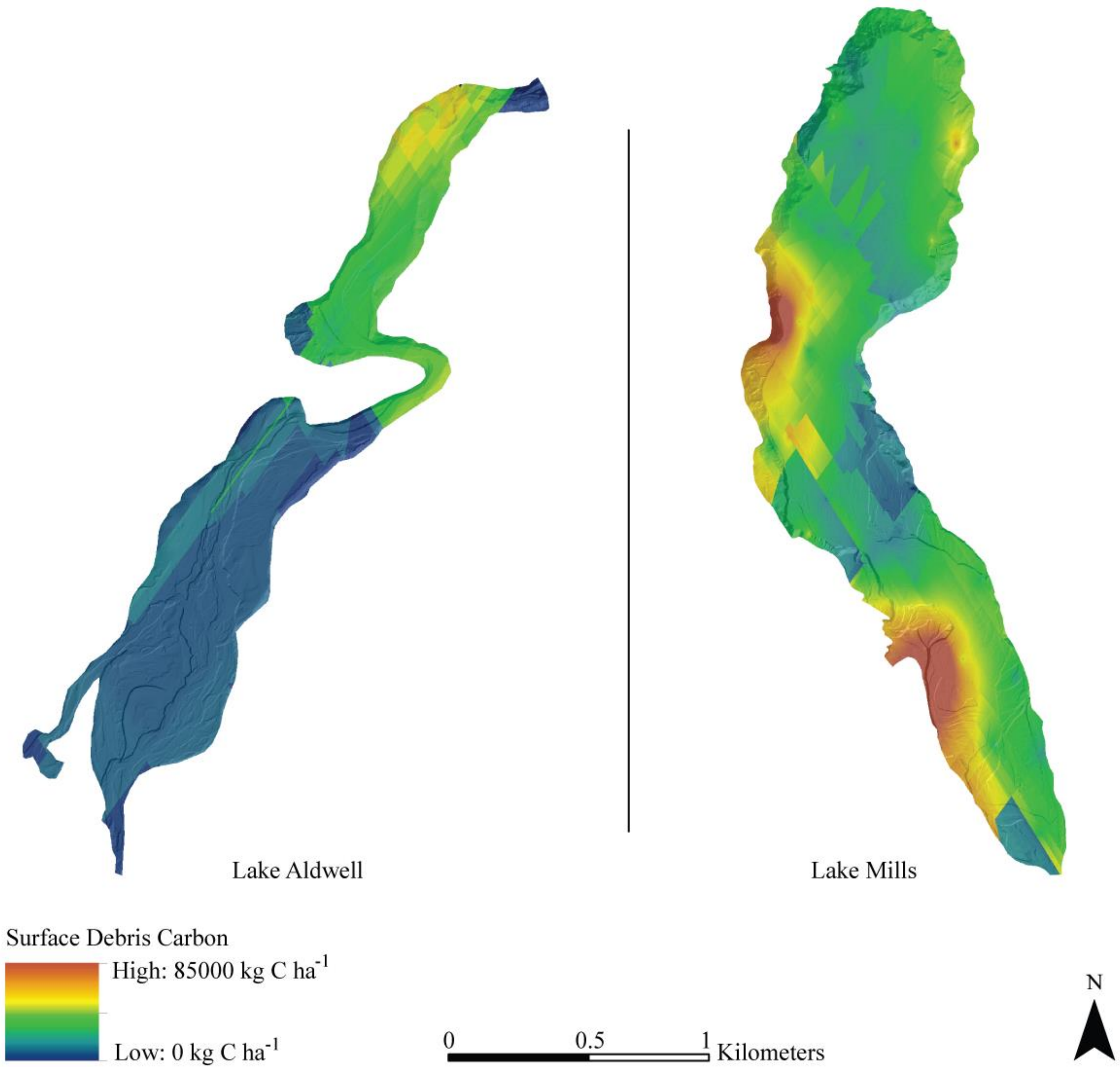
Map 4.1. Kriged carbon concentration of former Lake Mills sediments to a depth of 4 m. Outliers at the 1% significance level are not included.

Carbon Concentration of Former Lake Aldwell



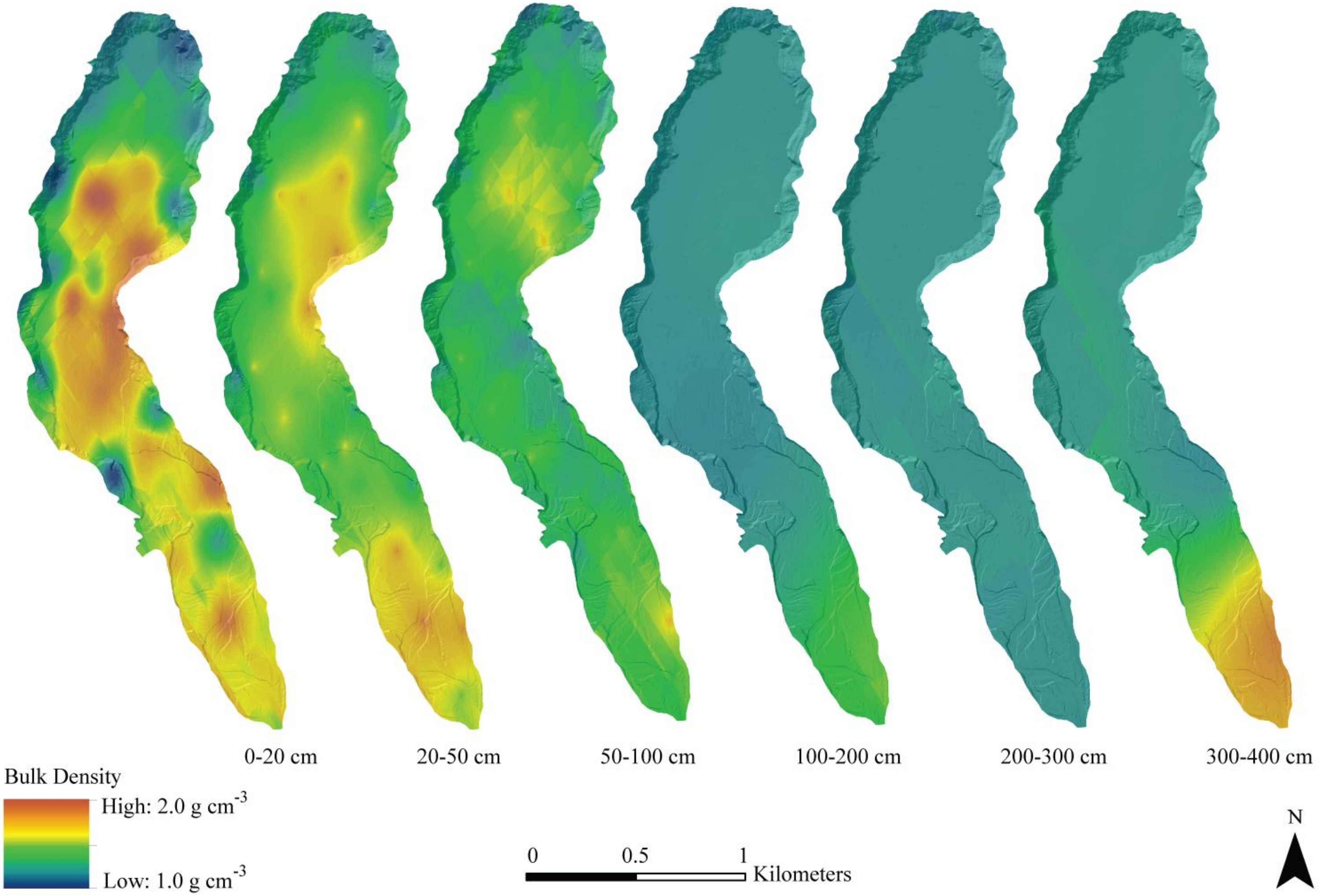
Map 4.2. Kriged carbon concentration of former Lake Aldwell sediments to a depth of 4 m. Outliers at the 1% significance level are not included.

Surface Woody Debris Carbon of Former Lake Aldwell and Lake Mills



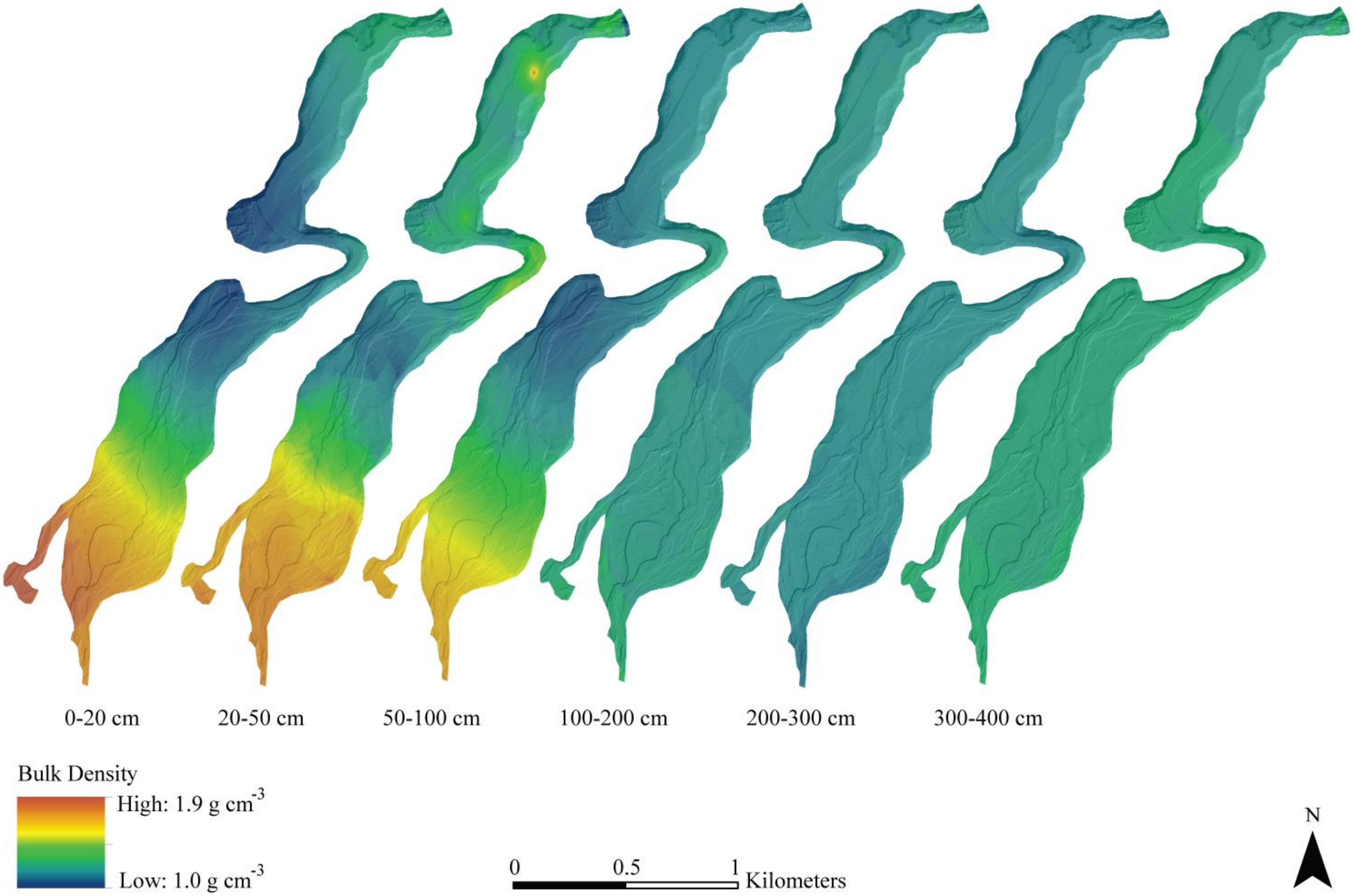
Map 4.3. Kriged mass of surface woody debris carbon of former Lake Mills and Lake Aldwell.

Bulk Density of Former Lake Mills



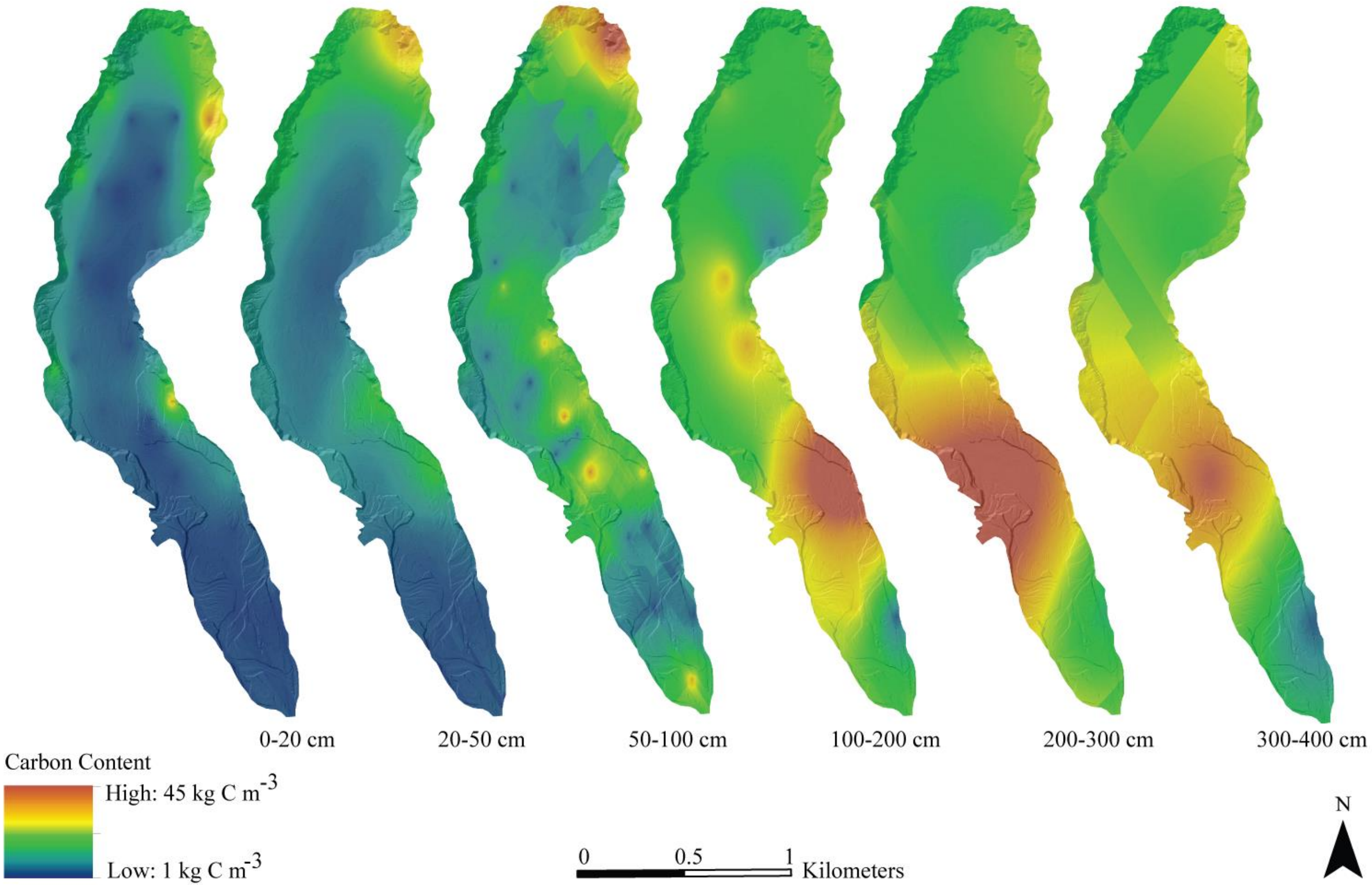
Map 4.4. Kriged bulk density of former Lake Mills sediments to a depth of 4 m.

Bulk Density of Former Lake Aldwell

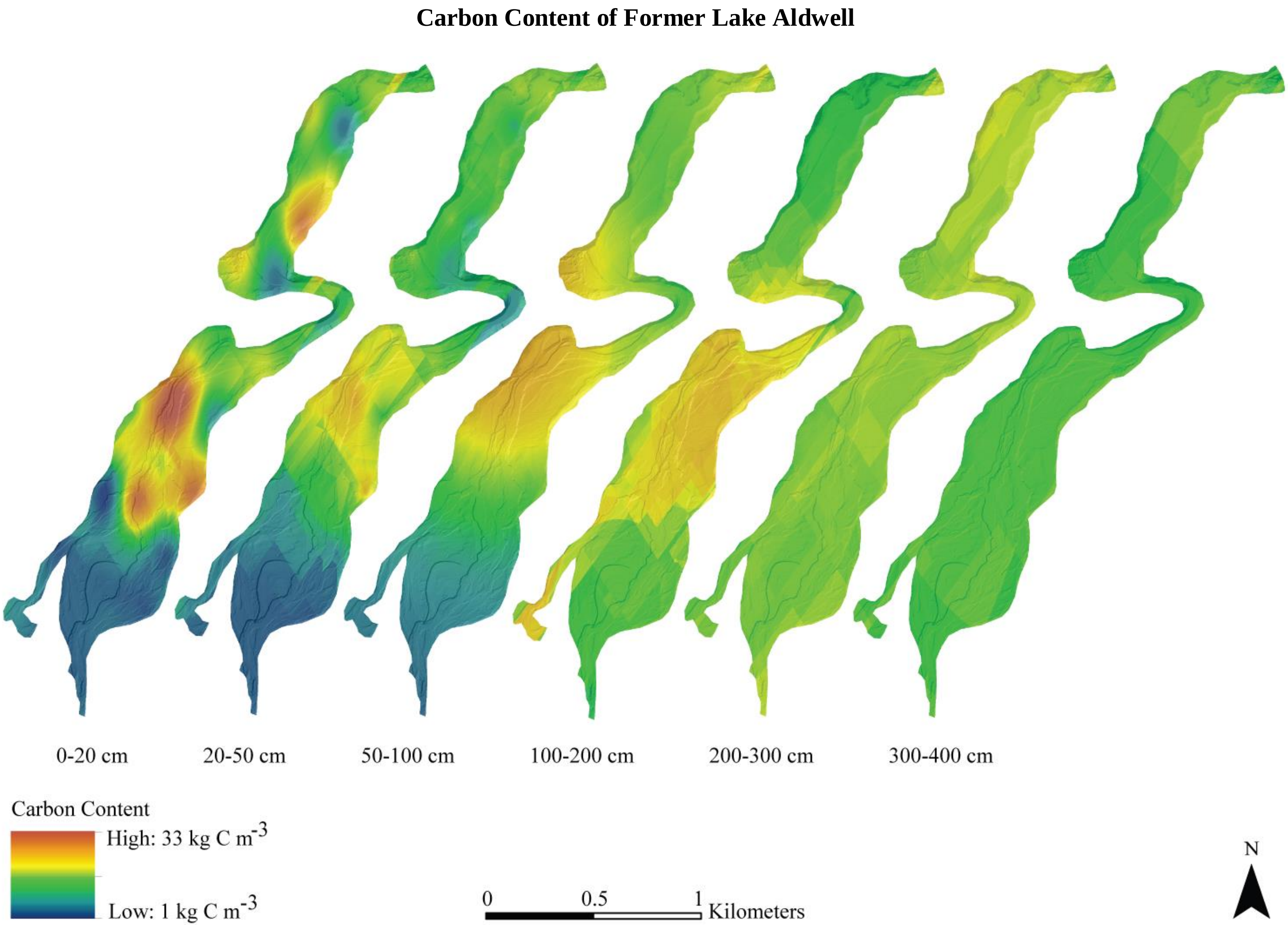


Map 4.5. Kriged bulk density of former Lake Aldwell sediments to a depth of 4 m.

Carbon Content of Former Lake Mills

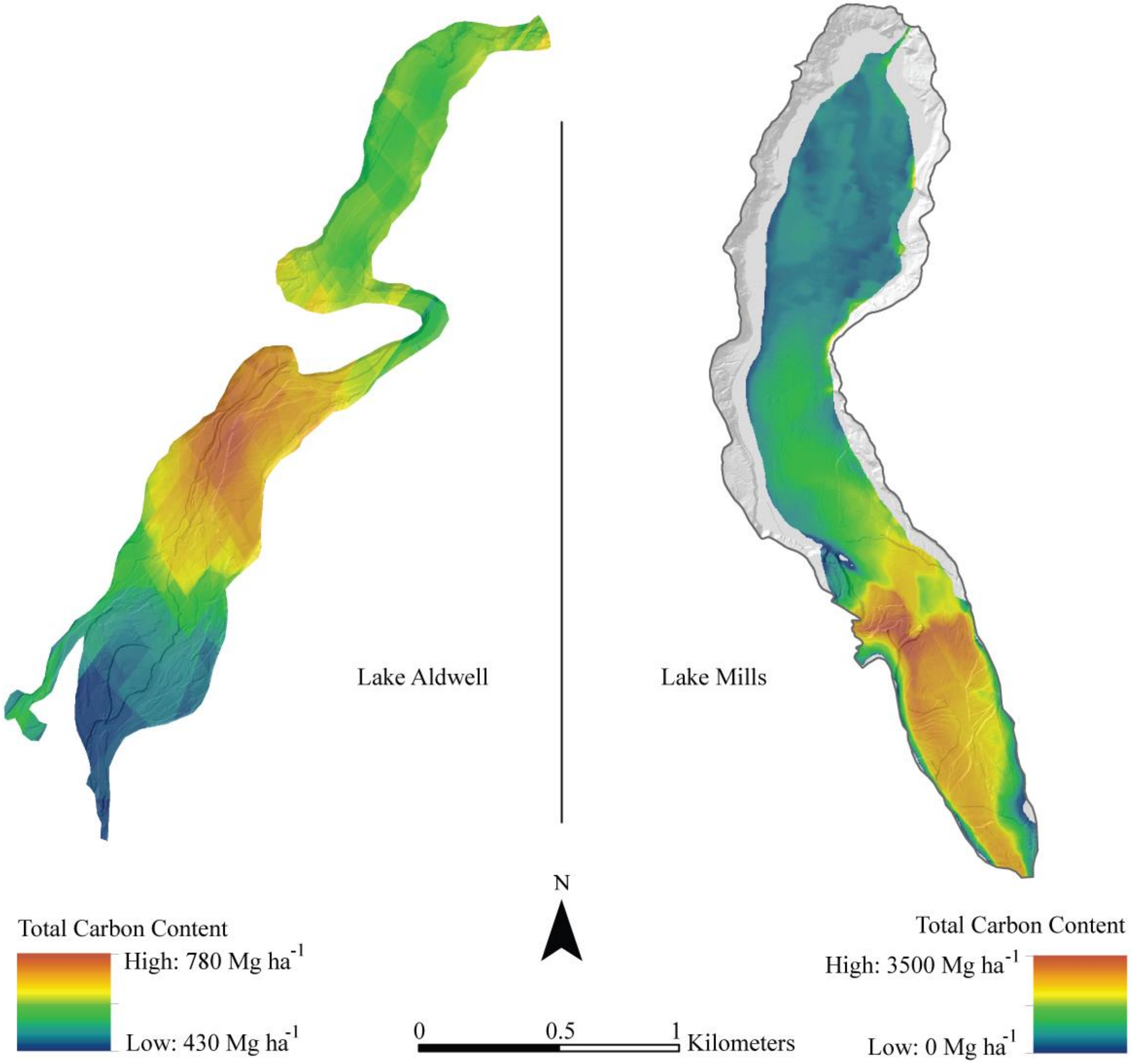


Map 4.6. Kriged carbon content of former Lake Mills sediments to a depth of 4 m. Measurements are in kilograms of carbon per cubic meter; outliers at the 1% significance level are not included.



Map 4.7. Kriged carbon content of former Lake Aldwell sediments to a depth of 4 m. Measurements are in kilograms of carbon per cubic meter; outliers at the 1% significance level are not included.

Total Sediment Carbon Content of Former Lake Aldwell and Lake Mills



Map 4.8. Kriged total sediment carbon content of former Lake Aldwell and Lake Mills. Lake Aldwell depth is calculated only to 4 m; Lake Mills depth data obtained from Bountry *et al*., 2010 and extends to 28.7 m from the surface at an average of 11.7 m.

5. Discussion

Comparison of Lake Sediments to Surrounding Soils and Sources of Carbon

The Elwha River Valley was once occupied by Glacial Lake Elwha. The Cordilleran continental ice sheet crossed the strait of Juan de Fuca and entered the U-shaped Elwha River Valley (USDI Bureau of Reclamation, 1995). Simultaneously, alpine glaciers of the Olympic Mountains pushed downward, carving their way into the valley below, releasing large amounts of sediment and water. The damming of the Elwha River Valley by the Cordilleran ice sheet, combined with this runoff formed Glacial Lake Elwha (Tabor, 1975). The terraces that exist above former Lake Mills and Lake Aldwell, where Glacial Lake Elwha once existed, serve both as a comparison of the physical and chemical properties of these soils and sediments, as well as a way to predict how the newly exposed sediments of former Lake Mills and Lake Aldwell will develop into a soil.

Mussman (2006) looked at the pedogenesis surrounding former Lake Mills and Lake Aldwell in four separate locations, three of which are on the east side of former Lake Mills, one of which is on the northwest side; all fall within the inundation area of former Glacial Lake Elwha. The average carbon concentration within the O horizon from all of these plots is 37.5%, within the A horizon it is 5.6%, the B horizon is 0.84%, and the C horizon average is 0.46% (Mussman, 2006). At three of these plots Mussman reached a depth of 102 cm, while the fourth (the one at the northwest side of former Lake Mills) had a depth of 78 cm. This analysis gives an idea of what will likely happen to the soil within both former Lake Mills and Lake Aldwell over the next few thousand years. It is clear that as vegetation takes root, and successional pathways lead to more mature forests, the top 5-35 cm (to the bottom of the A horizon) of sediment will have a net increase in carbon. Beyond this depth carbon readings are similar, or slightly less, than that of former Lake Mills and Lake Aldwell sediments. This could potentially be the result of leaching from percolation, decomposition of organic matter by microorganisms, or it could be a result of Mussman's (2006) small sample size.

The hillsides adjacent to former Lake Mills and Lake Aldwell are where a portion of the allochthonous sediment carbon came from. Transported by streams and creeks, this carbon ultimately came from terrestrial detritus and biomass of living organisms. With an average carbon concentration of 37.5% in the O horizon, and 5.6% in the A horizon directly around former Lake Mills (Mussman, 2006), it is probable that a significant portion of the carbon contained in the sediments of both reservoirs originates from erosion. Further, subalpine forests and meadows make up approximately 30% of the land in Olympic National Park and are thought to be considerable carbon sinks. These subalpine regions are also contributing to the input of sediment carbon to the Elwha River. Prichard *et al.* (2000) examined soil physical characteristics in the northeast portion of Olympic National Park (within the Elwha River watershed) and found a range of soil carbon from 4.3 to 14.2%. The input of allochthonous organic matter from the Elwha River and other stream inputs is evident in Map 4.8, where carbon content is consistently high within the alluvial fans produced by the Elwha River and Boulder Creek. This is a commonly observed phenomena, where the riverine zone of a reservoir contains a greater amount of allochthonous organic material, with a steady decrease closer to the dam. As a comparison, Thornton *et al*. (1981) estimated that 60% of sediment entering Lake Red Rock, Iowa stayed within its delta.

The Elwha River watershed is virtually pristine, with only a few trails, roads, and one small homestead within its borders. Therefore, any changes in sediment load from incoming streams and rivers are assumed to be of natural origin. When the total sediment volume found from the 1994 Lake Mills drawdown experiment is divided by the 67 years the reservoir had been in place since 1927, the average incoming sediment load is 158,000 m^{-3} yr^{-1} (Bountry *et al*., 2010). From 1994 to 2010 (16 years) the incoming sediment average for Lake Mills was 310,000 m^{-3} yr^{-1} (Bountry *et al*., 2010), roughly double the amount from the previous 67 years. The long term average, from 1927 to 2010, of sediment input for Lake Mills is thus 187,000 m^{-3} yr^{-1}. The increase in sedimentation during 1994 to 2010 is thought to be due to an increase in mass wasting events upstream as well as large flood events (Bountry *et al*., 2010). As an example, the largest flood event on record since the building of the Glines Canyon dam was in 2007, where water flow of 1,000 m^{-3} s^{-1} was recorded at McDonald Bridge. In 2006 another flood event occurred, and a peak flow of 600 m^{-3} s^{-1} was recorded (Bountry *et al*., 2010). Fires also likely play a key role in erosion and sedimentation of the Elwha River, with large areas such as Geyser Valley having a mean fire return interval of 127 years (Wendel, 2009), and recent forest fires not being uncommon in the Elwha watershed, such as the Rica Canyon fire of 1977.

A portion of the organic carbon found in former Lake Mills and Lake Aldwell also likely came from autochthonous sources, or *in situ* primary production by planktonic algae, planktonic phototropic bacteria, attached algae (periphyton), and rooted macrophytes (Kritzberg *et al*., 2005). Although the total photosynthetic production of organic matter by these organisms is largely undetermined, many of their contributions, working environments, and attributes are known (Kimmel *et al*., 1990). The Federal Energy Regulatory Commission (FERC) (1991) found during the years from 1987 to 1989, that values for pH and alkalinity were neutral to slightly-alkaline within the Elwha River and Lake Mills, typical of oligotrophic (low biological activity) environments (Wetzel, 2001). Nutrient concentrations in the Elwha River during this same time period were also found to be low in comparison to other non-contaminated lakes and reservoirs. Nitrate, ammonia, total phosphorus, and orthophosphorus concentrations are below thresholds known to limit algal production (Federal Energy Regulatory Commission, 1991; Wetzel, 2001). As an example, total phosphorus concentrations in uncontaminated lakes range from 0.01 to 0.03 mg l (as P); the Elwha River, from 1987 to 1989 had an average total phosphorus concentration of 0.01 mg l (as P) (Federal Energy Regulatory Commission, 1991). This low nutrient availability suggests lower photosynthetic production than what might be seen in other reservoirs and lakes in similar environments.

Autochthonous carbon input is generally greatest within the lacustrine zone of the reservoir, often the area closest to the dam (Kimmel *et al*., 1990). Within reservoirs, irregular and dynamic inflows of water can have a significant effect on environmental conditions that foster biotic communities, making every reservoir different, however, certain characteristics can be assumed for Lake Mills and Lake Aldwell. Within the delta region of Lake Mills and Lake Aldwell, it is expected that the high turbidity, sediment instability, and reduced light availability preclude significant photosynthetic activity, even if nutrient availability was high. As turbidity is reduced and reservoir depth increases, primary productivity increases with greater light penetration. Light limitation is often the greatest control of productivity in reservoirs (Wetzel, 2001), which is generally controlled by suspended clay and silt within the water column. It should be noted that the nutrient limitations within the lacustrine zone becomes the limiting factor to production when light needs are met. From 1927 to 1994 when the average yearly sediment load into Lake Mills was 158,000 m^{-3}, photosynthetic production was likely much higher than from 1994 to 2010, when sediment loads were roughly double at 310,000 m^{-3} yr^{-1} (Bountry *et al*., 2010). This is visible in Map 4.1 where sediment deeper than 1 m in the northern half of the reservoir is generally very homogenous and has a higher concentration of carbon than the same location from a depth of 0 – 1 m. Alternatively, this could be from coarse mineral debris distributed over the top portion of Lake Mills during the reservoir drawdown, when the Elwha River's course was still being established.

The ratio of carbon to nitrogen within sediments can also offer insight into where organic carbon has originated from and its nature within a reservoir (Emery, 1960). There is a significant difference between then C/N ratios of terrestrial plants (54), aquatic plants (5 – 21), and animal matter (3 – 6) (Hyne, 1978). The high C/N ratio (low nitrogen concentration) of terrestrial plant matter is mostly due to lignin, a compound solely composed of hydrogen, carbon and oxygen, and can compose up to 50% of woody material in some species (Brauns & Brauns, 1952). Lignin is a compound that is almost exclusively found in vascular land plants (Brauns & Brauns, 1952). The correlation between C/N ratios and sediment origin was shown by Kemp *et al*. (1977) in Great Lake sediments, as well as Hyne (1978) in the Fort Gibson Reservoir and Lake Texoma sediments. The average C/N ratio of sediments in former Lake Mills is 9, while former Lake Aldwell is 13. The difference in both reservoirs C/N ratio is likely due to the nature of sedimentation within the reservoir rather than the degradation of carbon itself. Lake Aldwell has a lower rate of sedimentation than does Lake Mills and a higher C/N ratio is expected. The lower rate at which inorganic material is brought in by the Elwha River means there is a higher concentration of organic compounds within the sediment. Having a higher C/N ratio suggests that there is a higher concentration of lignin within former Lake Aldwell sediment than former Lake Mills sediment (Kimmel *et al*., 1990). Since lignin primarily comes from allochthonous sources, it is likely that a higher percentage of Lake Aldwell's organic carbon has allochthonous origins than does Lake Mills. Higher rates of degradation within Lake Aldwell, due to lower rates of sedimentation, could also cause increases in C/N ratios, due to other compounds being preferentially degraded prior to lignin, increasing carbon concentration in relation to nitrogen. The C/N ratios in former Lake Mills are on average lower, signifying higher autochthonous, *in situ* sources of carbon than Lake Aldwell. However much autochthonous production occurred within former Lake Mills and Lake Aldwell, historically there has always been a large amount of sediment incoming from the Elwha River watershed. Dissolved organic matter of allochthonous origin (like that from the Elwha River) generally constitutes the primary source of external carbon loading into freshwater systems (Wetzel, 2001). Still, *in situ* primary production clearly plays a significant role in carbon sequestration within deeper regions of both reservoirs. It is also clear that having sequential reservoirs on the Elwha River has played an important role on its environment, directly influencing sediment carbon concentration.

Spatial Variability of Sediment Carbon

There were visible longitudinal gradients as well as substantial spatial variability in sediment deposition and particle size in former Lake Mills and Lake Aldwell. Within reservoirs, particulate organic matter often settles within the headwater region or delta, since river velocities decrease rapidly within this area and particles settle out quickly (Kimmel *et al.*, 1990). This was evident from sampling in former Lake Mills, where pockets of particulate organic matter, such as leaves, twigs, and stems were interlayered with coarse cobble layers. This led to isolated pockets of carbon, predominately within the delta region of former Lake Mills, but present throughout the upper meter of sediment in both reservoirs.

Downstream from the delta, both in former Lake Mills and Lake Aldwell, is the transition zone. In reservoirs this is generally where silts, coarse to medium clays, and fine particulate organic matter settle. These particles do not have the same sorptive capacity as fine clays, but organic carbon can attach itself to these particles and settle with them (Hyne, 1978). Generally, within this zone, fine particulate organic matter will undergo biological decomposition, which can cause depletion of dissolved oxygen. Anoxic conditions can result in an increase of ammonium concentrations as well as the solubilization of iron, phosphorus and manganese adsorbed to particulate matter (Kimmel *et al*., 1990). This in turn causes an increase in ionic strength of dissolved constituents, and an increase in the flocculation and sedimentation of fine particles (Kimmel *et al*., 1990). When these particulates drop within the water column, oxygen concentrations can be lower, causing further reduction and increasing of ionic strength. This positive feedback ultimately intensifies the process. However, the transition zone is markedly dynamic and is strongly influenced by both reservoir discharge as well as river inflow (Wetzel, 2001). This means that chemical and physical properties within this zone, such as anoxic conditions, can shift dramatically with changes in current, temperature, or mixing. Sediments deeper than 1 m in former Lake Mills show how dramatic this zone can be (see Map 4.6 and 4.8). This is where the edge of the Elwha River delta and Boulder Creek delta merge and follow into deeper sections of the reservoir. This also happens to be where the highest concentrations and contents of carbon are found, and explains the high sedimentation rates and sequestration of carbon. Similarly, in former Lake Aldwell the transition zone is the location of the highest recorded carbon concentrations and content, just south of the Goose Neck, and north of the former Lake's delta (see Map 4.8).

Beyond the transition zone, typically in the deepest part of a reservoir adjacent to the dam wall, is the lacustrine zone. This zone in reservoirs is known to settle out colloidal material and fine clay. As previously mentioned, it is also the location where the majority of autochthonous production of organic material generally occurs (Hyne, 1978). Within reservoirs beyond the Elwha River, carbon concentration and content is often highest where the original river thalweg falls, as this is the deepest section of the reservoir within all zones (Hyne, 1978). Development of an anoxic environment can occur within the lacustrine zone, but depends on reservoir hydrometeorology and shape as well as how the reservoir is operated (Kimmel *et al*., 1990). In either former Lake Mills or Lake Aldwell, more research is needed to determine if this happened.

The variability of carbon both with depth and laterally across sediments is significant in both former Lake Mills and Lake Aldwell. Carbon concentrations in the top meter of former Lake Mills are often low, averaging 0.95% (Map 4.1, Table 4.1.). This is most likely due to the high prevalence of mineral material ranging from sand to boulders within the upper layers of sediment. Finer sediments (< 2 mm) often had greater, more consistent carbon values. This finding is not unique; Anderson *et al.* (1981) found that only small amounts of carbon can be associated with sand, while substantially greater amounts can be found in coarse and fine silt, and the greatest amount found in coarse clays. This is something that was first confirmed by Trask *et al*. (1932), and later confirmed repeatedly by various researchers. Organic materials are often found in the deepest parts of basins because of their light density and because they are adsorbed onto clay minerals (Hyne, 1978). The top 20 cm of Lake Mills' consists of 43% particles greater than 2 mm. Given this, it should be no surprise that this upper fraction also has the lowest carbon concentration of any depth (0.76% carbon on average). With increase in depth (20 cm to 1 - 2 m) comes a decrease in particle size within former Lake Mills, a slight increase in carbon concentration (1.46% carbon on average) and a significant increase in carbon content (3.4 to 15.3 kg C m^{-3}).

The same does not necessarily apply to former Lake Aldwell, where only the southern delta region had substantial coarse mineral material. When looking at carbon concentration spatially (Map 4.2) this is quite visible, as former Lake Adlwell's carbon concentration is lowest in this coarse delta region, especially within the 0-20 cm depth, and higher elsewhere. The southern section of former Lake Aldwell has a higher concentration of carbon, with the top 0-20 cm being highly variable, likely from the Elwha River changing its course and unevenly distributing coarse material, as well as from the regrowth of vegetation during the year prior to sampling. Former Lake Aldwell's carbon concentration and content becomes more homogenous with depth, as does its sediment size class, with slightly higher carbon concentration numbers in its southern half.

In addition to sediment size class, topography, river velocity and currents play a significant role in carbon distribution and accumulation throughout both reservoirs. As water moves and collects into streams and flows down elevation gradients, complex water movement occurs. When these streams and rivers enter into Lake Mills and Lake Aldwell several basic mechanisms take over transport of dissolved and particulate matter; these include advection, convection, diffusion, dispersion, entrainment, mixing, settling, and sheer. All of these mechanisms are extremely dynamic; they change from location to location, some have time scales that are measured in seconds while others are in months and have an impact ranging from millimeters to a whole reservoir. Reservoirs are never in a steady state and the analysis of transport mechanisms that Lake Mills and Lake Aldwell may have had are beyond the scope of this paper, but should be recognized as an important factor in the spatial distribution of sediment and carbon within both reservoirs.

Carbon in Other Reservoir Sediments

Although few studies have quantified carbon sequestration in sediments of small reservoirs of temperate regions, it is clear they bury an exceptional amount of carbon in relation to other aquatic systems. Mulholland & Elwood (1982) estimated that organic carbon concentration of reservoir sediments across the United States is relatively constant from 1.5 to 2%; slightly more than Lake Mills' sediment average of 1.13%, and within range of Lake Aldwell's sediment average of 1.65% carbon. One study by Ritchie (1989) on the carbon content of small reservoir sediments (<4,000 km^{-2}), found that carbon concentration has a broader range than what was found by Mulholland & Elwood (1982), from 0.3 to 5.6%, with a mean of 1.9 ± 1.1%, which would put both former Lake Mills and Lake Aldwell well within this average. Because reservoirs tend to receive higher rates of sedimentation per year than do lakes (about 2 cm yr^{-1} on average within the United States (Mulholland & Elwood, 1982), and an average of 3.8 ± 3.3 cm yr^{-1} within a range of 0.6-14.1 cm yr^{-1} in small reservoirs (Ritchie, 1989)) these impoundments have a greater sequestration rate of total organic carbon by volume. This same finding holds true in former Lake Mills, which on average, from 1927 to 2010, received 11.2 cm yr^{-1} of sediment over its total inundation area (167 ha). Former Lake Aldwell has a much higher error in calculating average sediment accumulation due to no pre-dam survey taking place, and thus sediment depths are currently unknown. However, Childers *et al*. (2000) was able to predict a total sediment volume of 3,000,000 m^{-3} ±765,000 m^{-3}. Using this figure, Lake Aldwell had an average accumulation of sediment, from 1913 to 1994, of 3.4 ±0.88 cm yr^{-1} over its total inundation area (107 ha). However, it is estimated that 1,700,00 m^{-3} of the sediment in former Lake Aldwell was captured during the 14 years prior to the building of the Glines Canyon Dam on Lake Mills in 1927, making the yearly average lower after that time period, with one study estimating a total sediment accumulation rate of 24,000 m^{-3} yr^{-1} prior to 1927 (Federal Energy Regulatory Commission, 1991).

Ritchie (1989) found that small reservoirs (<4,000 km^{-2}), like that of former Lake Mills or Lake Aldwell, within the U.S. have a wide range of carbon sedimentation rates, from 26 to

3,700 g C m^{-2} yr^{-1} with a mean of 675 g C m^{-2} yr^{-1}. Lake Mills' average carbon accumulation rate is estimated to be 1,140 g C m^{-2} yr^{-1} (1927 to 2010). This is above the United States small reservoir average, but well within the range found by Ritchie (1989). Lake Aldwell's carbon accumulations rates have been calculated using a combination of sedimentation data stated previously, as found in Childers *et al*. (2000), and average carbon content values found in Table 4.7. Rates between 1913 and 1994 averaged 512 ± 131 g C m^{-2} yr^{-1}, which is very close to the values found by Ritchie (1989) for small reservoirs.

Dry bulk density for reservoir sediments within the United States generally fall between 0.7 to 1.3 g cm^{-3} (Dendy & Champion, 1978). Former Lake Mills' sediments have an average bulk density of 1.37 g cm^{-3} from 0-500 cm, with a total range from 0.88 – 2.01 g cm^{-3}. Former Lake Aldwell has a slightly lower value at 1.25 g cm^{-3} from 0- 400 cm, with a range of 0.26 – 2.05 g cm^{-3}. Both former Lake Mills and Lake Aldwell have an average sediment bulk density that is within normal range, but at the higher end of the scale. This could be from a higher mineral content than average, something that is visible from the organic carbon concentration values found in Tables 4.1 and 4.2. It could also be from a large coarse fraction within the upper layers, often ranging from gravel to boulders.

The Future of Former Lake Mills and Lake Aldwell Sediment

Former Glacial Lake Elwha serves as a useful reference for what will likely happen in the long term to the carbon and sediments from both former Lake Mills and Lake Aldwell. With the assumption that the original parent material from Glacial Lake Elwha had a similar carbon concentration to that of former Lake Mills and Lake Aldwell, the carbon within the developed O and A horizons of the soils surrounding former Lake Mills is much higher than most sediments sampled. This is not surprising, as with increased vegetative cover comes an increase in carbon input. Below the A horizon (~35 cm), carbon values are similar, to slightly less than that of former Lake Mills and Lake Aldwell sediments (Mussman, 2006).

Currently, large amounts of sediment remain within former Lake Mills and Lake Aldwell, as a series of terraces. Undoubtedly, erosion will play a significant role in the ultimate fate of a portion of this sediment. However, the goal of the reservoir drawdown is to stabilize this sediment and expedite the growth of native species (Chenoweth, 2007; Mussman *et al*., 2008). As a soil develops from this lacustrine source, a switch from anaerobic to aerobic decomposition is expected, especially in upper sediment layers. Mussman (2006) did find that fine-textured soils surrounding former Lake Mills had gleyed horizons, indicating anaerobic conditions in lower soil profiles. This means that clays and silts within former Lake Mills and Lake Aldwell, especially within deep layers, may continue to be anaerobic. Due to this, it is probable that vegetative cover adapted to this type of environment will be prevalent in areas with very fine sediment particle size. Over time it is expected that a climax forest similar to that surrounding former Lake Mills and Lake Aldwell will develop, as well as a typical soil that is found under such a forest with a lacustrine parent material.

6. Conclusions

Former Lake Mills contains an estimated 159 Gg C within 15.6 million m^{-3} of sediment (Bountry *et al*., 2010). The average carbon accumulation rate within former Lake Mills is estimated at 1,140 g C m^{-2} yr^{-1} from 1927 to 2010. This is an amount that is above the U.S. national small reservoir average by 465 g C m^{-2} yr^{-1} but well within a normal range (Ritchie, 1989). Carbon concentration in former Lake Mills sediments had an average of 1.13%, with a general increasing trend in concentration with depth and amount of fine particles. This concentration is lower than the national average for small reservoirs but well within the normal range (1.9 ± 1.1% across the U.S.).

Former Lake Aldwell contains an estimated 64 Gg C within the top 4 m of sediment. This may be an overestimation as actual sediment depth within former Lake Aldwell is unknown, and a sediment depth of 4 m—regardless of location—was used to calculate total carbon content. The average carbon accumulation rate within former Lake Aldwell is estimated at 512 ± 131 g C m^{-2} yr^{-1}, which is similar to the values found by Ritchie (1989) of 675 g C m^{-2} yr^{-1} for small reservoirs in the U.S. Former Lake Aldwell had an average carbon concentration of 1.65%; a value somewhat lower than the national average, but well within range of many other temperate reservoir sediments.

Soils surrounding former Lake Mills and Lake Aldwell that were once inundated by Glacial Lake Elwha during the Pleistocene serve as a reference for predicting the fate of sediments left behind from dam removal. Below the O and A horizons, within the B horizion, these soils generally have carbon values that are similar, to slightly less than that of former Lake Mills and Lake Aldwell, and organic top layers that have considerably higher carbon contents (Mussman, 2006). Further studies should be conducted to better understand the fate of this carbon after dam removal, as well as to measure and map the depths of Lake Aldwell's sediments for higher clarity of current and future research along the Elwha River.

7. References

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Appendix 1

Generalized extreme studentized deviate (ESD) test for outliers of sediment carbon concentration.

#	Potential outlier value (%C)	Test Statistic value, R_i	Critical value, λ_i (5%)	Critical value, λ_i (1%)
1	12.77	10.47	3.73	4.10
2	6.24	5.80	3.73	4.10
3	5.02	4.71	3.73	4.10
4	4.47	4.23	3.73	4.10
5	4.20	4.02	3.73	4.10
6	3.88	3.73	3.72	4.10
7	3.71	3.60	3.72	4.10
8	3.33	3.17	3.72	4.10
9	3.27	3.15	3.72	4.10
10	3.21	3.12	3.72	4.10

For 5% significance level, there are 6 Potential Outliers
Potential outliers are:
12.77, 6.24, 5.02, 4.47, 4.20, 3.88

For 1% Significance Level, there are 4 Potential Outliers
Potential outliers are:
12.77, 6.24, 5.02, 4.47

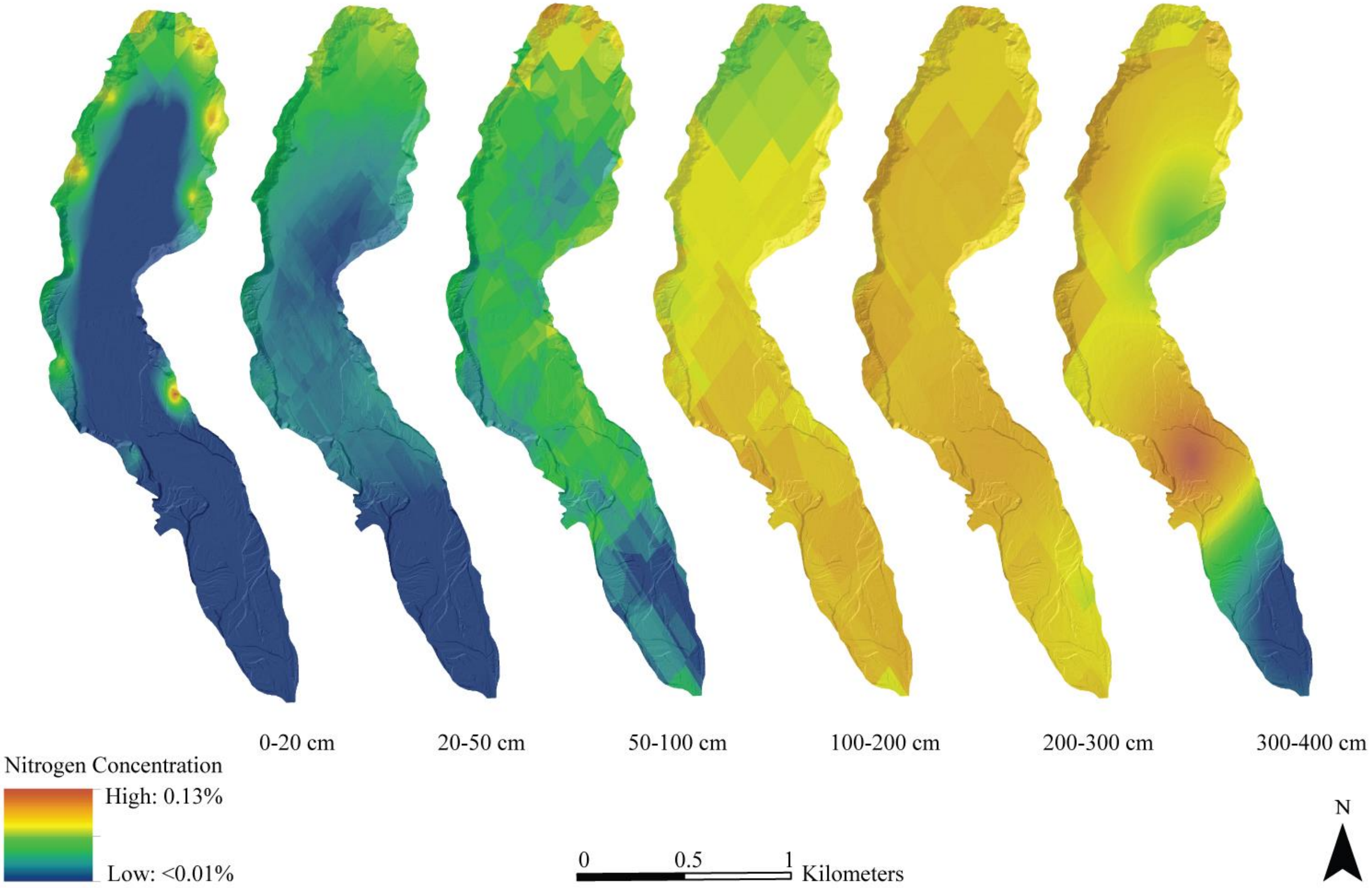
Appendix 2

Estimated sediment gradation and volume in millions of m^{-3} for former Lake Mills and Lake Aldwell. Data taken from *Alluvium Distribution in Lake Mills, Glines Canyon Project and Lake Aldwell, Elwha Project, Washington* (United States Department of the Interior, 1995).

	Clay, Silt <0.075 mm	Sand 0.075-5 mm	Gravel 5-75 mm	Cobbles 75-300 mm	Total Volume (million m^{-3})
Lake Mills					
Rica Canyon, Cat Creek Fan, Boulder Creek Fan	0.06	0.36	0.65	0.11	1.18
Delta Area	1.26	3.27	0.76	0.04	5.33
Reservoir Floor and Prodelta	3.72	0.31	0	0	4.03
Total Volume	**5.04**	**3.94**	**1.41**	**0.15**	**10.54**
Percent Total	**48%**	**37%**	**13%**	**1%**	
Lake Aldwell					
Delta Area	0.55	0.65	0.12	0.04	1.36
Reservoir Floor and Prodelta	1.43	0.18	0	0	1.61
Total Volume	**1.98**	**0.83**	**0.12**	**0.04**	**2.97**
Percent Total	**67%**	**28%**	**4%**	**1%**	

Appendix 3

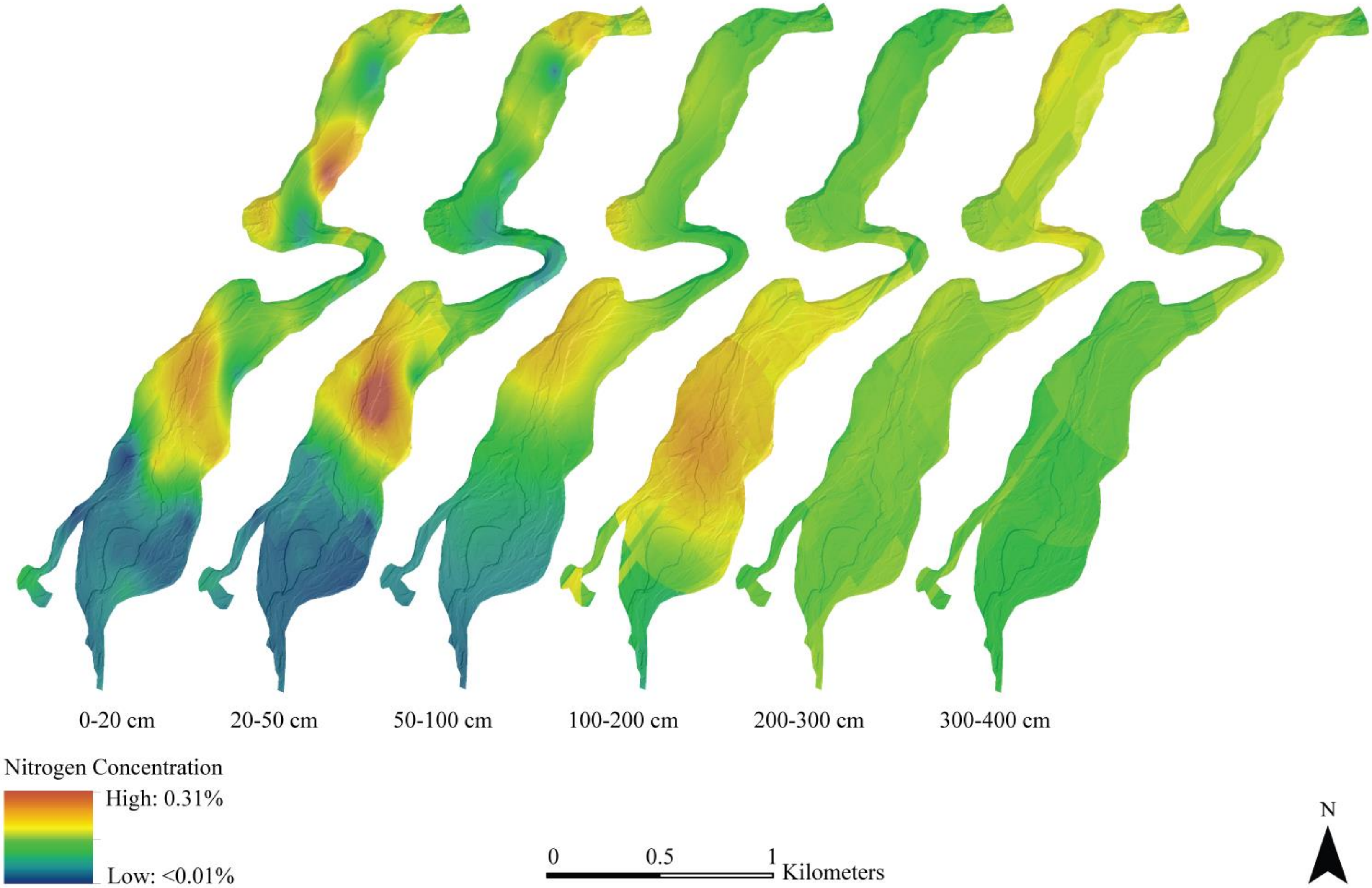
Nitrogen Concentration of Former Lake Mills



Kriged nitrogen concentration of former Lake Mills sediments to a depth of 4 m.

Appendix 4

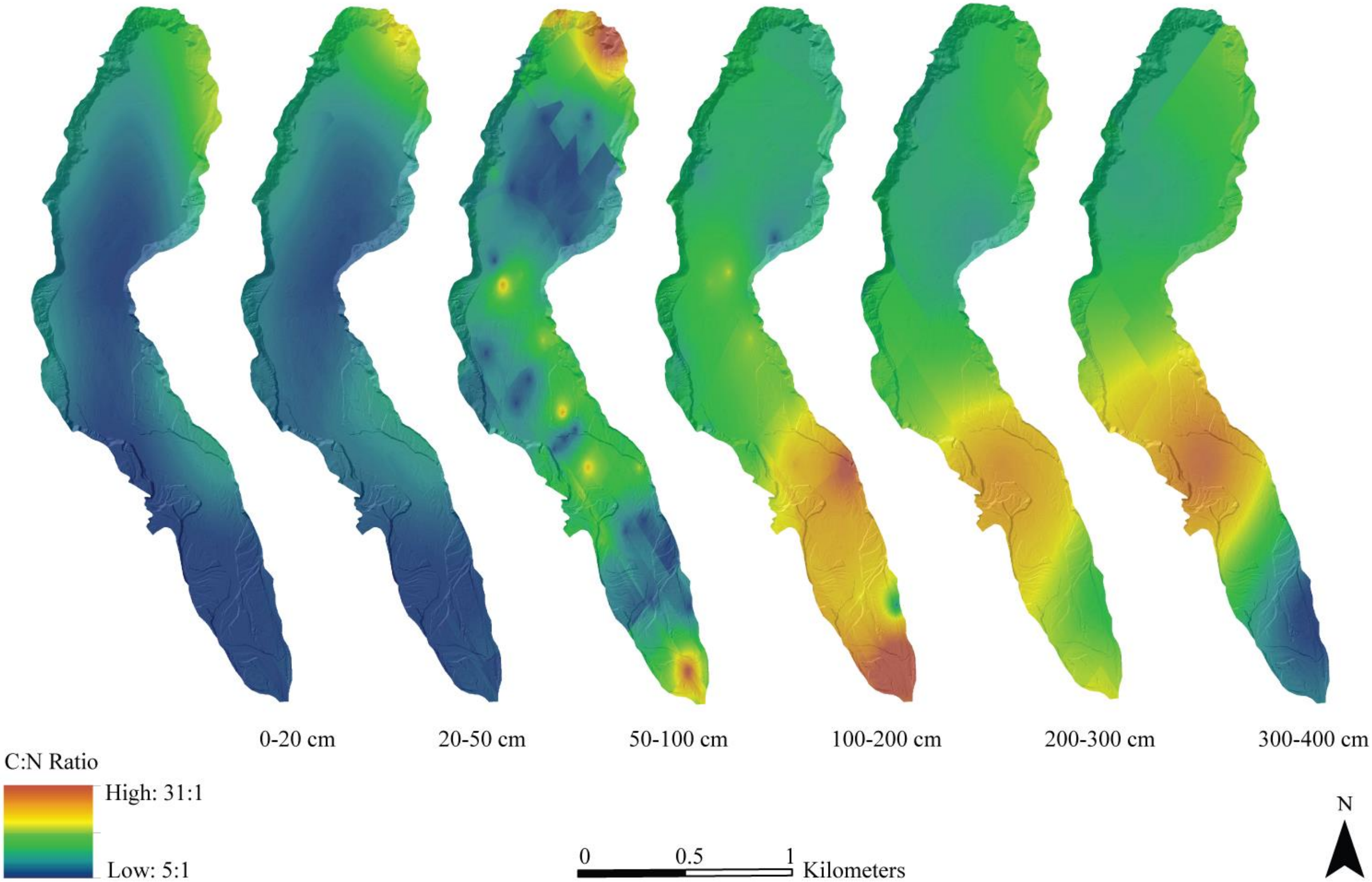
Nitrogen Concentration of Former Lake Aldwell



Kriged nitrogen concentration of former Lake Aldwell sediments to a depth of 4 m.

Appendix 5

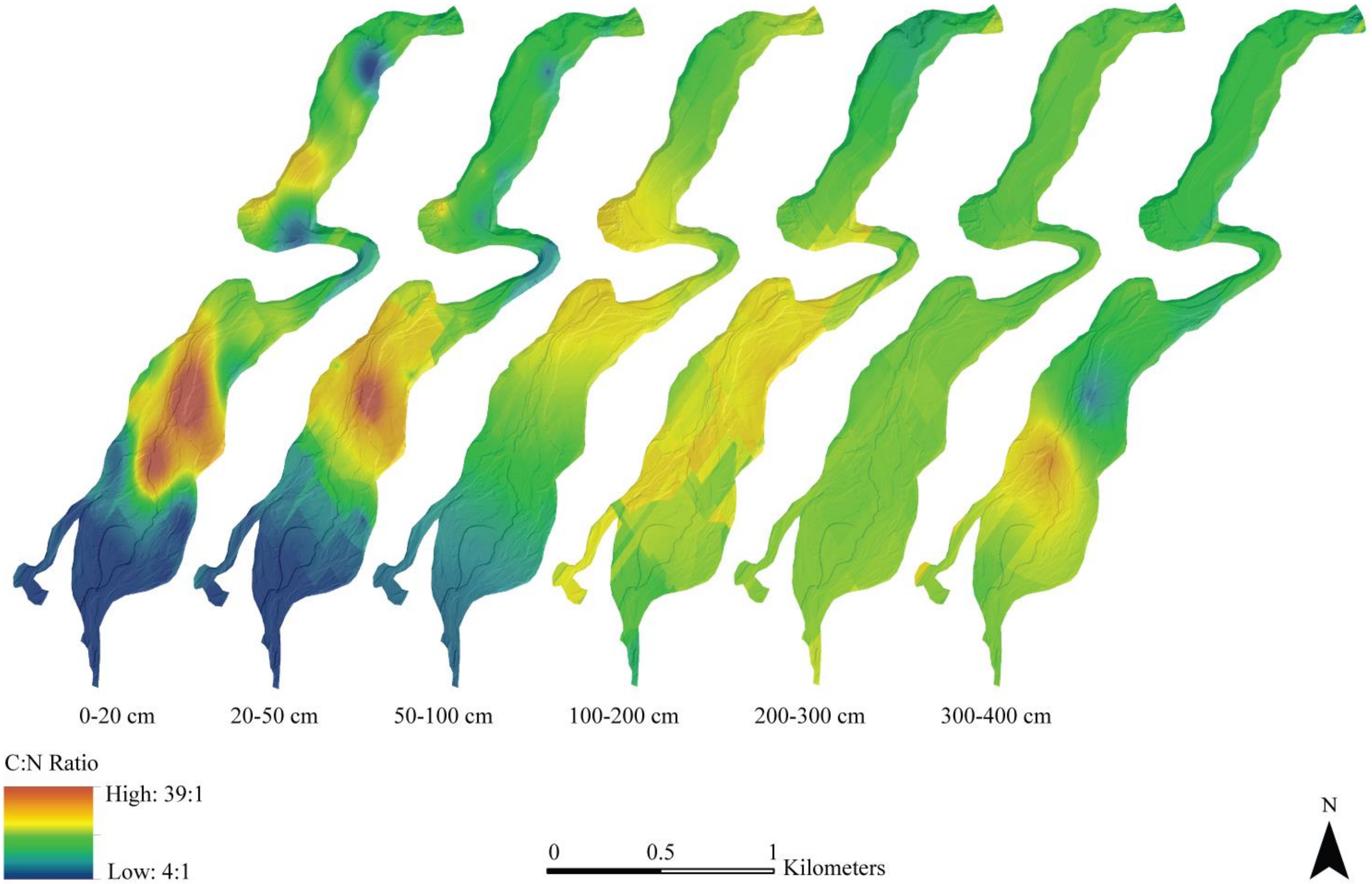
Carbon to Nitrogen Ratios of Former Lake Mills



Kriged carbon to nitrogen ratios of former Lake Mills sediments to a depth of 4 m.

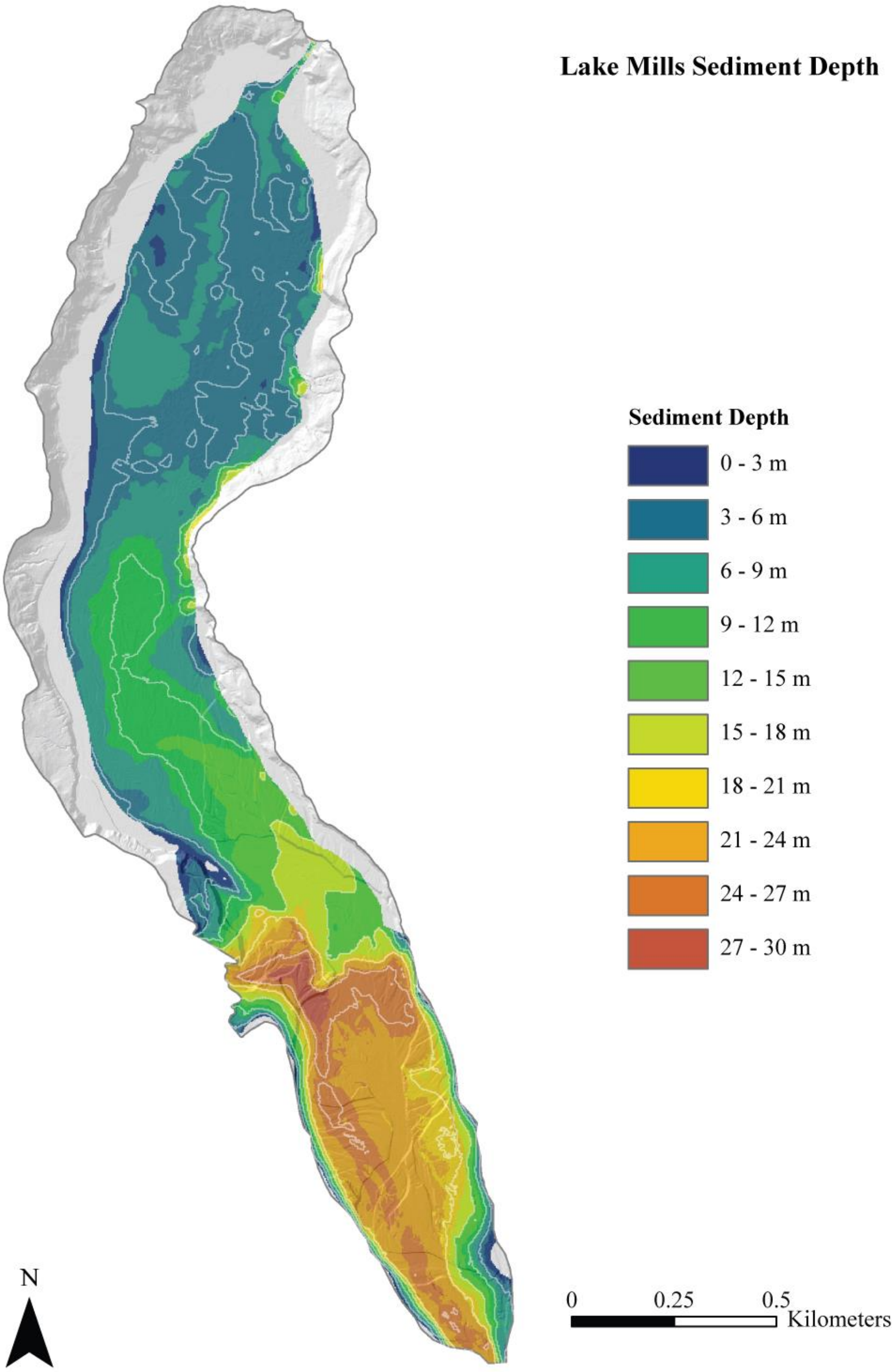
Appendix 6

Carbon to Nitrogen Ratios of Former Lake Aldwell



Kriged carbon to nitrogen ratios of former Lake Aldwell sediments to a depth of 4 m.

Appendix 7



Former Lake Mills sediment depth by meter. Contour intervals at 5 m. Data obtained from Bountry *et al.* (2010).