DISSERTATION

FLOODPLAIN ORGANIC CARBON STORAGE IN THE CENTRAL YUKON RIVER BASIN, INTERIOR ALASKA

Submitted by

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ABSTRACT

FLOODPLAIN ORGANIC CARBON STORAGE IN THE CENTRAL YUKON RIVER BASIN, INTERIOR ALASKA

River channels and floodplains transport, transform, deposit, and store organic carbon (OC) as active participants in the carbon cycle. Two of the largest stocks of OC in floodplains include soil and downed large wood (LW). This dissertation investigates floodplain OC stocks in LW and soil, and the geomorphic controls on soil OC stocks in the central Yukon River Basin in the Yukon Flats region of interior Alaska. The Yukon Flats region contains discontinuous permafrost, has a semiarid boreal climate, and has experienced little human modification. Almost all studies of floodplain OC have occurred in the temperate regions, despite permafrost regions storing large amounts of OC in the subsurface due to cold and wet conditions. In addition, relatively little is known about the geomorphic processes that control soil OC distribution on the landscape, particularly over large regions. Wood has been removed for navigation and infrastructure protection in many river corridors, and thus knowledge of natural wood loads, particularly on floodplains, is limited. I first present floodplain downed large wood measurements for the Yukon Flats region, and compare those measurements to downed wood loads in unaltered floodplains in two additional biomes, the subtropical lowlands and the semiarid temperate mountains. Average volumes of downed LW are 42 m^3ha^{-1}, 50 m^3ha^{-1}, and 116 m^3ha^{-1} in the semiarid boreal, subtropical, and semiarid temperate sites, respectively. I find patterns in LW loads reflect climatic controls, such as decay rate and primary productivity, as well as increases in floodplain downed wood loads with recent disturbances such as fire. Next, I

assess the geomorphic controls on floodplain soil OC concentrations along the Yukon River and four of its tributaries using a large dataset of floodplain soil samples, finding that river basin characteristics and geomorphic unit characteristics likely influence the spatial distribution of soil OC on the landscape. Average OC concentration within floodplain soil is 2.8% (median = 2.2%). Most floodplain soil OC likely comes from riparian vegetation, which is influenced by channel migration rates and the development of geomorphic units within the floodplain. Greater variability in OC concentrations among geomorphic units compared to among river basins indicates that a bottom-up approach to estimating OC on the landscape (scaling up from small-scale landscape units) may be necessary. Finally, I estimate the soil OC stock in the floodplains of the Yukon Flats and find that my estimate results in approximately an 80% increase in OC stock when compared to a previously published database. The residence time of floodplain sediment is constrained using radiocarbon dates taken from cutbanks, and indicates that OC may be stored in floodplains for over 7000 years before being eroded by the channel. This dissertation provides much needed information on the geomorphic controls on floodplain OC storage in permafrost regions, which are undergoing relatively rapid warming due to anthropogenic climate change. In addition, it highlights the importance of accounting for floodplains as unique landscape units and mediators of OC fluxes, water, and nutrients.

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DEDICATION

I dedicate this dissertation to my parents, Susan Blom and Rob Lininger, who have encouraged my curiosity about the natural world and inspired me to continue learning; to my husband, Micah Nelson, who has supported me in pursuing my goals; and to my daughter, Sylvia Mae Nelson, who reminds me what is important in life and brings me joy every day.

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Chapter 1 Introduction

Until recently, rivers have been seen as neutral pipes in the carbon cycle, transporting carbon from the land to the ocean (Cole et al., 2007). However, recent work has highlighted that river corridors (channels and floodplains) actively transport, erode, deposit, store, and transform carbon (Aufdenkampe et al., 2011; Battin et al., 2009; Regnier et al., 2013; Sutfin et al., 2016). Accounting for the role of river corridors in the terrestrial carbon cycle may help constrain the terrestrial carbon budget, which is not well quantified (Battin et al., 2009). Estimates for the amount of carbon that is buried in rivers, lakes, and floodplains each year ranges from 0.2-1.6 Pg C yr^{-1}; this large range highlights the lack of information on the role of floodplains in the carbon cycle. This dissertation investigates floodplain organic carbon (OC) storage in soil and downed large wood (LW) in the Yukon Flat region of interior Alaska, contributing to knowledge of the role of river corridors in the carbon cycle.

Almost all studies of floodplain OC storage and dynamics are from middle-latitude temperate regions with moderate climates (e.g., Cierjacks et al., 2010; Ricker and Lockaby, 2015; Sutfin and Wohl, 2017), but high latitude permafrost regions store large amounts of organic carbon (OC) in the subsurface, with estimates indicating that approximately half of all subsurface OC could be stored in these regions (Hugelius et al., 2014; Jobbágy and Jackson, 2000). With anthropogenic climate change disproportionately warming the high latitudes (IPCC, 2014), there is concern that OC in permafrost will be released to the atmosphere via microbial respiration with permafrost thaw and degradation (Schuur et al., 2008). The decomposition of OC stored in permafrost could further enhance warming, creating a positive feedback (Koven et al., 2015; Schuur et al., 2015). Thus, accurately estimating the spatial distribution of OC on the landscape in high latitude regions is important for accounting for current OC stocks and predicting future changes due to warming. Floodplains have not been included as distinct from uplands in previous assessments of carbon stocks and fluxes in the high latitudes (e.g., Stackpoole et al., 2017), but fluxes to the Arctic Ocean of OC, nutrients, and water are mediated by floodplain interactions. Assessing floodplain OC stocks in the Yukon Flats, a region of discontinuous permafrost with extensive floodplains, is addressing this gap in knowledge.

The few studies that have investigated geomorphic influences on floodplain soil OC have indicated that sedimentation patterns, grain size differences, and riparian vegetation govern the spatial distribution of OC within floodplains (Appling et al., 2014; Cierjacks et al., 2011; Pinay et al., 1992). However, studies of floodplain OC storage have been conducted on relatively small rivers or across small spatial extents on larger rivers (e.g., Appling et al., 2014; Ricker and Lockaby, 2015; Sutfin and Wohl, 2017). This limits the ability to assess geomorphic controls on floodplain OC storage across spatial scales. For example, do differences in floodplain soil OC occur primarily among river basins (large-scale variation), or do they occur among geomorphic units at the spatial scale of a reach (small-scale variation)? Because the Yukon Flats is a large inland alluvial basin and the field sampling extent in this thesis is extensive, this dissertation is able to address questions of geomorphic controls on floodplain OC across spatial scales.

Downed LW within river corridors influences fluvial processes, is important for providing habitat and nutrients for biota, and is a relatively large OC stock (Ballinger et al., 2010; Harmon et al., 1986; Jeffries et al., 2003; Sutfin et al., 2016). LW can cause sedimentation, channel avulsion, and other geomorphic effects (Sear et al., 2010; Wohl et al., 2012), and has been increasingly used to enhance habitat for restoration and river management (Roni et al., 2015). However, LW removal from river corridors for navigation and infrastructure protection has been widespread in the temperate regions (Wohl et al., 2017b), resulting in a lack of knowledge regarding natural wood loads in river corridors. The Yukon Flats region, which is located in a high-latitude river basin with a continental subarctic climate, has not experienced wood removal and humans have not modified the rivers, thus the region provides an opportunity to assess LW loads in an unaltered environment.

This dissertation seeks to address the gaps in knowledge regarding floodplain soil OC and downed wood through the following objectives: 1) assess the quantity of LW and OC storage in floodplain LW within the Yukon Flats region of interior Alaska and compare that OC storage in LW to unaltered floodplains from different biomes (Chapter 2); 2) determine the geomorphic controls on OC storage in soil across spatial scales, from the reach to the river basin (Chapter 3); and 3) estimate the stock of soil OC across the Yukon Flats region, compare this estimate to previously published datasets, and constrain the residence time of floodplain sediment and soil OC within the seasonally thawed layer (Chapter 4). Chapters 2-4 are journal articles that have been published or are currently in review. In Chapter 5, I summarize the key findings of this work and suggest future research related to floodplain OC storage in high latitude regions.

Chapter 2 Floodplain downed wood volumes: a comparison across three biomes[1]

Summary

Downed large wood (LW) in floodplains provides habitat and nutrients for diverse organisms, influences hydraulics and sedimentation during overbank flows, and affects channel form and lateral migration. Very few studies, however, have quantified LW volumes in floodplains that are unaltered by human disturbance. We compare LW volumes in relatively unaltered floodplains of semiarid boreal lowland, subtropical lowland, and semiarid temperate mountain rivers in the United States. Average volumes of downed LW are 42.3 m^3ha^{-1}, 50.4 m^3ha^{-1}, and 116.3 m^3ha^{-1} in the semiarid boreal, subtropical, and semiarid temperate sites, respectively. Observed patterns support the hypothesis that the largest downed LW volumes occur in the semiarid temperate mountain sites, which is likely linked to a combination of moderate-to-high net primary productivity, temperature-limited decomposition rates, and resulting slow wood turnover time. Floodplain LW volumes differ among vegetation types within the semiarid boreal and semiarid temperate mountain regions, reflecting differences in species composition. Lateral channel migration and flooding influence vegetation communities in the semiarid boreal sites, which in turn influences floodplain LW loads. Other forms of disturbance such as fires, insect infestations, and blowdowns can increase LW volumes in the semiarid boreal and semiarid temperate mountain sites, where rates of wood decay are relatively slow compared to the subtropical lowland sites. Although sediment is the largest floodplain

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carbon reservoir, floodplain LW stores substantial amounts of organic carbon and can influence floodplain sediment storage. In our study sites, floodplain LW volumes are lower than those in adjacent channels, but are higher than those in upland (i.e., non-floodplain) forests. Given the important ecological and physical effects of floodplain LW, efforts to add LW to river corridors as part of restoration activities, and the need to quantify carbon stocks within river corridors, we urge others to quantify floodplain and instream LW volumes in diverse environments.

2.1 Introduction

Downed large wood (>10 cm in width and >1 m in length) within river corridors, which we define as channels and floodplains, is geomorphically and ecologically important (Harmon et al., 1986; Jeffries et al., 2003; Pettit and Naiman, 2006; Collins et al., 2012). Downed floodplain large wood (LW) exerts controls on physical process and form in river corridors. Floodplain LW can be a source of wood to the channel as channels migrate, erode banks, and transport wood from the floodplain (Benda and Sias, 2003; Latterell and Naiman, 2007). Dispersed and jammed (i.e., accumulated in piles) LW on floodplains can influence floodplain inundation and sedimentation patterns by increasing hydraulic resistance during overbank flow (Jeffries et al., 2003; Sear et al., 2010), and can influence channel planform and lateral migration rates (Collins et al., 2012; Polvi and Wohl, 2012).

Numerous studies document reciprocal interactions among in-channel LW, floodplain LW, floodplain vegetation, floodplain turnover time, and channel form and process (e.g., Piégay and Gurnell, 1997; Gurnell et al., 2000, 2002; O'Connor et al., 2003; Gurnell and Petts, 2006; Wohl, 2013a). Few studies, however, document floodplain downed LW loads along unmanaged rivers. Our primary objective is to provide such documentation in three regions (semiarid boreal lowland, subtropical lowland, and semiarid temperate mountain) and to examine potential controls on wood loads.

In addition to geomorphic effects, downed floodplain LW provides habitat for riparian and terrestrial biota by providing shelter and food to birds, mammals, amphibians, and aquatic and terrestrial invertebrates (Harmon et al., 1986; Braccia and Batzer, 2001; Bull, 2002; Mac Nally et al., 2002; Ballinger et al., 2010). LW creates sites of nutrient hotspots as the wood decomposes (Schowalter et al., 1998), and accumulations of LW within the floodplain are associated with sites of seedling establishment and the regrowth of riparian vegetation (Pettit and Naiman, 2006). Floodplain LW is also a significant organic carbon (OC) stock within river-floodplain systems (Wohl et al., 2012; Sutfin et al., 2016). Globally, dead LW can be 10-20% of the above-ground biomass of forests, resulting in a stock estimated at 36-72 Pg C (1 Pg = 10^{15}g = 1 Gigaton) (Cornwell et al., 2009).

Although there is a great deal of literature within the forest ecology discipline on downed and dead LW in upland forests (e.g., Russell et al., 2015), which we define as forests located outside of floodplains, very little attention has been given to downed LW within floodplains. The geomorphic and ecological importance of floodplain LW, as well as the unique character of riparian zones, indicates that further attention should be paid to LW loads and patterns in LW loads across different biomes. Riparian ecosystems have high spatial heterogeneity, displaying mosaics of landforms and vegetation, and they are dynamic transition zones between the aquatic and terrestrial realms (Gregory et al., 1991; Naiman and Décamps, 1997). Riparian vegetation commonly differs from upland vegetation, with riparian species undergoing fluvial disturbances (e.g., lateral channel migration) as well as upland disturbances (e.g., landslides, debris flows), and riparian forests are more productive compared to upland forests (Naiman and Décamps, 1997). Recent efforts to restore LW to river corridors for ecological and geomorphic benefits (e.g., Abbe and Brooks, 2011) also provide motivation for exploring LW loads in unaltered floodplain environments across diverse environments.

2.1.1 Dynamics of floodplain LW

The sources of downed LW in the floodplain include lateral inputs from upland areas, lateral inputs of wood from the channel via flooding and deposition, and mortality and breakage of standing trees within floodplain forests or adjacent terraces and uplands (Harmon et al., 1986). Inputs from upland areas likely dominate in high-relief catchments and valley segments closely coupled to unstable hillslopes on which landslides and debris flows introduce substantial volumes of LW to the floodplain and channel (e.g., May and Gresswell, 2003). In contrast, lateral inputs of wood from the active channel to the floodplain likely dominate where overbank flows transport substantial quantities of wood onto the floodplain or where channel avulsion and lateral accretion allow in-channel logjams to be incorporated into the floodplain (Collins et al., 2012). LW floated onto the floodplain during overbank flows is likely to be concentrated along the floodplain margin close to the channel or at the upstream end of secondary channels near island heads (Piégay and Gurnell, 1997), rather than being evenly distributed across the floodplain.

We focus on LW on the floodplain surface and not in the subsurface, within the active channel, or on the channel margins. Consequently, we expect wood recruitment from floodplain forests via breakage and mortality to dominate floodplain wood loads on most river segments, particularly those with relatively low gradients and in low-relief terrains along which laterally and longitudinally extensive floodplains are most likely to be present.

The relative importance of the causes of LW recruitment is likely to vary both spatially and temporally. Lateral channel inputs can create concentrations of LW along the channel-floodplain boundary. Floodplain forest mortality can dominate LW loads in the floodplain interior, and valley side slope inputs can dominate LW loads at the floodplain margins. Disturbances, such as fire, floods, wind storms, and hurricanes, can greatly increase LW loads by causing mortality and breakage of riparian trees (Moroni, 2006; Harmon, 2009). For example, mass mortality of floodplain forests during hurricanes can create a pulsed and episodic input of downed LW to the floodplain (Phillips and Park, 2009), whereas individual mortality provides a much smaller, continuous input of downed LW.

Reduction of LW loads on the surface of the floodplain can occur through removal by river transport, burial, and through decay (Harmon et al., 1986). Decay involves fragmentation of wood pieces, leaching dissolved materials and resulting weight loss, and microbial metabolism (Harmon et al., 1986). Size reduction via fragmentation could result in the wood piece no longer belonging in the large wood class and could make resulting smaller wood pieces more susceptible to floating and removal during overbank flows. Rates of wood decay vary among tree species at a site and among sites as a function of moisture, temperature, piece size, abrasion, breakage, and microbial decomposition (Harmon et al., 1986; Harmon, 2009). Decay rates are usually investigated for specific species within relatively small study areas (e.g., Kueppers et al., 2004; Ricker et al., 2016) and are only generally constrained for ecosystem types at a global scale (Harmon et al., 2001). There are multiple metrics used to report the speed at which large wood or organic matter decays. Most studies use the single exponential model of decay described by Olson (1963), in the form of $Y_t = Y_0e^{-kt}$, where Y_0 is the initial quantity of wood, Y_t is the quantity left at time t, and k is the decay constant. Wood decomposition can then be described by the decay constant *k*, the half-life of the wood (0.693/*k*), or the turnover time of the wood (1/*k*) (Olson, 1963; Harmon et al., 1986). In this paper, we report wood turnover times from the literature for the purpose of comparing biomes.

Patterns in upland downed LW loads can be related to broad-scale climatic factors. As latitude increases, forest biomass and net primary productivity generally decrease, leading to a smaller source pool for downed LW (Harmon et al., 1986; Krankina and Harmon, 1995; Saugier et al., 2001). However, decomposition generally decreases with colder climates at higher latitudes, potentially offsetting the effect of decreased productivity (Harmon et al., 1995; Harmon, 2009). Similarly, decreasing temperature with increasing elevation limits decomposition at higher elevations. Mountainous regions that experience orographic precipitation and significant snow accumulation can provide the moisture necessary for increased productivity relative to surrounding lowlands (Schimel et al., 2002), and differences in disturbance regimes in mountainous environments compared to lowland environments can also influence downed LW loads.

2.1.2 Objectives and hypothesis

The objectives of this paper are to: examine patterns in downed LW volumes across three biomes in floodplains unaltered by human modifications; determine the quantity of organic carbon stored in floodplain LW; infer primary influences on floodplain LW volumes, including investigating the influence of vegetation types and disturbance; and compare floodplain LW loads to upland LW loads and in-channel LW loads. Patterns here refer to differences between regions and differences within a region as a result of difference in vegetation community and disturbance. In this context, human modifications include timber harvest, log floating for timber delivery to mills, flow regulation, channelization, construction of artificial levees, road construction in riparian zones, riparian forest management, and floodplain drainage. Floodplains unaltered by human activities can provide a baseline for natural floodplain LW loads, facilitating quantification of human alteration of wood loads through reduced wood recruitment and transport or direct wood removal.

Field sites include the central Yukon River Basin in interior Alaska (semiarid boreal lowlands), Congaree National Park in South Carolina (subtropical lowlands), and subalpine and montane conifer forests in the Rocky Mountains of Colorado (semiarid temperate mountains). In each of these sites we focus on naturally disturbed sites, rather than on managed forests or sites impacted by human disturbance, and we assume that floodplain vegetation is the dominant source of floodplain LW. We posit that biomes with high forest productivity along with slow decay rates will have the largest downed wood volume (Harmon, 2009; Sutfin et al., 2016). Because these conditions are met in the semiarid temperate mountain sites, we hypothesize that these sites will have the highest LW volume.

2.2 Study areas

2.2.1 Semiarid boreal lowlands: The Yukon Flats region, Alaska, USA

The Yukon Flats is a large alluvial basin located in the central Yukon River basin in the dry boreal zone of interior Alaska (Figure 2.1, Figure 2.2, Table 2.1). The climate is continental subarctic (Gallant et al., 1995) with discontinuous to continuous permafrost underlying the more than 30,000 km^2 of the floodplains of the Yukon River and multiple tributaries (Jorgenson et al., 2008). Floodplain vegetation types include herbaceous vegetation, shrubs (willows (*Salix* spp.) and alders (*Alnus* spp.)), deciduous tree species (balsam poplar (*Populus balsamifera*), aspen (*Populus tremuloides*), and white birch (*Betula papyrifera*)), spruce forest (white (*Picea glauca*) and black spruce (*Picea mariana*)), and mixed forests (spruce and deciduous). Wildfire return interval ranges from 37 to 166 years, with a mean recurrence interval of circa 90 years (Drury and Grissom, 2008). Other disturbances include blowdowns and movement of river ice that damages and topples vegetation. High flows occur in the spring due to snowmelt, with infrequent ice jam floods causing more intense flooding. Decay rates of downed wood for a variety of tree species in this location are unknown, but are likely to be extremely slow given the cold temperatures and low mean annual precipitation (Harmon et al., 1986; Gallant et al., 1995) (Table 2.1).

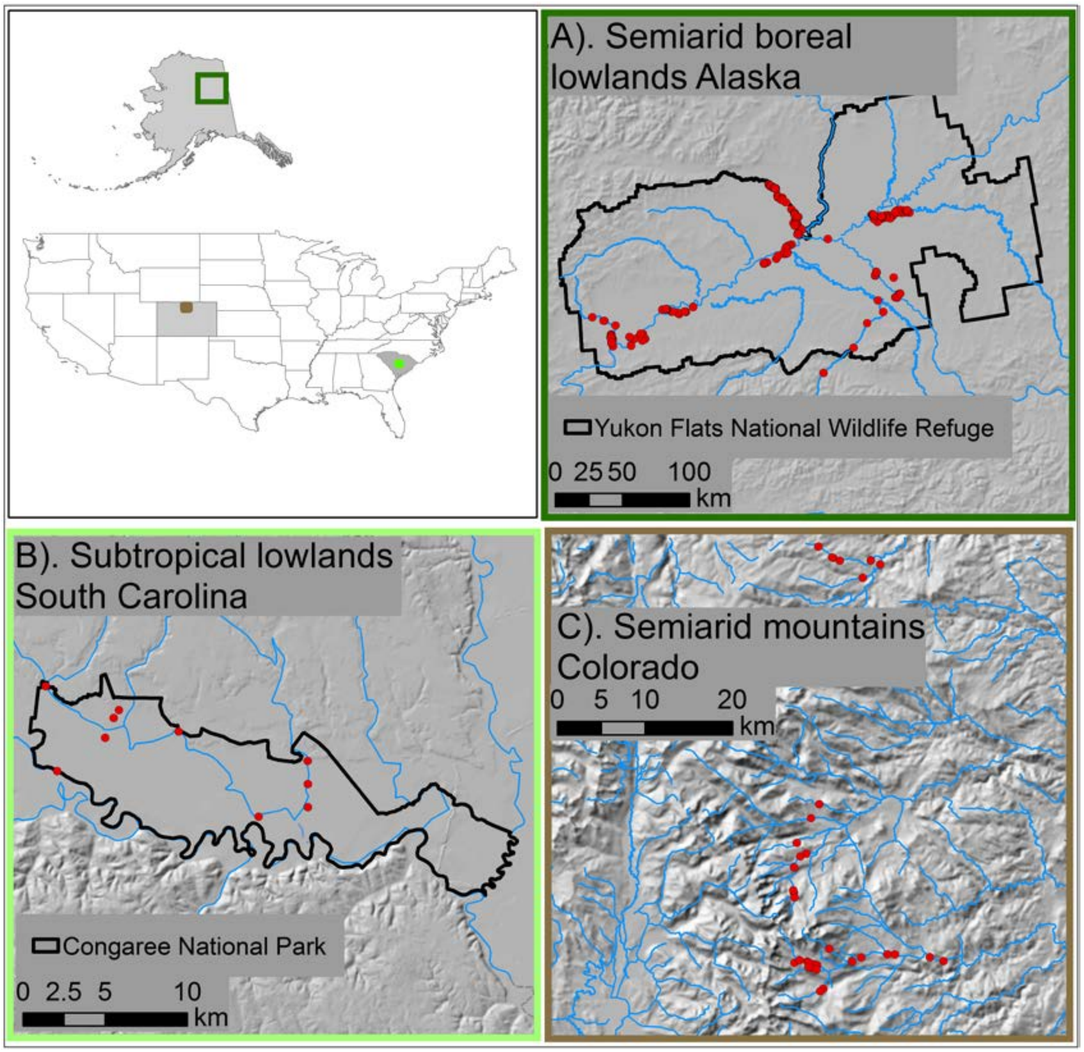

Figure 2.1. Map showing location of the three study regions. Locations of measurements are shown as red dots for each of the locations.

Figure 2.2. Photos of the study regions, showing floodplains in the boreal lowlands in Alaska (A), the subtropical lowland floodplain in South Carolina (B), and the semiarid mountains in Colorado (C). In (A), the two main channels of the Yukon River are approximately 500-700 meters wide. In (B), the fallen log at the center of the photo on the Congaree floodplain is approximately 6 meters in length. In (C), the distance between the two standing trees in the center of the photo is approximately 3 meters. Photo of the semiarid mountains by Lina Polvi Sjöberg.

Table 2.1. Characteristics of the study sites

Region	Mean annual precipitation (mm)	Mean annual temperature (°C)	Drainage areas of study sites (km^2)	Wood turnover time (years)
Boreal lowlands, Alaska	170	-1	4,000-510,000	Unknown
Southern Rockies subalpine	800-1000	4	3-96	600-900[a]
Southern Rockies montane	400	7	<40	300-400[a]
Subtropical lowlands, South Carolina	1220	17.6	110-18,100	4-5[b]

[a] (Kueppers et al., 2004)
[b] (Ricker et al., 2016)

2.2.2 Subtropical lowlands: Congaree National Park, South Carolina, USA

The subtropical lowland study sites are located within Congaree National Park in South Carolina (Figure 2.1, Figure 2.2, Table 2.1). Common tree species include baldcypress (*Taxodium distichum*), water tupelo (*Nyssa aquatic*), loblolly pine (*Pinus taeda*), sweetgum (*Liquidambar styraciflua*), green ash (*Fraxinus pennsylvanica*), and red maple (*Acer rubrum*). Disturbances include blowdowns and flooding. Although blowdowns associated with hurricanes are the major disturbance on longer time scales, the study sites have not been recently influenced by a hurricane. Rainfall-generated flooding is most frequent during winter and early spring, but can occur at any time during the year. Invertebrate activity contributes to extremely fast wood turnover time (4-5 years) for downed wood on the floodplain (Ricker et al., 2016) (Table 2.1).

2.2.3 Semiarid temperate mountains: Rocky Mountains, Colorado, USA

Sites in the Rocky Mountains are located on the eastern side of the continental divide in a semiarid climate (Figure 2.1, Figure 2.2, Table 2.1). One group of sites lies within subalpine forest (3500-2850 m elevation) dominated by Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), aspen (*Populus tremuloides*), and limber pine (*Pinus flexilis*) (Veblen and Donnegan, 2005). Snowmelt dominates the hydrograph (Jarrett, 1989), and disturbances include wildfire and blowdowns. Stand-killing fires in the uplands recur at intervals greater than 100 years and commonly greater than 400 years (Veblen and Donnegan, 2005), although estimated fire return intervals may be different in floodplain valley bottoms with wetter ground conditions. Blowdowns have irregular recurrence intervals and typically only affect isolated trees within small stands (< 30 ha), but can recur at intervals of one to two decades (Wohl, 2013b). Wood turnover time in the subalpine zone ranges from 600-900 years (Kueppers et al., 2004) (Table 2.1).

A second group of sites lies within the montane forest (2850-1750 m elevation), which is dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*), with blue spruce (*Picea pungens*), aspen, willow (*Salix* spp.), river birch (*Betula fontinalis*), and grasses in riparian areas (Veblen and Donnegan, 2005). Low-severity wildfires recur at intervals of five to thirty years and stand-replacing fires recur at intervals of 40-100 years (Veblen and Donnegan, 2005), although again this may differ in the valley bottoms. Blowdowns occur, but are less common than in the subalpine zone. In the montane zone, snowmelt creates annual peak flows, but rainfall convective storms can produce peak flows through the summer (Jarrett, 1989). Wood turnover time in the montane zone is 300-400 years, which is slightly faster than in the subalpine zone (Kueppers et al., 2004) (Table 2.1).

2.3 Methods

2.3.1 Field methods

At the semiarid boreal lowland site, we measured the diameter and length of downed LW along transects within the floodplain (n = 122). We used the line-intersect method to convert diameters of the wood pieces along the transects into wood volume in m^3ha^{-1} (Van Wagner, 1968), with the form $V = \frac{\pi^2 * \sum d^2}{8L}$, where V is the volume of wood per unit area, d is the piece diameter, and L is the length of the transect line. We classified the floodplain transects by vegetation type and by presence or absence of recent natural disturbance. We determined that the location experienced recent disturbance if there was clear and widespread evidence of that disturbance. For example, if there were a significant number of charred standing dead trees and downed LW, we determined that fire was a recent disturbance at the location. Vegetation types include herbaceous vegetation, deciduous/shrub, mixed forest with deciduous and conifer species, white spruce forest, and black spruce forest. We also measured basal area using a Panama angle gauge at each transect location. Basal area is an expression of the cross-sectional area of tree trunks as a fraction of the total ground area, and it is a measure of biomass in the riparian forest.

Measurements were taken in the floodplains of five rivers within the Yukon Flats (Dall River, Preacher Creek, Yukon River, Black River, and Chandalar River). On two of the five rivers, diameter along the tape (tape diameter) and the diameter measured in the plane perpendicular to the long axis of the piece that best represents the downed wood piece as a cylinder (off-tape diameter) are available. On three of the five rivers, only the off-tape diameter of the downed wood is available for each piece. Because the line-intersect method uses the tape diameter, we performed regression analysis for the two rivers with both tape diameter and off-tape diameter to correct LW volumes for the three rivers where only off-tape diameters are available (see Appendix A). We regressed log LW volumes calculated with off-tape diameter vs. log LW volumes using tape diameter, forcing the intercept to zero. We then inverted and back-transformed the regression, getting an equation to predict LW volumes for those locations where only LW volumes using off tape diameter was available (see supplemental information for further discussion of this process). We believe this adjustment is appropriate, and the same results for the comparisons among biomes were found when using LW volumes from the two rivers with diameter along the tape as when using LW volumes for all five rivers with adjusted values for three of the rivers.

Downed LW in the floodplains of the study rivers (Congaree River, Cedar Creek, and Toms Creek) within Congaree National Park in the subtropical lowland site was measured using strip sampling, in which all LW was measured in a transect within the floodplain that was 10 m wide (Wohl et al., 2011). For each piece, the length and diameter that best represented the downed wood piece as a cylinder was measured, resulting in an estimate of wood volume per area. The vegetation type was noted, as was evidence of disturbance (in this case, transects that experienced recent flooding or no evidence of recent flooding). Similarly to the sites in Alaska, widespread evidence was used as an indicator of recent disturbance. Vegetation was classified as tupelo, riverbank/levy forest, or mixed bottomland hardwoods. The basal area of the surrounding forest, which provides a measure of forest stand density, was also measured using a Panama angle gauge. In addition to floodplain LW, all LW within the stream channel at each study reach was measured.

Downed LW within floodplains of the Rocky Mountains in the semiarid temperate site was measured using fixed-area sampling, in which the length and end diameters for all LW was measured within a specific area of the floodplain along a study reach (n = 40), which was the length of approximately 10 bankfull widths. We used the average of the end diameters, along with piece length, to get wood volume. As with the other study areas, we noted the vegetation type and whether the reach was recently disturbed. Vegetation types included montane, subalpine, or non-coniferous vegetation (i.e., sedges and grasses, aspen, willow). We used additional data on downed LW volumes from the montane zone from Jackson and Wohl (2015). Basal areas for floodplain forest adjacent to the channel were measured with a Panama angle gauge in some of the reaches in which downed wood was measured and are available from Jackson and Wohl (2015) and Livers and Wohl (2016). In-stream LW volumes, also available for some of the reaches where floodplain LW measurements were taken, are from Livers and Wohl (2016).

Comparisons between census methods of measuring downed wood (measuring every piece of LW within a specified area) and the line-intersect method show that the line-intersect method can slightly overestimate LW volume (Marsh et al., 1999; Warren et al., 2007), but systematic bias due to surveyor error is not a problem with the method (Ringvall and Ståhl, 1999). Overestimation of LW volumes using the line-intersect method is not an issue for our analyses and comparative results, because we expect the region in which the line-intersect method was used (the semiarid boreal sites) to be the one with the lowest LW volume. Thus, if differences among biomes are present within our data, we can assume that differences would also be present if LW volume measurements had been taken using census methods in the boreal biome.

2.3.2 Analyses

LW volume per hectare was multiplied by an average value of wood density for each site (representative values taken from (Forest Products Laboratory, 2010) to get LW mass per hectare. We assumed 400 kg m^{-3} for the semiarid boreal lowland and semiarid temperate mountain sites and 530 kg m^{-3} for the subtropical lowland site. We then multiplied the mass of wood per hectare (Mg ha^{-1}) by 0.5 to get mass of organic carbon per hectare (Mg C ha^{-1}), as approximately half of wood mass is organic carbon (Russell et al., 2015).

In order to determine statistically significant differences in LW volumes (m^3ha^{-1}) and mass of organic carbon (Mg C ha^{-1}) among biomes and among vegetation types and disturbance groups within biomes, we used non-parametric Kruskal-Wallis and Wilcoxon rank-sum pairwise comparisons (due to non-normality in the data), with a Bonferroni correction for multiple comparisons if needed. We used a 95% confidence interval to determine significance. We also used the Kruskal-Wallis and Wilcoxon rank-sum pairwise comparisons to determine statistically significant differences among biomes in downed LW length, diameter, and basal area of the surrounding vegetation. We used Spearman's correlation coefficient (ρ), which tests for a monotonic relationship between two variables, to determine correlation between basal area and LW volume. All statistical analyses were completed using the R statistical package (R Core Team, 2014).

2.4 Results

Significant differences exist among biomes with respect to downed LW volumes, organic carbon mass in LW, LW diameter, and LW length (Figure 2.3). The mean value of LW volume is the lowest in the semiarid boreal biome (42.3 m^3ha^{-1}) and highest in the semiarid temperate biome (116.3 m^3ha^{-1}). There are significant differences in LW volumes between the semiarid boreal biome and the subtropical biome ($p < 0.0001$) and between the semiarid boreal biome and the semiarid temperate biome ($p = 0.025$). When not adjusting for multiple comparisons with the Bonferroni method, there are significant differences among all three biomes. For organic carbon mass in wood, the pattern is similar for that of LW volume, with the boreal biome being significantly different than the subtropical biome ($p < 0.001$) and the semiarid temperate biome ($p < 0.0001$). We completed the analyses of determining differences in downed LW volume and carbon mass among groups with the subalpine and the montane as separate groups, resulting in 4 different groups. However, there were no significant differences between the subalpine and montane; the comparisons with the two sub-groups in the semiarid mountains and the boreal lowlands and subtropical lowlands did not change with the subdivision of the semiarid mountain biome; and the semiarid mountain sites are geographically close together despite the division between subalpine and montane. Thus, we will present only the comparison among the three main biomes.

The mean diameter of downed LW is lowest in the boreal and highest in the semiarid temperate, with significant differences among each pairwise comparison (boreal-subtropical $p < 0.0001$; boreal-temperate $p < 0.0001$; subtropical-temperate $p = 0.0095$). The mean length of downed LW was the lowest in the subtropical region and highest in the boreal region, with significant differences in length between the subtropical and boreal ($p < 0.0001$) and between the subtropical and semiarid temperate ($p < 0.001$).

There are also significant differences in basal area between the semiarid boreal and the subtropical biomes ($p < 0.0001$) and the boreal and semiarid temperate biomes ($p < 0.0001$) (Figure 2.4a). For reaches in which disturbances have not modified the standing forest in recent years (undisturbed reaches), there is a weak significant relationship between LW volumes and basal area within the semiarid boreal biome ($\rho = 0.33$, $p = 0.0008$) and no relationship in the subtropical biome ($\rho = -0.098$, $p = 0.6004$; Figure 2.3b). However, in the semiarid temperate biome, as basal area increases, LW volumes also increase ($\rho = 0.73$, $p = 0.001$) (Figure 2.4b).

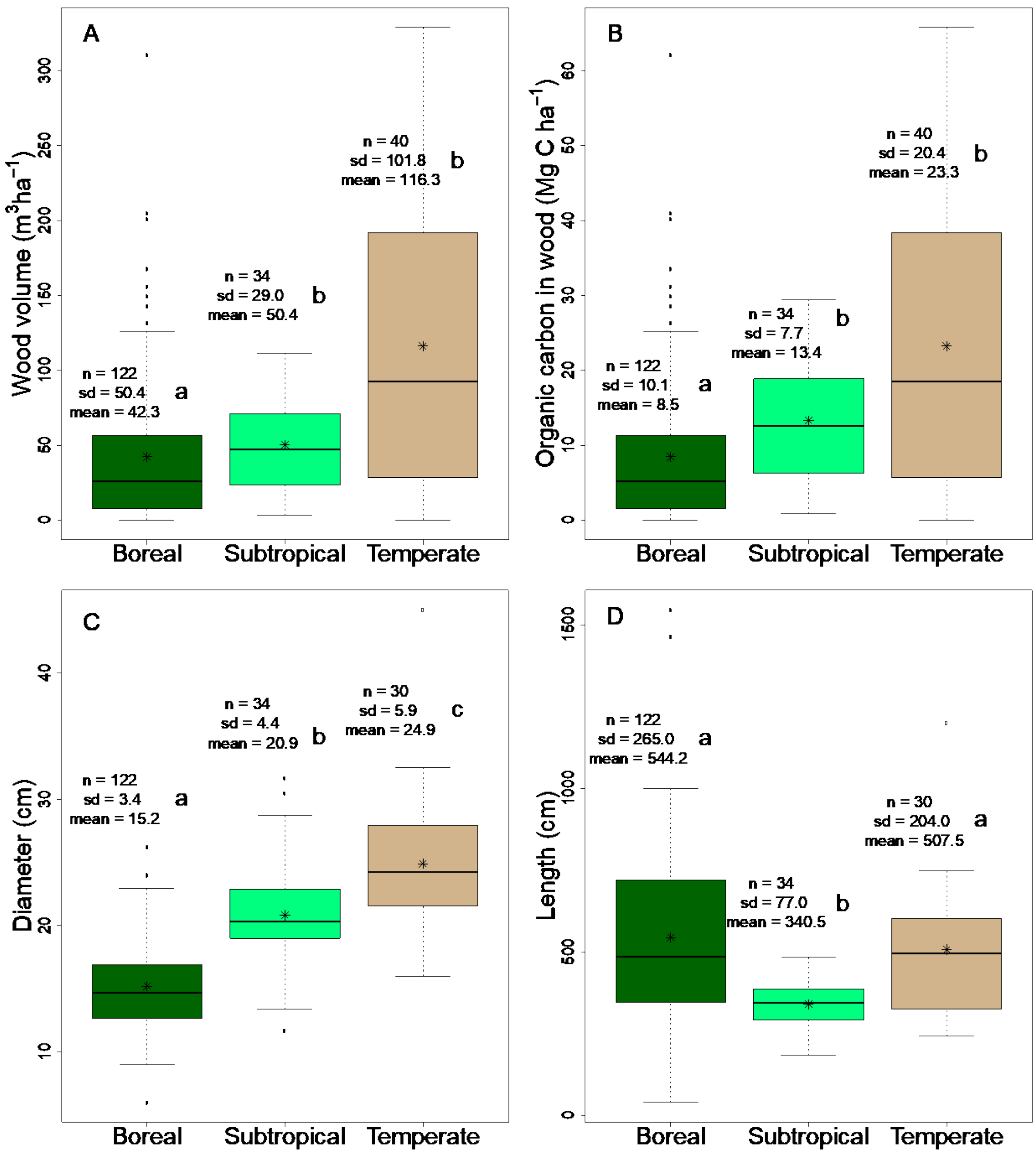

Figure 2.3. Comparisons among the three study regions in wood volume (A), organic carbon in wood (B), downed wood length (C), and downed wood diameter (D). For boxplots, the star within the box indicates the mean value, the solid line within the box indicates the median value, the box ends are the upper and lower quartile, and the whiskers are the 10th and 90th percentile. Significant differences between pairwise comparisons are indicated with contrasting letters (a, b, c).

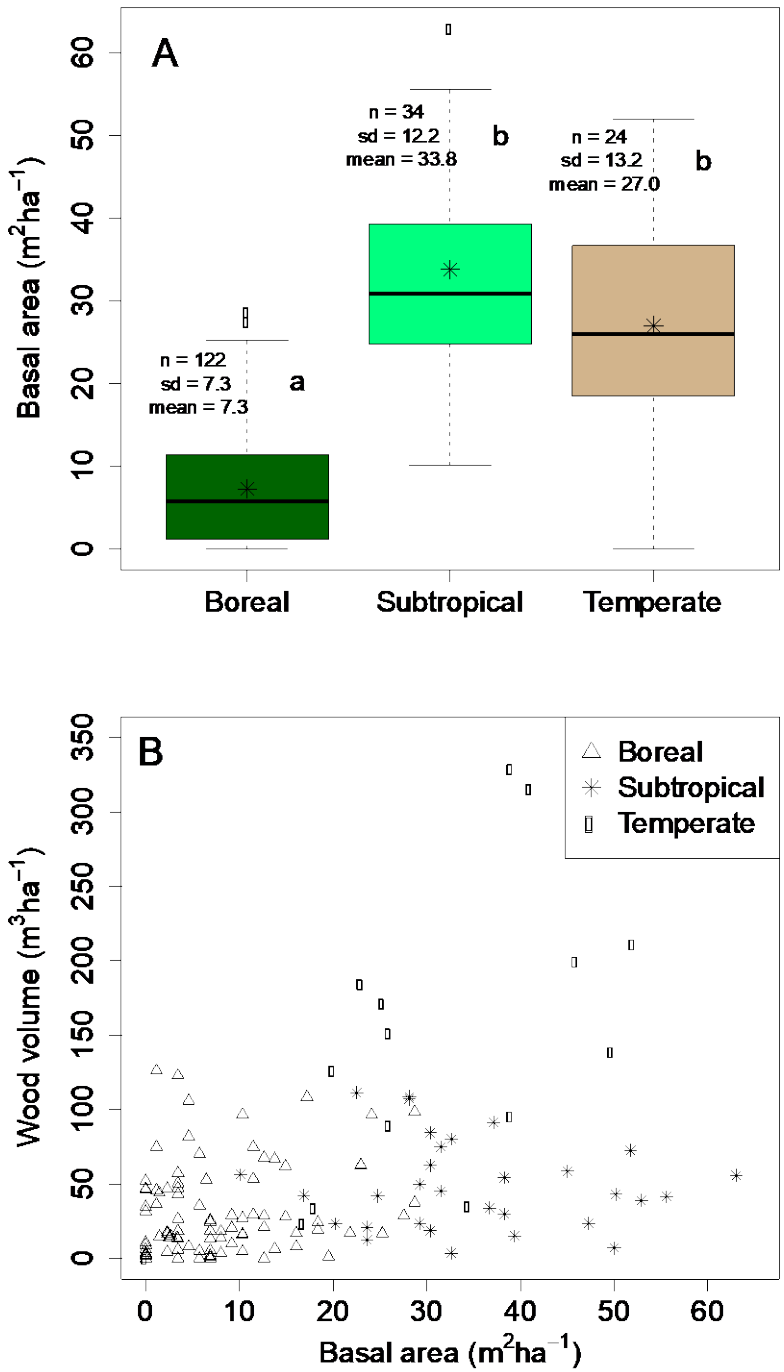

Figure 2.4. Basal area measurements for each region (A), showing significant differences, and scatterplot of wood volume vs. basal area for reaches that are undisturbed (B). For boxplots, the star within the box indicates the mean value, the solid line within the box indicates the median value, the box ends are the upper and lower quartile, and the whiskers are the 10^{th} and 90^{th} percentile. Significant differences between pairwise comparisons in (A) are indicated with contrasting letters (a, b, c).

Intra-region comparisons of LW volumes between recently disturbed and undisturbed sites also show significant differences in the semiarid boreal region ($p < 0.0001$) and the semiarid temperate region ($p = 0.041$), but not in the subtropical region ($p = 0.45$) (Figure 2.5). LW volumes among vegetation types are also different within the semiarid boreal and semiarid temperate regions (Figure 2.6). In the boreal region, significant differences occur between the herbaceous vegetation type and: 1) white spruce forest ($p < 0.0001$), 2) deciduous forest ($p < 0.0001$), and 3) mixed forest ($p = 0.0032$), and also between black spruce and white spruce ($p = 0.0014$) and black spruce and deciduous forest ($p = 0.023$). In the semiarid temperate region, significant differences occurred between LW volumes in the non-coniferous vegetation and the subalpine vegetation ($p = 0.002$). However, there is a significant difference between all three pairwise comparisons in the semiarid temperate region when no Bonferroni correction for multiple comparisons is made. In-stream LW volume measurements are significantly larger than floodplain LW volumes in the subtropical ($p = 0.044$) and the semiarid temperate ($p = 0.002$) biomes (Figure 2.7), but measurements of in-stream LW volumes are not available for the boreal lowland site.

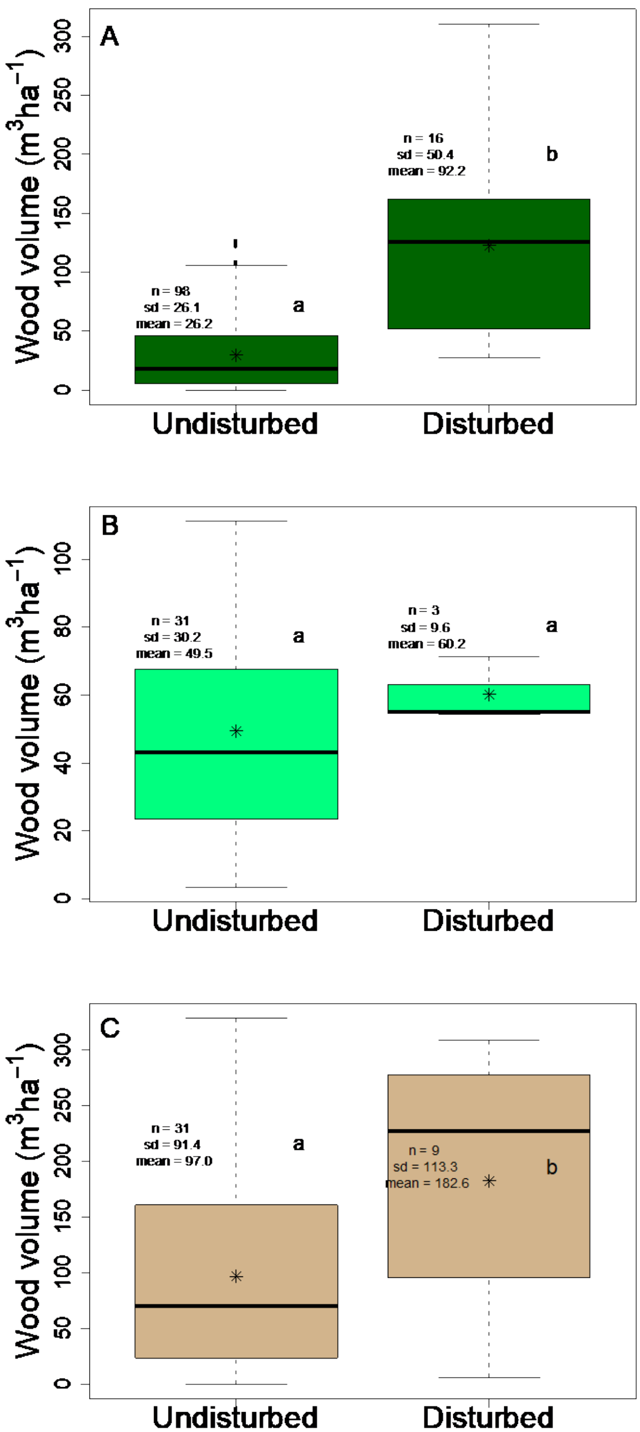

Figure 2.5. LW volume in undisturbed and disturbed sites in the boreal (A), subtropical (B), and temperate (C) biomes. For boxplots, the star within the box indicates the mean value, the solid line within the box indicates the median value, the box ends are the upper and lower quartile, and the whiskers are the 10th and 90th percentile. Significant differences between groups are indicated with contrasting letters (a, b).

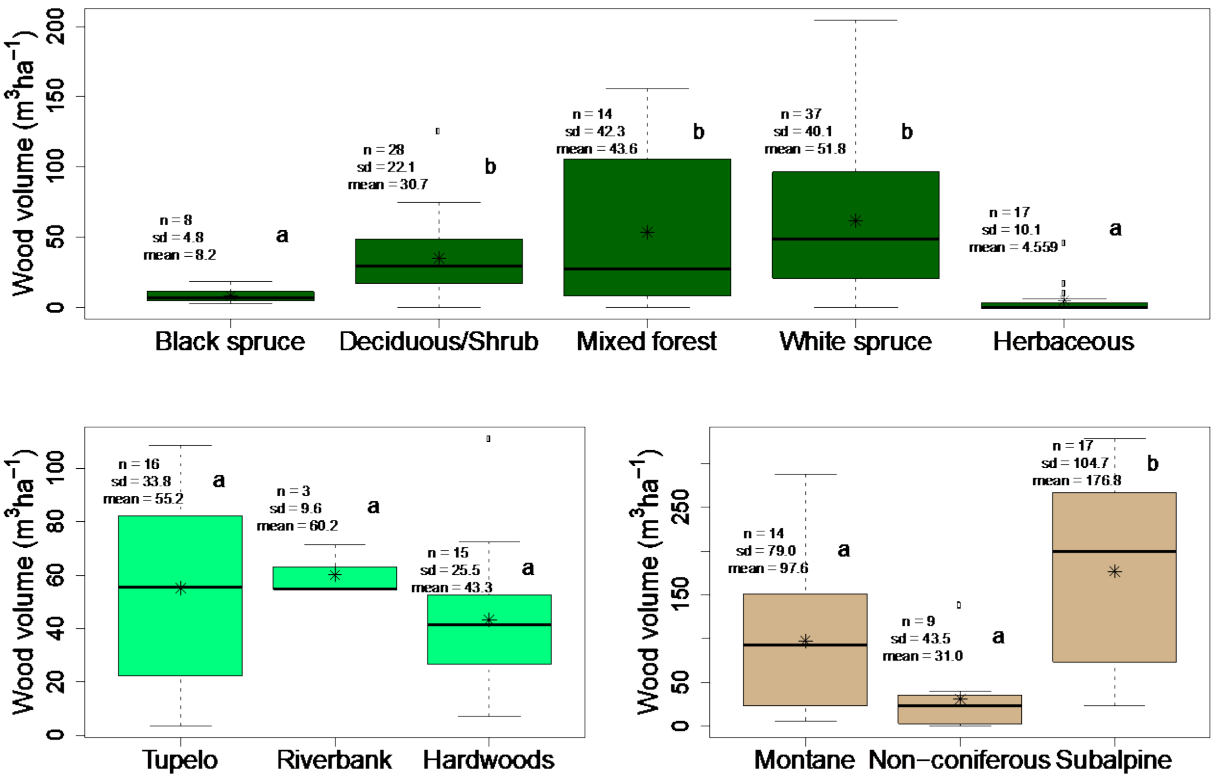

Figure 2.6. Differences in wood volume among vegetation type within each biome. For boxplots, the star within the box indicates the mean value, the solid line within the box indicates the median value, the box ends are the upper and lower quartile, and the whiskers are the 10th and 90th percentile. Significant differences between groups are indicated with contrasting letters (a, b, c).

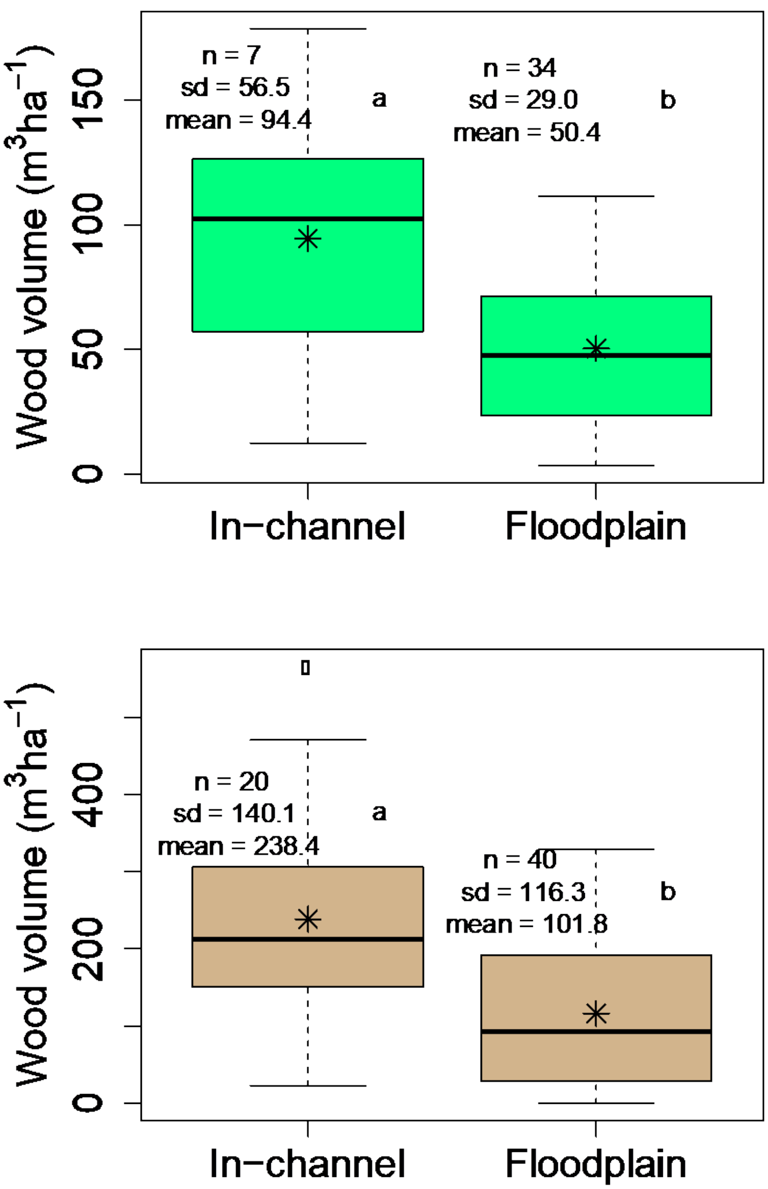

Figure 2.7. Comparison of instream wood volume to floodplain wood volume for the subtropical lowlands (top) and the semiarid mountains (bottom). For boxplots, the star within the box indicates the mean value, the solid line within the box indicates the median value, the box ends are the upper and lower quartile, and the whiskers are the 10th and 90th percentile. Significant differences between groups are indicated with contrasting letters (a, b).

2.5 Discussion

2.5.1 Patterns in floodplain LW loads and inferred influences

We hypothesized that the semiarid temperate mountain sites, which have relatively high forest net primary productivity (NPP) and slow wood turnover time, have the largest downed wood volumes. The general trend of high LW loads in regions with high NPP and slow wood turnover time is observed for downed LW in upland environments (Harmon et al., 1986; Krankina and Harmon, 1995; Harmon, 2009). This hypothesis assumes that floodplain LW is primarily recruited from floodplain forest, so that variables such as basal area, which can be used as a proxy for NPP within a particular floodplain forest stand, and regional values of NPP and downed wood turnover time, are likely to strongly influence floodplain LW volumes. Sites in the semiarid temperate mountains, the region of highest relief in our study, have no evidence of LW inputs from hillslope mass movements. At the semiarid boreal and subtropical sites, we did not directly observe concentrated inputs of LW from the channel to the floodplain surface, with a few exceptions at the upstream end of secondary channels or along the margins of the floodplain.

Variations in diameter and length of downed LW pieces among biomes demonstrate some of the differences in forest productivity and wood turnover time (Figure 2.3c & 2.3d). The smallest average diameter of downed wood occurs in the semiarid boreal biome, reflecting the smaller amount of forest biomass due to smaller trees. The length of downed LW pieces was the smallest in the subtropical biome, which could be attributed to the fast wood turnover time at this site (4-5 years) (Ricker et al., 2016). Because the wood pieces decay so quickly, commonly the downed wood appears shortened and is not preserved in its entire length. However, breakage of LW during transport and/or delivery to the floodplain surface and decay of LW over time complicates piece length and diameter differences or similarities among regions (Merten et al., 2013).

The significant correlation between basal area and floodplain LW volumes in undisturbed areas in the semiarid temperate region lends support to our assumption that forest stand biomass influences floodplain LW volumes (Figure 2.4B). The lack of observed correlation in the subtropical biome may reflect the fast wood turnover rate; floodplain LW decays so quickly in the subtropical biome that the standing stock of trees may not accurately reflect the downed LW volume. In the semiarid boreal region, a weak significant correlation between basal area and floodplain LW volumes indicates that as standing biomass increases, downed LW loads also increase. The relationship may be weak in part due to legacies of disturbance undetected by observations in the field or due to the fact that the boreal trees are smaller in diameter and may have not been adequately characterized by the Panama angle gauge. Additional support for the inference that most of the floodplain downed LW results from floodplain forest mortality comes from the low LW volumes in the non-coniferous vegetation in the semiarid temperate mountains and the herbaceous vegetation in the semiarid boreal lowlands (Figure 2.6). The low LW volumes in the non-forest vegetation types indicate that river deposition may not be important for total LW volumes in these study regions. However, the presence of some LW in the herbaceous vegetation (boreal) and non-coniferous vegetation (semiarid temperate) types demonstrates that deposition of LW via flooding and/or channel migration does contribute to floodplain LW volume. As described previously, trees on the floodplain may result in more blockage of floating LW, reducing deposition of LW from the channel to the floodplain. However, on floodplain surfaces with shorter and less dense vegetation (e.g., the herbaceous type in the boreal and the non-coniferous vegetation in the semiarid mountains), it is possible that LW could move more easily onto the floodplain and be deposited by high flows.

Globally, forest biomass and NPP decrease from the tropics to the high-latitudes due to reductions in growing season length and colder climates (Kucharik et al., 2000; Saugier et al., 2001). NPP in a Louisiana swamp, which is similar in climate and characteristics to the subtropical site, has been estimated to be approximately 550 g C m^{-2} yr^{-1} (Conner and Day, 1976). In comparison, estimates for NPP in the semiarid temperate region range from 268-506 g C m^{-2} yr^{-1} in undisturbed sites in the montane zone and 230-310 g C m^{-2} yr^{-1} in the subalpine zone (Bradford et al., 2008; Dore et al., 2010). Average observed NPP in boreal evergreen forests range from around 300-400 g C m^{-2} yr^{-1} (Kucharik et al., 2000; Saugier et al., 2001), although this estimate isn't specific to the Yukon Flats region in interior Alaska, which is the location of the semiarid boreal sites. Although the ranges of NPP values overlap, the general trend is that NPP is lowest in the boreal biome and highest in the subtropical biome, which aligns with global trends in forest productivity. Although lowest values for NPP for the montane and subalpine regions are somewhat lower than the general NPP measurements for boreal regions, the high value for the montane region is higher than the values for boreal regions. In addition, the Yukon Flats is a semiarid region, which may result in lower NPP compared to boreal regions generally. Basal area measurements among biomes also show the trend of low values in the boreal region, with basal area in the boreal region significantly smaller than basal area measurements in the semiarid temperate and subtropical regions (Figure 2.4a). However, basal area values do not differ significantly between the subtropical and semiarid temperate sites, which may reflect the diversity of stand ages in both populations and the fact that the high estimates of NPP in the semiarid temperate biome are relatively close to the NPP estimate in the subtropical region.

Our hypothesis that the highest floodplain LW volumes occur in the semiarid temperate mountains, which has a slow wood turnover time and relatively high forest productivity (indicated by high basal area measurements and values of NPP), is supported by the comparison of LW volumes among the three biomes presented in this study. The semiarid boreal and semiarid temperate sites have much longer wood turnover times compared to the subtropical site, but the semiarid site also has relatively high forest productivity and large basal area. This results in the semiarid temperate region having the optimal conditions for the largest floodplain LW volumes among biomes. However, there is not a statistically significant difference in medians between the subtropical lowland and semiarid temperate sites when correcting for multiple comparisons. But, due to the small number of multiple comparisons (3), not correcting for multiple comparisons could be considered appropriate, and statistically significant differences in medians among all biomes were present without using the Bonferroni correction. Although the results showing the semiarid temperate mountains with the highest LW volume support the optimal conditions for carbon storage posited by Sutfin et al. (2016), we stress that this is a preliminary conclusion because of the limited number of sites assessed here.

There are few studies that quantify floodplain LW volume in either managed floodplains or those without human alteration. In a more humid boreal region in northern Sweden, mean floodplain LW volume in old-growth riparian forests unmanaged by humans is 67.8 m^3 ha^{-1} (Dahlström and Nilsson, 2006), which is higher than the mean in the semiarid boreal site in Alaska (42.3 m^3 ha^{-1}) and the subtropical site in South Carolina (50.4 m^3 ha^{-1}). The basal area in the Swedish sites is much greater than the basal area in the Alaskan sites (means of 27.7 vs 7.3

m^2 ha^{-1}), reflecting that the boreal sites in Alaska represent floodplain downed LW across all vegetation types (not solely old-growth forests as in the Swedish sites) and that the wetter climate in Sweden likely results in larger trees. Busing and Fujimori (2005) measured downed LW in a stand of old-growth redwood trees in northern California within the riparian zone of Bull Creek and found LW volumes of 743 m^3 ha^{-1} (262 Mg ha^{-1}). This amount of downed LW far exceeds LW in other locations due to the large size of coastal redwoods. Mean downed floodplain LW (in this case, LW > 7.6 cm in diameter) in mass per area in an unaltered tropical dry floodplain forest is 14.8 Mg ha^{-1}, which is a volume per area of 28.4 m^3 ha^{-1} (Jaramillo et al., 2003). Average LW volume per area in a seasonally flooded lowland forest in the Peruvian Amazon has been reported to be 42.8 m^3 ha^{-1} (10.3 Mg ha^{-1}) (Chao et al., 2008). The low LW volumes in the dry and wet tropical floodplain forests further indicate that tropical/subtropical regions, despite high forest productivity, may have lower floodplain LW volumes due to fast wood turnover times. Figure 2.8 shows mean floodplain downed LW mass (in Mg ha^{-1}) across climate types in floodplains that have not been altered by human activities using values from this study and additional references. Each climate type in Figure 2.8 is represented by only one study, and data are missing for human unaltered floodplains for subtropical dry climates. However, a general trend can be seen in floodplain LW mass that supports our inference that LW loads peak in areas with high forest productivity combined with slower wood turnover times.

2.5.2 Patterns in LW loads due to vegetation type and disturbance

In the semiarid boreal lowlands, the significant differences in LW volume among vegetation types are broadly reflective of the size and spatial density of trees within each vegetation type. The lowest LW volumes occur in herbaceous and black spruce vegetation types. Herbaceous areas of the floodplain do not have trees for a source of downed LW, and most of the black spruce forests in our study area overlie shallow permafrost and generally have much smaller trees compared to white spruce forests and some deciduous forests. The other vegetation types (deciduous/shrub, mixed forest, and white spruce) have similar LW volumes.

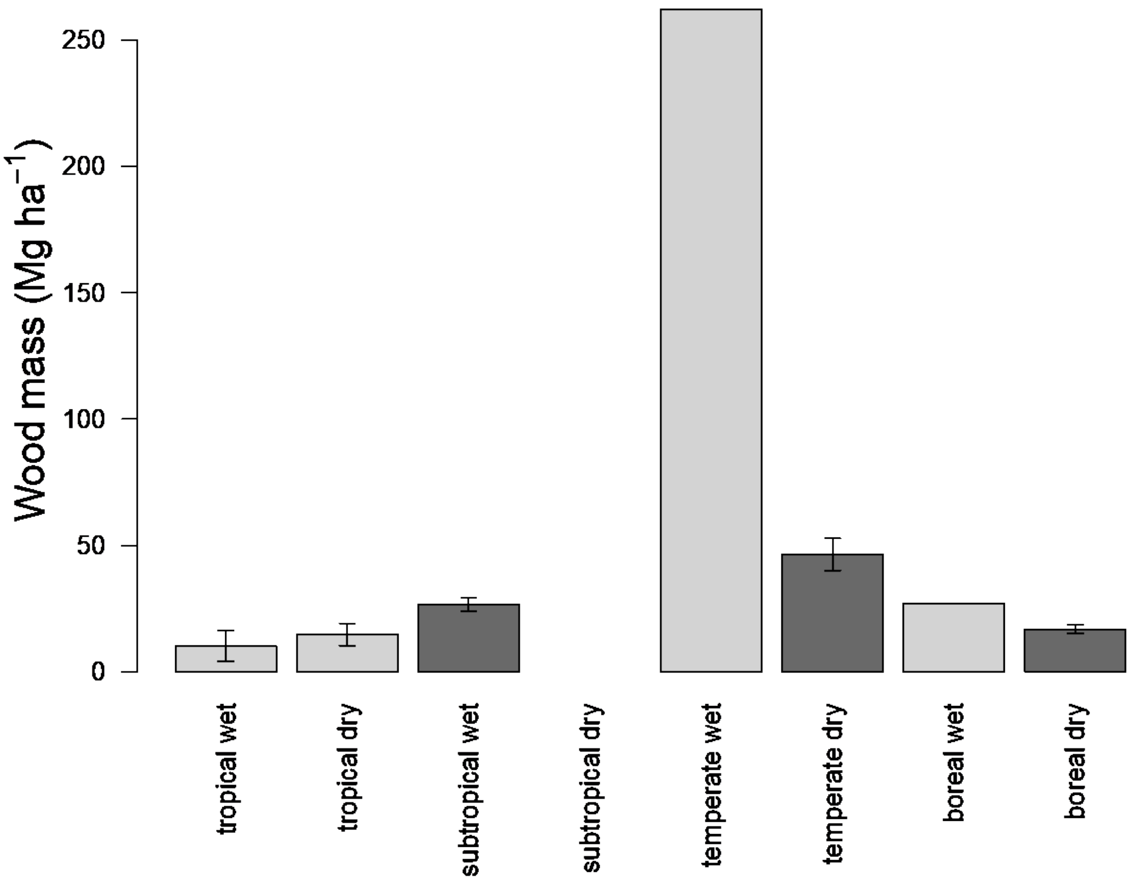

Figure 2.8. Patterns of floodplain LW mass per area across multiple climates, showing mean value with error bars representing ± one standard error (when available). Dark gray bars are the study regions presented in this paper. LW mass from floodplains that have not been altered by human activities are not available for subtropical dry environments. References for values are: tropical wet (Chao et al., 2008), tropical dry (Jaramillo et al., 2003), subtropical wet (this study), temperate wet from old-growth redwood stands in northern California (Busing and Fujimori, 2005), temperate dry (this study), boreal wet (Dahlström and Nilsson, 2006), and boreal dry (this study).

Fluvial migration and flooding exert controls on floodplain succession and vegetation type in Alaskan boreal forests (Van Cleve et al., 1993; Yarie et al., 1998), and thus fluvial migration, flooding, and the deposition of new floodplain areas control downed LW volumes. Floodplain successional stages include bare surfaces (with potentially herbaceous vegetation) that can be characterized as ~0-5 yrs in age, shrubs that can develop after ~5-40 years, deciduous forests that usually develop after ~40-100 years, white spruce stands that develop after ~100-500 years, and black spruce stands that may develop after centuries to millennia (Walker et al., 1986; Van Cleve et al., 1993; Chapin III et al., 2006). These differences in successional development correspond to substantial differences in type of vegetation, tree size, and recruitment potential for downed floodplain LW. Thus, although fluvial dynamics may not directly affect floodplain LW volume by transporting large amounts of LW into or out of the floodplain, river processes indirectly affect floodplain LW via the disturbance caused by channel migration. Channel migration can 'reset' the process of vegetation succession by eroding floodplain land at any stage of successional development and by creating new floodplain land for vegetation to colonize.

In the semiarid temperate mountains region, forested vegetation types (subalpine and montane) have higher downed LW volumes compared to non-coniferous vegetation, although the difference between montane and non-coniferous vegetation is not significant when correcting for multiple comparisons (Figure 2.6). The semiarid temperate sites have channels with much lower lateral mobility and much smaller floodplains. Stand-killing wildfires and blowdowns appear to be the primary mechanisms that reset forest succession in this environment.

We infer that natural disturbances increase floodplain LW volumes at the boreal and semiarid temperate sites because wood recruited to the floodplain during these disturbances does not decay as quickly as in the subtropical sites (Figure 2.5). Although hurricanes can create substantial wood loads at the subtropical site, this wood decays so rapidly (4-5 year turnover time (Ricker et al., 2016)) that higher floodplain LW volumes probably do not persist for decades or longer following this type of disturbance. The disturbed sites in the subtropical region are sites that were recently subjected to flooding, which likely does not transport LW into as well as out of the floodplain due to living trees blocking LW transport. In contrast, disturbances such as fire and blowdowns, which occur in the semiarid boreal and semiarid temperate sites and cause breakage and mortality, directly deliver LW to the floodplain surface.

Floodplain LW volumes in regions with relatively slow wood turnover times may increase where warming climate creates greater wood recruitment as a result of increase in disturbances such as wildfire. In the boreal lowlands region, warming climate may result in more frequent fires (Rupp and Springsteen, 2009), and may also result in less geomorphically stable floodplains if permafrost thaw permits greater bank erosion and faster lateral channel migration. The net effect on floodplain LW of more frequent fires versus greater channel migration is difficult to predict. Climate change may also result in shifts in vegetation composition and the advance of treeline to higher latitudes and elevations (Tape et al., 2006; Harsch et al., 2009; Shuman et al., 2014). Net primary productivity could increase due to CO_2 fertilization, increasing forest biomass and affecting LW loads, but this increased growth may be limited by nitrogen availability (Norby et al., 2010). In the western U.S., fire frequency may increase with climate change (Liu and Wimberly, 2016), potentially altering floodplain wood loads in the semiarid temperate mountain region. However, the net effects of changing fire frequency and severity on downed LW loads in the boreal lowlands and the western U.S. are difficult to predict, as more intense and frequent fires may reduce downed LW load through increased combustion and through a reduction in time available for tree growth if fire return intervals are reduced (Harmon, 2009).

2.5.3 Organic carbon storage in floodplain LW

Although floodplain LW can be an important reservoir of organic carbon along river corridors, it is typically not the largest reservoir. In a summary of OC storage along floodplains in various biomes, Sutfin et al. (2016) emphasize that floodplain sediment is a much larger reservoir for OC than downed LW. In diverse river corridors (channels and floodplains), OC mass per area measurements range from 1.7 to 2500 Mg C ha^{-1} in LW and 1.4 to 7735 Mg C ha^{-1} in floodplain sediment (Sutfin et al., 2016). Values for OC in sediment for sites in Congaree National Park range from 148 to 1118 Mg C ha^{-1} (Ricker and Lockaby, 2015), which is much larger than the 0.9-29.5 Mg C ha^{-1} found in LW in the subtropical biome in this study. Similarly, OC mass per area in sediment is larger across multiple sites in the subalpine zone in the Colorado Rockies (Wohl et al., 2012). There is very little information about OC in floodplain sediment for boreal regions, but the high latitudes store a large amount of OC in the subsurface (Hugelius et al., 2014), indicating that there are likely large amounts of OC in floodplain sediment in the boreal region discussed in this study. In addition to being an OC stock within river corridors, LW can promote sedimentation within floodplains and channels (Jeffries et al., 2003; Sear et al., 2010), further enhancing the stock of OC in sediment.

2.5.4 Floodplain versus upland and instream LW loads

We did not measure upland LW loads in the study areas, but representative values are reported in the forest ecology literature (Table 2.2). We found only one other study that provided data for explicit comparisons of instream and floodplain LW mass in old-growth forests, which is an examination of 13 streams (average bankfull width 2.4 m) in old-growth boreal conifer forest of northern Sweden (Dahlström and Nilsson, 2006). An additional study in the tropical dry forest provided LW mass for floodplain and upland environments (Jaramillo et al., 2003). Based on these limited data, river transport appears to concentrate LW within the active channel, creating greater wood loads than in adjacent floodplain environments. This may not be the case for higher-order floodplain rivers with large drainage areas, such as those in the boreal lowlands biome, but the lack of data for floodplain LW loads prevents comparisons of in-stream and floodplain LW as drainage area increases.

Table 2.2. Comparison of upland, floodplain, and channel LW mass (in Mg ha^{-1}) in human unaltered environments. Values are means plus or minus one standard error if available, or ranges (denoted by a "-"), with Mg ha^{-1} (mass) on the first line of the cell and $m^3 ha^{-1}$ (volume) italicized in the second line of the cell if available. Values are from this study unless otherwise indicated.

Region	**Upland LW (Mg ha^{-1}; *m^3ha^{-1}*)**	**Floodplain LW (Mg ha^{-1}; *m^3ha^{-1}*)[a]**	**Channel LW (Mg ha^{-1}; *m^3ha^{-1}*)[a]**
Boreal lowlands, Alaska	7.6[b]	16.9 ±1.8 *42.3 ± 4.6*	Not available
Semiarid mountains, Colorado	2.6-52[c] *12.4-188.8*	46.5 ± 6.44 *116.3 ± 16.1*	95.4 ±12.2 *238.4 ± 30.5*
Subtropical lowlands, South Carolina	5.6-7.7[d] *11.7-15.8*	26.5 ± 2.6 *50.4 ± 5.0*	50.0 ± 11.3 *94.4 ±19.8*
Old-growth boreal conifer forest, northern Sweden	7.4[e] *18.5*	27.1[f] *67.8*	36.5[g] *91.2*
Tropical dry forest, central coast of Mexico	11.9[g] *17.7*	14.8[g] *28.4*	Not available
Tropical wet forest, western Amazon, Peru	30.9-45.8[h] *74.7-108.8*	10.3 ± 6.1[h] *42.8 ± 20.1*	Not available

[a] conversions of wood volumes per unit area to wood mass per unit area for the three biomes in this study assumed density of 400 kg m^{-3} for boreal lowlands, 400 kg m^{-3} for semiarid mountains, and 530 kg m^{-3} for subtropical lowlands based on approximate wood densities of tree species at each site
[b] (Gould et al., 2008), boreal forests in central Alaska, volume per area measurements were not reported in the paper.
[c] old-growth subalpine in Rocky Mountain National Park (Arthur and Fahey, 1990), (Robertson and Bowser, 1999), mature ponderosa pine stands in the Colorado Front Range (montane)
[d] (McMinn and Crossley, 1996), upland hardwood in South Carolina and Georgia on land not owned by the forest industry
[e] (Jönsson and Jonsson, 2007), old-growth boreal forests in central Sweden, assumes density of 400 kg m^{-3} in order to transform wood volume per unit area to wood mass per unit area
[f] (Dahlström and Nilsson, 2006), assumes a density of 400 kg m^{-3} in order to transform wood volume per unit area to wood mass per area

[g] (Jaramillo et al., 2003)
[h] (Chao et al., 2008)

Floodplains appear to have greater LW loads per area relative to nearby uplands in most regions (Table 2.2), but these comparisons are limited by the lack of data on floodplain LW loads and the fact that the upland wood loads are generalized across broad regions, whereas the floodplain data are for specific sites (Table 2.2). Table 2.2 gives values for LW loads in uplands compared to floodplain LW loads. An exception to floodplain LW loads being greater than upland forest LW loads may occur in wet tropical environments, where frequent flooding in riparian forests accelerates decomposition rates (Chao et al., 2008). For example, Chao et al. (2008) found that floodplain forests in the western Amazon had lower mean LW loads (10.3 Mg ha^{-1}) compared to non-floodplain forests (30.9-45.8 Mg ha^{-1}) in part due to faster decomposition rates and the floodplain forest containing tree species that are less dense than the tree species in non-floodplain forests. Nevertheless, larger LW loads in floodplain environments relative to uplands seem reasonable, as riparian forests tend to be more productive than upland forests (Naiman and Décamps, 1997).

2.5.5 Patterns of LW loads in upland forests

Due to the small number of studies on floodplain downed LW loads, it is useful to infer patterns in LW loads from upland environments unaltered by human disturbances to inform potential patterns across climates in floodplain LW loads. Figure 2.9 provides examples of the ranges of values for downed LW mass per area in upland forests from 17 different articles for sites in which there has not been recent natural or human disturbance. Although Figure 2.9 is not an exhaustive review of published values for LW loads, we expect floodplain downed LW mass to vary similarly across a range of climatic conditions. However, floodplain LW loads may be larger in most climates (Table 2.2). The potential similarities in trends between floodplain and upland environments are exemplified by the similar trends in LW mass across climates seen in Figure 2.8 and Figure 2.9.

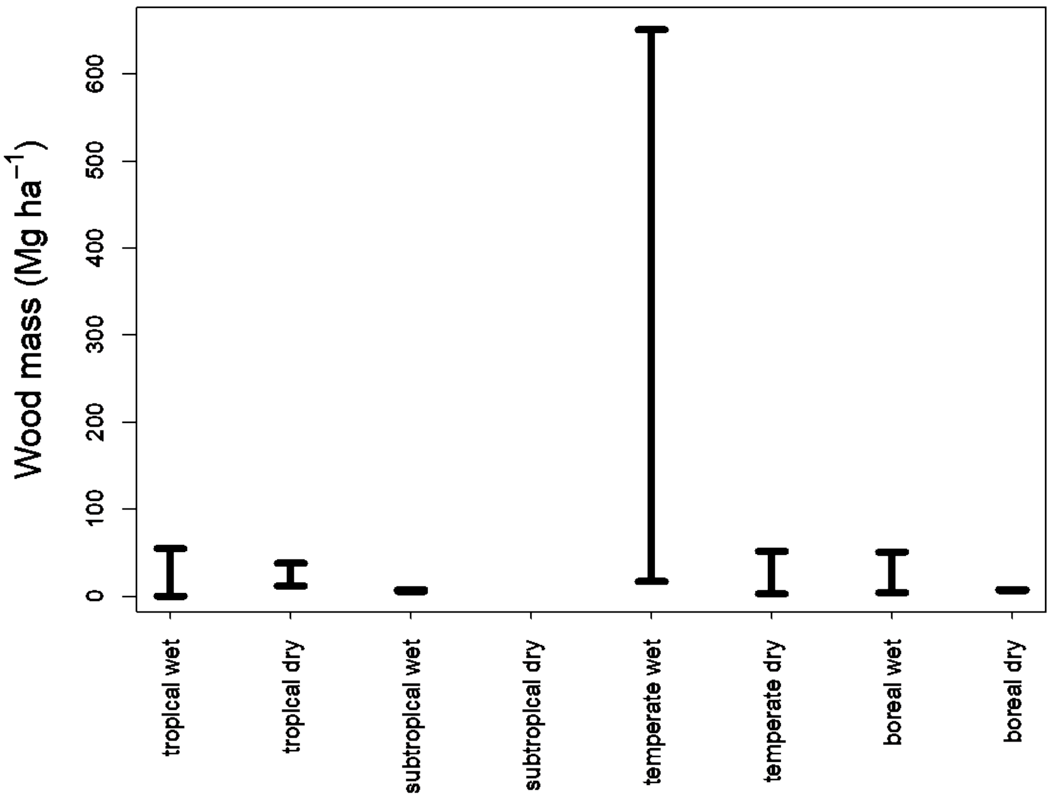

Figure 2.9. Ranges of downed LW mass per area from uplands in different climates, representing sites that have not been recently disturbed and have not been altered by human disturbances (e.g., logging). Values were not found for sites in subtropical dry environments unaltered by human activities. References for values are: tropical wet (Chao et al., 2008; Silva et al., 2016), tropical dry (Harmon et al., 1995; Jaramillo et al., 2003), subtropical wet (McMinn and Crossley, 1996), temperate wet (Davis et al., 2015; Grier and Logan, 1977; Muller and Liu, 1991; Spies et al., 1988), temperate dry (Arthur and Fahey, 1990; Herrero et al., 2014; Robertson and Bowser, 1999), boreal wet (Gould et al., 2008; Hély et al., 2000; Jönsson and Jonsson, 2007; Krankina and Harmon, 1995), boreal dry (Gould et al., 2008).

2.6 Conclusion

Our findings indicate that LW volumes are greatest in the semiarid temperate mountain sites, which we attribute to the combination of relatively high forest productivity and slow wood turnover time. Differences in floodplain LW loads exist between vegetation types in the semiarid boreal lowlands and the semiarid temperate mountains, and natural disturbances increase floodplain LW loads in environments where relatively slow wood decay preserves the wood recruited by these disturbances. In addition, comparisons with other studies suggest that floodplains have greater LW loads than adjacent upland forests, but smaller LW loads than adjacent channels. However, more data are needed to support these trends, as there is limited information on floodplain downed LW loads.

The lack of published data on floodplain LW loads is striking. At least 35 papers present basic data on instream LW loads in old-growth or naturally disturbed forests, but we could find only a few studies that present analogous data for naturally disturbed floodplains. This likely reflects at least in part the focus of LW quantification studies on relatively small, steep streams that commonly have minimal floodplain area. Nonetheless, the dearth of floodplain LW quantifications is particularly important in the context of increasing efforts to restore LW to river corridors (Abbe and Brooks, 2011; Wohl et al., 2016). Although many of these efforts focus on introducing LW to channels (Lawrence et al., 2013; Jones et al., 2014), particularly in the form of engineered logjams (Gallisdorfer et al., 2014), floodplain LW in many respects provides an easier target for restoration, although this type of restoration does not directly impact fish habitat unless flooding conditions occur. Dispersed or concentrated LW is less likely to be remobilized in floodplain environments, and to create hazards for infrastructure in the river corridor, because of the trapping potential created by living vegetation. As reviewed in the introduction, floodplain LW can provide numerous ecological benefits and create hydraulic resistance and enhanced deposition of sediment and organic matter in floodplains, thus helping to stabilize floodplains. Greater emphasis on quantifying floodplain LW in future studies will help to fill in gaps of our knowledge of LW loads in unmanaged forests in diverse environments, provide a better understanding of how floodplain LW loads have been reduced in managed riparian areas, and will facilitate more rigorous testing of some of the patterns inferred in this study.

Data Availability

The data analyzed are included in Table A.1 in appendix A.

Chapter 3 Geomorphic controls on floodplain soil organic carbon in the Yukon Flats, interior Alaska, from reach to river basin scales[2]

Summary

Floodplains accumulate and store organic carbon (OC) and release OC to rivers, but studies of floodplain soil OC come from small rivers or small spatial extents on larger rivers in temperate latitudes. Warming climate is causing substantial change in geomorphic process and OC fluxes in high latitude rivers. We investigate geomorphic controls on floodplain soil OC concentrations in active-layer mineral sediment in the Yukon Flats, interior Alaska. We characterize OC along the Yukon River and four tributaries in relation to geomorphic controls at the river basin, segment, and reach scales. Average OC concentration within floodplain soil is 2.8% (median = 2.2%). Statistical analyses indicate that OC varies among river basins, among planform types along a river depending on the geomorphic unit, and among geomorphic units. OC decreases with sample depth, suggesting that most OC accumulates via autochthonous inputs from floodplain vegetation. Floodplain and river characteristics, such as grain size, soil moisture, planform, migration rate, and riverine DOC concentrations, likely influence differences among rivers. Grain size, soil moisture, and age of surface likely influence differences among geomorphic units. Mean OC concentrations vary more among geomorphic units (wetlands = 5.1% vs. bars = 2.0%) than among study rivers (Dall River = 3.8% vs. Teedrinjik River = 2.3%), suggesting that reach-scale geomorphic processes more strongly control the spatial distribution

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[2] Chapter published as Lininger, K. B., Wohl, E., & Rose, J. R. (2018). Geomorphic Controls on Floodplain Soil Organic Carbon in the Yukon Flats, Interior Alaska, From Reach to River Basin Scales. *Water Resources Research*. https://doi.org/10.1002/2017WR022042

of OC than basin-scale processes. Investigating differences at the basin and reach scale is necessary to accurately assess the amount and distribution of floodplain soil OC, as well as the geomorphic controls on OC.

3.1 Introduction

Rivers are increasingly recognized as important and active components in the terrestrial carbon cycle, as sites of carbon processing, transport, and storage (Battin et al., 2009; Cole et al., 2007; Stackpoole et al., 2017; Sutfin et al., 2016; Wohl et al., 2017a). However, less attention has been paid to the geomorphic controls on and quantity of carbon stored in floodplain soils. In addition, most studies of floodplain soil organic carbon (OC) have been conducted in the temperate zone (Sutfin et al., 2016). Anthropogenic climate change has resulted in the disproportionate warming of the high latitudes, including Alaska, relative to other regions (ACIA, 2005; IPCC, 2014; U.S. Environmental Protection Agency, 2016). There is concern that permafrost warming and thaw (Jorgenson et al., 2006; Romanovsky et al., 2010, 2013) may result in the release of subsurface OC into the atmosphere and cause further warming (Koven et al., 2011; Schädel et al., 2016; Schuur et al., 2008, 2015). High latitude permafrost zones store large amounts of carbon in the subsurface, in part due to reduced decomposition rates with cold temperatures (Davidson and Janssens, 2006; Jobbágy and Jackson, 2000), with estimates indicating that there are approximately 1035 Pg (1 Pg = 1 billion tons) in the top 3 meters of soil (Hugelius et al., 2014). This is approximately half of the amount of carbon stored in the top 3 meters of the subsurface outside of permafrost regions (Jobbágy and Jackson, 2000), highlighting the importance of determining controls on the spatial distribution of carbon in the subsurface in high latitude regions.

Geomorphic processes, such as channel migration, sediment loading to rivers, and bank erosion, may be altered as the climate continues to warm and permafrost thaws (Rowland et al., 2010), indicating the need to understand how geomorphology and river processes influence floodplain soil OC in order to detect ongoing and future changes. We investigate the geomorphic controls on OC concentrations (%) across a large region in the Yukon Flats (YF) in interior Alaska, an area with discontinuous permafrost in the boreal zone. Our study area includes the mainstem Yukon River and four tributaries, allowing for the assessment of geomorphic controls on floodplain soil OC across spatial scales, from the reach to the river basin. To our knowledge, this is the first study to evaluate spatial variations in floodplain OC concentrations in relation to geomorphic processes across spatial scales, and one of only a very few studies of OC concentrations in the active layer (seasonally thawed layer) of a floodplain underlain by discontinuous permafrost in the boreal zone.

Floodplains act as temporary storage areas and exchange sites for sediment and nutrients moving from the terrestrial landscape to the ocean (Dunne et al., 1998; Junk et al., 1989). The Arctic Ocean receives large amounts of dissolved organic carbon (DOC) relative to other oceans (Dittmar and Kattner, 2003; Holmes et al., 2012; Stein and Macdonald, 2004), with the flux of DOC from Arctic watersheds more than double the flux from temperate watersheds (Raymond et al., 2007). Particulate organic carbon (POC) exports from high latitude rivers, although smaller than DOC exports (McClelland et al., 2016), may be buried in offshore sediments without being decomposed, resulting in a carbon sink in the ocean (Hilton et al., 2015). In addition, river POC can be thousands of years old, indicating that POC may be stored for long periods of time before reaching the Arctic Ocean and sourced from frozen river banks (Guo et al., 2007; Hilton et al., 2015). The terrestrial-aquatic carbon cycle in the arctic and boreal zones will likely be modified due to anthropogenic warming and associated permafrost thaw, as the active layer deepens and flowpaths through the landscape change (Frey and McClelland, 2009; Striegl et al., 2005; Walvoord and Kurylyk, 2016; Walvoord and Striegl, 2007). For example, fluxes of DOC from the Yukon River decreased from the late 1970s to the early 2000s (Striegl et al., 2005). This reduction in exports may be due to increased proportion of baseflow relative to surface flow due to permafrost thaw (Walvoord et al., 2012). There is also evidence of active-layer thicknesses increasing within the Yukon Basin (O'Donnell et al., 2014). The change in flowpaths could result in greater interaction between DOC and mineral soil and the release of carbon into the atmosphere due to microbial processing (Striegl et al., 2005). Decrease in DOC export could also result from an increase in adsorption of OC onto mineral grains as permafrost thaws and flow paths change (Frey and McClelland, 2009; Kawahigashi et al., 2006). Because floodplains mediate fluxes of water, DOC, and POC, understanding the geomorphic controls on floodplain soil OC and establishing baseline information on floodplain soil OC is imperative for understanding and detecting future changes to river exports.

3.1.1 Potential geomorphic controls on floodplain soil OC across spatial scales

Existing studies of floodplain OC have been restricted to relatively small rivers or to small spatial extents on larger rivers (Cierjacks et al., 2011; Sutfin and Wohl, 2017). Investigating geomorphic controls over large regions on rivers with differing drainage areas facilitates the interpretation of geomorphic controls on floodplain soil OC at spatial scales ranging from a river basin (lengths of 10^2-10^6 km), to a river segment (lengths of 10^1-10^2 km), to a river reach (lengths of 10^0 km) (Figure 3.1).

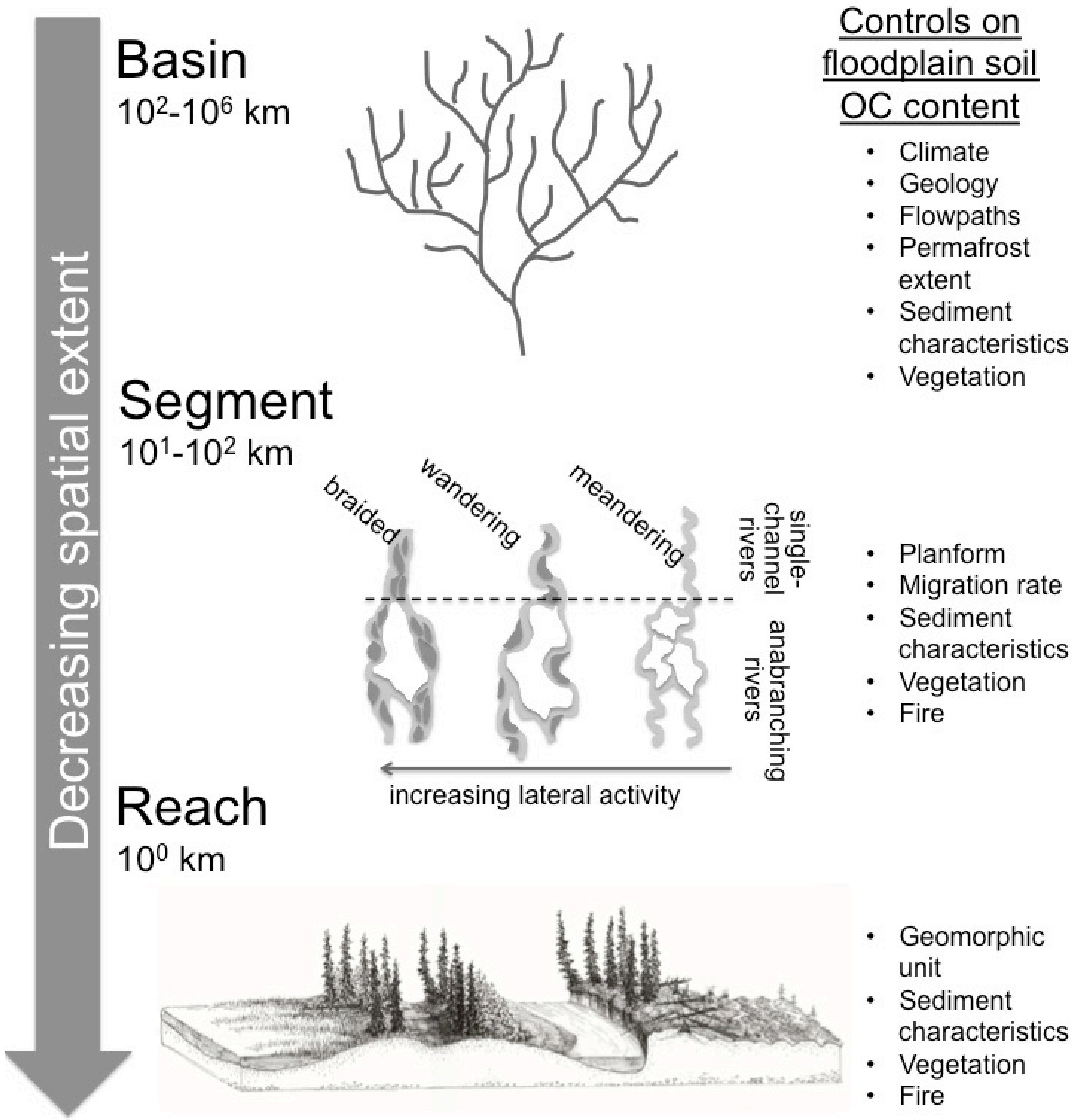

Figure 3.1. The varying spatial scales of influences on floodplain soil OC, from the river basin to the reach, with examples of factors that control soil OC at each scale.

Systematic analyses of relationships between geomorphic controls and soil OC concentrations at differing spatial scales allow us to evaluate whether OC concentrations can be adequately estimated using a top-down approach based on basin-scale characteristics or whether it is more accurate to use a bottom-up approach in which OC concentrations characteristic of local patches are aggregated to estimate basin-scale OC. In addition, analyses across spatial scales inform our understanding of the geomorphic controls on floodplain OC concentration. Determining the spatial scale at which there is greater variation in OC concentrations, for example, could indicate which geomorphic processes exert the strongest influence on OC concentrations. Consequently, we address two primary questions in this research: How do differences in the spatial scale of analysis influence our quantification of OC concentration across large floodplains? How do differences in the spatial scale of analysis inform our understanding of the controls on OC concentrations in the mineral soil of floodplains?

Figure 3.1 highlights some controls on floodplain soil OC from a geomorphic perspective, although we recognize that floodplain soil OC is controlled by many complicated and diverse factors. Some controls cut across spatial scales. For example, floodplain soil OC generally increases with finer grain sizes (Appling et al., 2014; Hoffmann et al., 2009; Pinay et al., 1992), and sediment characteristics can vary between basins and segments, and within reaches. Similarly, soil OC can vary with surface vegetation (Appling et al., 2014; Jobbágy and Jackson, 2000; Van Cleve et al., 1993). River basins can have characteristic vegetation assemblages (e.g., boreal, tropical, etc.), but vegetation can also vary between segments and within a reach. Disturbances such as fire, occurring at the scale of a river segment or reach, can also impact floodplain soil OC by burning organic horizons and deepening the active layer via thawing permafrost (O'Donnell et al., 2011), which makes previously frozen carbon available for microbial mineralization.

At the river basin scale, climate can influence OC via temperature, precipitation, and resulting vegetation. For example, decomposition is generally slowed in cold, wet conditions, resulting in higher OC content (Chapin III et al., 2012; Davidson and Janssens, 2006; Jobbágy and Jackson, 2000; Johnson et al., 2011). The geology of a river basin can influence OC in floodplains through controls on lithology and tectonics, and thus the weathering, delivery, and grain size distribution of sediment entering river systems (Sutfin et al., 2016). In addition to influencing inputs to the floodplain surface, the vegetation of a river basin influences inputs of OC to the river network and OC exported from the basin. For example, the characteristics and quantity of exported DOC from Arctic river basins can vary with the relative proportions of wetlands or peatlands versus forests within the basin (Amon et al., 2012; Frey and Smith, 2005). Thus, vegetation and resulting riverine DOC concentrations and fluxes may also influence the character of floodplain soil OC due to floodplains acting as mediators of nutrient fluxes and sites of nutrient exchange. Subsurface flowpaths within the drainage basin influence the travel time of water through the subsurface and the type of sediment through which water flows; these characteristics can influence OC inputs to the river network as well (Kawahigashi et al., 2006; O’Donnell et al., 2012; Walvoord and Striegl, 2007). Permafrost extent within a river basin can control floodplain soil OC through influencing drainage patterns in the landscape (Walvoord and Kurylyk, 2016), DOC loads in rivers (Frey and Smith, 2005; Kawahigashi et al., 2004), and the degree and extent of microbial respiration of unfrozen carbon within the soil (Schuur et al., 2008). In addition, permafrost influences the degree and rate of bank erosion (Costard et al., 2014), which can release OC from floodplains into the river network.

At the river segment scale, channel planform type and migration rate may influence OC within floodplains. Different channel planforms imply different magnitudes of lateral movement, with braided channels more laterally active compared to wandering or high-energy meandering channels, which are more laterally active compared to stable meandering or straight channels (Nanson and Knighton, 1996). Increased lateral activity and migration rate can result in more frequent floodplain disturbance and re-setting of floodplain vegetation primary succession (Viereck et al., 1993). Erosion and re-deposition of bare sediments can also re-start the accumulation of OC in soil from vegetation inputs (Van Cleve et al., 1993; Zehetner et al., 2009). Channel planform can also imply differences in grain size. Braided rivers carry coarser loads in general compared to meandering channels (Schumm, 1981) and grain size influences OC content (Pinay et al., 1992).

At the river reach scale, geomorphic units could influence OC via differences in grain size and soil moisture. Previous studies have indicated that depositional environments have higher carbon content compared to erosional environments (Pinay et al., 1992), and OC can increase with increasing distance from the channel (Cierjacks et al., 2011). These trends have been linked to variations in grain size, with finer depositional and overbank deposits containing more OC (Cierjacks et al., 2011; Pinay et al., 1992). Soil moisture can vary among geomorphic units within a floodplain, as different geomorphic units can be located at different elevations relative to the water table (Hughes, 1997; Taylor et al., 1999). Grain size differences among geomorphic units may also result in differences in soil moisture, as finer grain sizes are able to retain more moisture compared to coarser grain sizes (Dingman, 2008). Geomorphic units also reflect the time since surface formation and associated time for OC to accumulate, e.g. with higher floodplain surfaces formed earlier than bar surfaces. Vegetation at the reach scale reflects geomorphology, with floodplain primary succession occurring from bare alluvial surfaces created via river migration and vegetation reflecting processes of sedimentation, flooding, and fluvial disturbance (Viereck et al., 1993; Whited et al., 2007).

3.1.2 Research objectives

We assess the geomorphic controls on OC concentration within the floodplains of five rivers over a cumulative distance of ~750 river km in the YF region, located in the central Yukon River Basin in interior Alaska. The large spatial extent allows for investigating controls at the basin, segment, and reach scales using statistical analyses of data from sediment samples within the YF floodplains. The basic research objectives are to determine whether: 1) significant differences exist in floodplain soil OC concentration among river basins located in the same climate and with similar permafrost characteristics, 2) river planform influences OC concentration, with more energetic planform types (e.g., braided or wandering) containing lower OC concentrations, 3) significant differences in OC concentration are present among geomorphic units (e.g., bars, fills, higher-standing floodplain surfaces, or wetlands) at the reach scale, and 4) the magnitude of variation in OC concentration differs among scales. If differences exist, the final objective is to explain these differences and examine the implications.

3.2. Study Area

The YF region is a Cenozoic sedimentary basin with surrounding uplands, located in the boreal zone in interior Alaska (Figure 3.2a) (Nowacki et al., 2003; Williams, 1962). The climate is continental subarctic, with winter temperatures ranging from -34 to -24 degrees C, summer temperatures ranging from approximately 0 to 22 degrees C, and a mean annual precipitation of approximately 170 mm (Gallant et al., 1995). Lake sediments (silt and clay) almost 90 m thick underlie alluvial deposits in the basin (Williams, 1962). The YF did not experience Pleistocene glaciation (Gallant et al., 1995; Pewe, 1975). The region is located in the discontinuous permafrost zone (50-90% coverage) (Jorgenson et al., 2008; Romanovsky et al., 2013), and the region contains many thaw and oxbow lakes. Permafrost extends to approximately 90 m below the surface near Fort Yukon, located near the center of the study region (Clark et al., 2009).

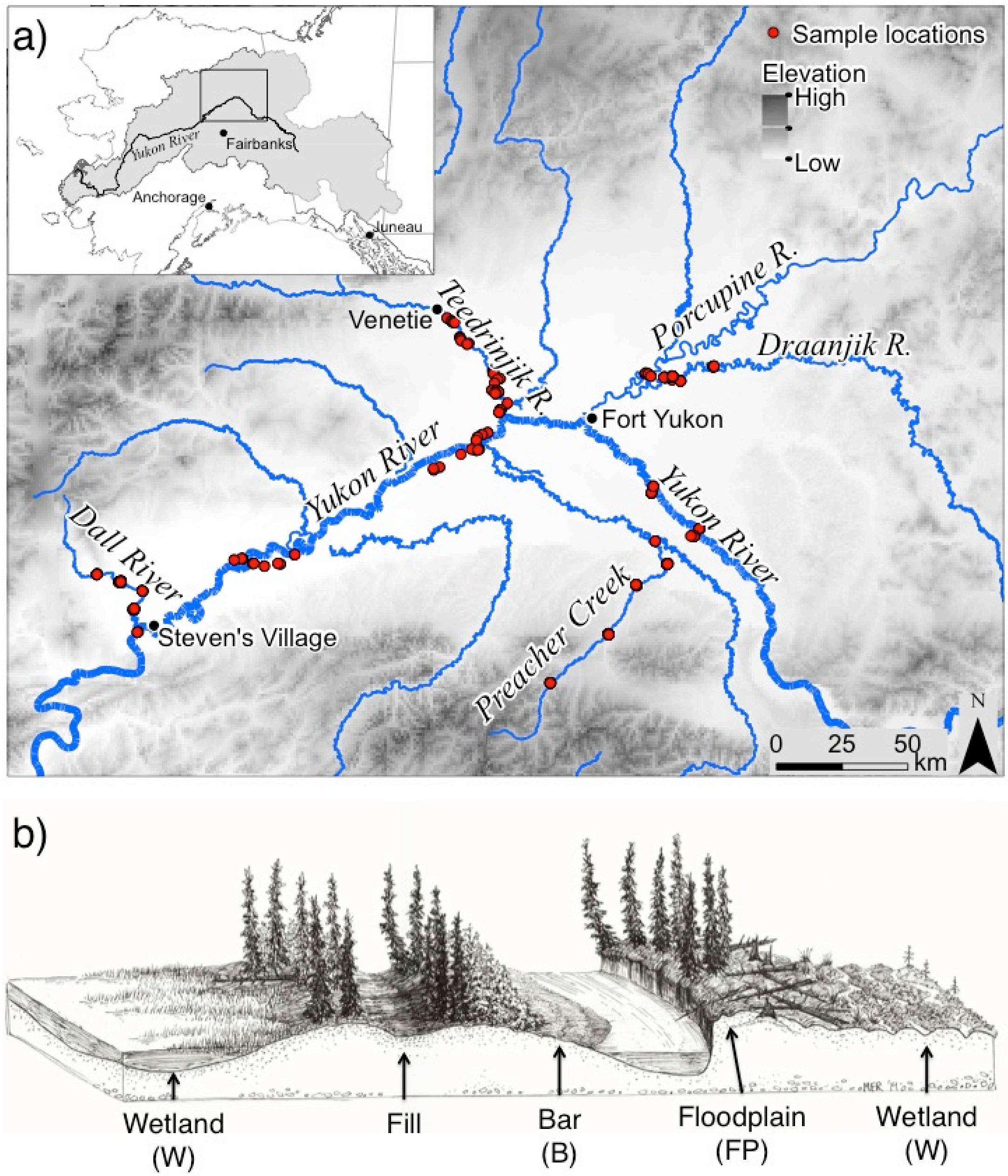

Figure 3.2. Study area showing the floodplain sampling locations along 5 study rivers within the Yukon Flats (a). Clustering of samples facilitates examination of segment-scale controls. Geomorphic units sampled in the floodplains of the Yukon Flats region (b). Illustration by Mariah Richards.

Soils within the region are classified as Entisols (young soils lacking well-developed horizons and formed in alluvium or outwash), Inceptisols (young soils with slightly better horizon development), and Gelisols (soils with permafrost within 2 m of the surface) (Brabets et al., 2000). Vegetation within the floodplains includes shrub vegetation (willows (*Salix spp.)* and alders (*Alnus spp.*)), deciduous trees (balsam poplar (*Populus balsamifera),* aspen (*Populus tremuloides*), and birch (*Betula papyrifera*)), white spruce forest (*Picea glauca*), mixed forests (spruce and deciduous), black spruce forest (*Picea mariana*), and wetlands (sedges and shrubs). Frequent fires influence vegetation dynamics, and fire return intervals range from 37 to 166 years, with a mean of about 90 years (Drury and Grissom, 2008). Floods in the YF can be caused by ice jams or from snowmelt (the spring freshet). Flood frequency is not well-known in the region due to limited accessibility and the remote nature of the basin, but 4 ice jam floods have occurred between 1949 and 1994 in Fort Yukon (Nakanishi and Dorava, 1994) prior to the construction of a levee, and local observations and river stage data in Fort Yukon indicates there may have been as many as 15 overbank flooding events in the past 35 years along the river near Fort Yukon (NOAA, 2017). River flow declines through the summer to baseflow, which occurs throughout the winter underneath frozen river surfaces (Walvoord et al., 2012).

We conducted fieldwork along 5 rivers with drainage areas ranging from 2,200-508,000 km^2: the Dall River (3700 km^2; sampled length ~ 80 river km), Preacher Creek (4,000 km^2; sampled length ~ 160 river km), the Draanjik (Black) River (16,500 km^2; sampled length ~ 75 river km), the Teedrinjik (Chandalar) River (29,000 km^2; sampled length ~ 80 river km), and the Yukon River (508,000 km^2 at Steven's Village, the downstream end of the study region, sampled river length ~ 350 river km) (Figure 3.2a). As the Yukon River enters the YF region, the planform of the river is braided, becoming a wandering anabranching river beginning after Fort

Yukon (Clement, 1999). We use the term wandering to denote a relatively laterally active anabranching planform (Desloges and Church, 1989; Nanson and Knighton, 1996). Clement (1999) defines a transitional segment in between braided and wandering segments on the Yukon, occurring from Fort Yukon downstream for approximately 90 km. However, we lump this transitional reach in with the wandering segment, as our samples for this segment occur well downstream of Fort Yukon and the transition to fully wandering is gradual. The Dall, which empties into the Yukon River, and the Draanjik, which flows into the Porcupine River, are single-thread meandering rivers with finer bed sediments and steep, high banks. Preacher Creek is a wandering river through most of its course, becoming meandering just before joining Birch Creek, a major tributary of the Yukon. The Teedrinjik River is a wandering river near Venetie, which was the upstream extent of sampled reaches (Figure 3.2a). The Teedrinjik displays anabranching meandering and single-thread meandering planforms before flowing into the Yukon River.

3.2 Materials and Methods

3.2.1 Fieldwork

In Summer 2014, we sampled along the Dall River and Preacher Creek. We stopped at intervals of 10s of kilometers to sample sediment within the floodplain along a transect perpendicular to the channel. At intervals of 20-30 m along each transect, depending on the channel width at the transect location, we sampled floodplain sediment at intervals that captured the variation in geomorphic and vegetation type. Each transect was associated with one river reach. We sampled at 5 reaches along the Dall River (total sampled locations = 62) and 4 reaches along Preacher Creek (total sampled locations = 65). We sampled along the Draanjik, Teedrinjik, and Yukon Rivers in Summer 2015. The rivers sampled in Summer 2015 are larger and the floodplains more complex, thus we modified our sampling procedure from a sampling transect to a sampling block (designated as a river reach). Within a reach of river, samples were located within patches representing the vegetation and geomorphic types present along the river reach. We sampled 4 reaches along the Draanjik River (sampled locations = 43), 5 reaches along the Teedrinjik River (sampled locations = 63), and 4 reaches along the Yukon River (sampled locations = 74). Two single-point samples were taken within each patch: one near the river bank and one sample 100 m into the floodplain. Samples were coded from both fieldwork years with the following identifications: river, reach, patch or point along a transect, sample ID number, depth ID number.

We also noted the geomorphic unit and surface vegetation of the sampled location. Geomorphic units include bars, fills (filled side channels and swales), higher floodplain surfaces that are not similar to any other geomorphic type, and wetlands that generally have permafrost or standing water (Figure 3.2b). All geomorphic units are located within the floodplain, and thus the wetland geomorphic unit denotes floodplain wetlands. The number of sampling locations in each geomorphic unit in each river basin is shown in Table B.1 in appendix B. Vegetation types include deciduous forest/shrub vegetation, white spruce forest, mixed deciduous and spruce forest, black spruce forest (usually containing permafrost), and wetland vegetation (grasses and shrubs). We noted whether there was evidence of disturbance, such as charred downed logs indicating recent fire, for each sampled location. In addition to capturing variability in geomorphic unit and vegetation type within the floodplains, we located reaches within different planform types if planform changed downstream along the river.

At each floodplain sample location, we separated the organic layer from the mineral sediment. We define the organic layer as material comprised of moss, litter, peat, and organic soil horizons above the boundary with mineral soil and excluding buried organic soil horizons (Pastick et al., 2014). At the beginning of the mineral sediment layer, we sampled with an auger (Summer 2014) or a sediment corer (Summer 2015) at increments of approximately 18 cm. The total sample depth at each location ended once we reached frozen soil (50.8% of sampled locations), gravels/cobbles/coarse sand (24.8% of locations), or 1 m in depth (18.2% of locations), or if we were unable to retrieve more due to wet conditions or unknown reasons (6.2% of sampled locations). The analyses presented in this paper focus only on the mineral soil samples, as this soil carbon stock is more stable over longer time periods (O'Donnell et al., 2011). In addition, the subsurface mineral soil is less subject to changes due to fire (O'Donnell et al., 2011). Organic layer depths varied by geomorphic unit, averaging 2.3 cm in bars, 3.4 cm in fills, 6.5 cm in floodplain surfaces, and 17.2 cm in wetlands.

3.2.2 Laboratory Analyses

OC concentration was determined by the Soil, Water, and Plant testing lab at Colorado State University. The samples were sieved to separate the < 2 mm fraction from the >2 mm fraction, and the total carbon concentration (%) in each <2 mm sample was found with a LECO TruSpec CN furnace (Nelson and Sommers, 1982). Each sample was also analyzed for inorganic carbon concentration through treating the sample with 0.4 HCl and measuring the CO_2 loss gravimetrically (Soil Survey Laboratory, 1996). Subtracting the inorganic carbon from the total carbon resulted in the OC concentration (%). A very small number of near-surface samples thought to be mineral soil in the field with very high OC concentrations were re-classified as organic soil materials according to NRCS guidelines (Soil Survey Staff, 1999) and left out of these analyses. Soil moisture was found by drying each sample for 24 hours at 105 degrees C and is expressed as the percent of mass lost divided by the initial, wet sample mass. We completed texture analyses on all mineral samples following USDA Natural Resources Conservation Service guidelines and the texture class was converted to an average percent fines (silt + clay) for that class using a texture triangle (Thein, 1979).

3.2.3 Statistical Analyses

We modeled OC concentration using a general linear mixed effects model in R to determine correlations between predictor variables and OC (R Core Team, 2014) with the lme4, lmerTest, and lsmeans packages (Bates et al., 2015; Kuznetsova et al., 2016; Lenth, 2015). The model included river, geomorphic unit, the interaction between river and geomorphic unit, the middle depth of each sample increment (cm), and the distance from the river channel (m) as fixed effects. We modeled the percent fines (silt + clay) and percent soil moisture as response variables using the same predictor variable above in order to determine whether there were significant differences in grain size and soil moisture among rivers and among geomorphic units. For each river on which multiple planforms were sampled (the Yukon and the Teedrinjik), we modeled OC concentration with planform, geomorphic unit, the middle depth of each sample increment (cm), and the distance from the river as fixed effects in order to determine whether there were significant differences in OC among planform types. The reach identification, patch or point along a transect, and the sample location (core location) were included as random effects in all models. The residuals of all models were checked for homogeneity of variances and response variables (%OC, %fines, % soil moisture) were log transformed if necessary. To test for significance of fixed effects (alpha = 0.05), we used type III tests. To determine whether significant differences existed for pairwise comparisons within river and geomorphic unit, the Tukey method to adjust for multiple comparisons was used. The associations between OC concentration and % fines and OC concentration and soil moisture were determined through visual inspection of plots.

In order to assess whether there are peaks in OC at depth within the floodplain, we assessed the percent change for each sample relative to the overlying sample. We used the consistent criteria that a sample should be at least 50% greater than the overlying sample and at least 0.5% OC concentration in order to be identified as a peak of OC at depth (Appling et al., 2014). This assessment informs whether there are buried OC layers within the soil caused by buried forest floors or the delivery of organics into the floodplain via flooding.

Because the vegetation types identified in the field are highly associated with geomorphic types, vegetation as a predictor variable was left out of the models. For example, deciduous/shrub vegetation was the only vegetation type on bars, black spruce forests were located only in wetlands, and white spruce forests were located only on higher standing floodplain surfaces (Table B.2 in appendix B). Vegetation on the surface is susceptible to fire disturbance, and thus the vegetation at the time of sampling may not accurately reflect the most dominant vegetation over the timescale of carbon accumulation in the mineral subsurface due to the influence of fire. Studies have demonstrated the vegetation within floodplains reflects river dynamics and flooding patterns (Whited et al., 2007), with primary succession starting from unvegetated bars to forested floodplain surfaces (Chapin III et al., 2006; Viereck et al., 1993). Also, previous studies have suggested that vegetation may influence near-surface carbon storage, but not necessarily deeper carbon storage (Appling et al. 2014). As our focus is on deeper mineral carbon stocks, we focus on geomorphic units. In addition, we did not separate samples into those with recent evidence of fire and those without, in part because fire has more influence on organic layer carbon compared to deeper mineral sediment (O’Donnell et al., 2011), and our analyses are restricted to mineral sediment. Because fire is a frequent natural disturbance in the YF, our samples included locations with recent and past fires that we were not able to age or identify, and thus our analyses assume that fire can occur throughout the landscape at regular intervals.

3.3 Results

The mean OC concentration and standard error of the mean of the entire dataset is 2.8% ± 0.1, with a median of 2.2% (basic summary statistics for OC%, % fines, and % soil moisture included in Table B.3 in appendix B). Average depths reached for sampled locations by river and by geomorphic unit are included in Table B.4 in appendix B. Two of the study rivers have different planform types along the sampled areas, the Yukon and the Teedrinjik Rivers, and OC concentration was modeled for each river using planform as a predictor variable. Planform does not significantly influence OC concentration on the Teedrinjik River ($p = 0.29$) (Figure B.1; Tables B.5 provides model summary). Along the Yukon River, the influence of planform depends on the geomorphic unit (Figure B.1; Table B.6 provides model summary). Significant differences in planform types exist for two of the geomorphic units: bars have higher OC concentrations in the wandering segment ($p = 0.025$), and wetlands have higher OC concentrations in the braided segment ($p = 0.049$), but there are no differences between the wandering and braided segments in fill and floodplain surfaces ($p = 0.141$ and $p = 0.205$, respectively).

Using the entire dataset, river, geomorphic unit, and middle sample depth influence OC concentration (Table B.7 in appendix B summarizes model results for models of OC concentration, % fines, and soil moisture). Pairwise comparisons among rivers indicate that the Dall River has significantly higher OC concentration than the Teedrinkjik River and Preacher

Creek (Figure 3.3). A comparison between the Draanjik River and the Teedrinjik River results in a p value of 0.072, which does not meet the significance level of 0.05 but indicates that differences may exist between the two rivers. The Yukon River OC concentration is not statistically different than any other river. Pairwise comparisons among geomorphic units show that wetlands have the highest OC concentration, followed by floodplain surfaces and fills, with bars having the lowest OC concentration (Figure 3.3). There is a greater difference in the highest and lowest OC concentrations among geomorphic units (wetlands = 5.1% vs. bars = 2.0%) than among rivers (Dall River = 3.8% vs. Teedrinjik River = 2.3%). The distance from the channel for the sample was not a significant influence on OC concentration. Summary statistics of OC concentrations, % fines, and % soil moisture by river and by geomorphic unit are included in supplementary Tables B.8 and B.9 in appendix B.

As sampling depth increases, OC concentration decreases ($p < 0.0001$) (Table B.7; Figure B.2), and the magnitude of the effect is relatively strong relative to the variation in OC % across all samples ($\beta = -0.185$; Table B.7; note that OC model is log-transformed). Analyses of potential peaks of OC in the subsurface indicate that there are very few sampling increments at depth that show large increases of OC relative to overlying samples. The percentage of samples in which OC concentration is greater than 50% of the concentration in the overlying sample is 4.2 % for Preacher Creek, 4.3% for the Dall River, 5.5% for the Draanjik River, 8.0% for the Yukon River, and 10.7% for the Teedrinjik River. These data support the model results demonstrating a decrease in OC concentration with increasing depth.

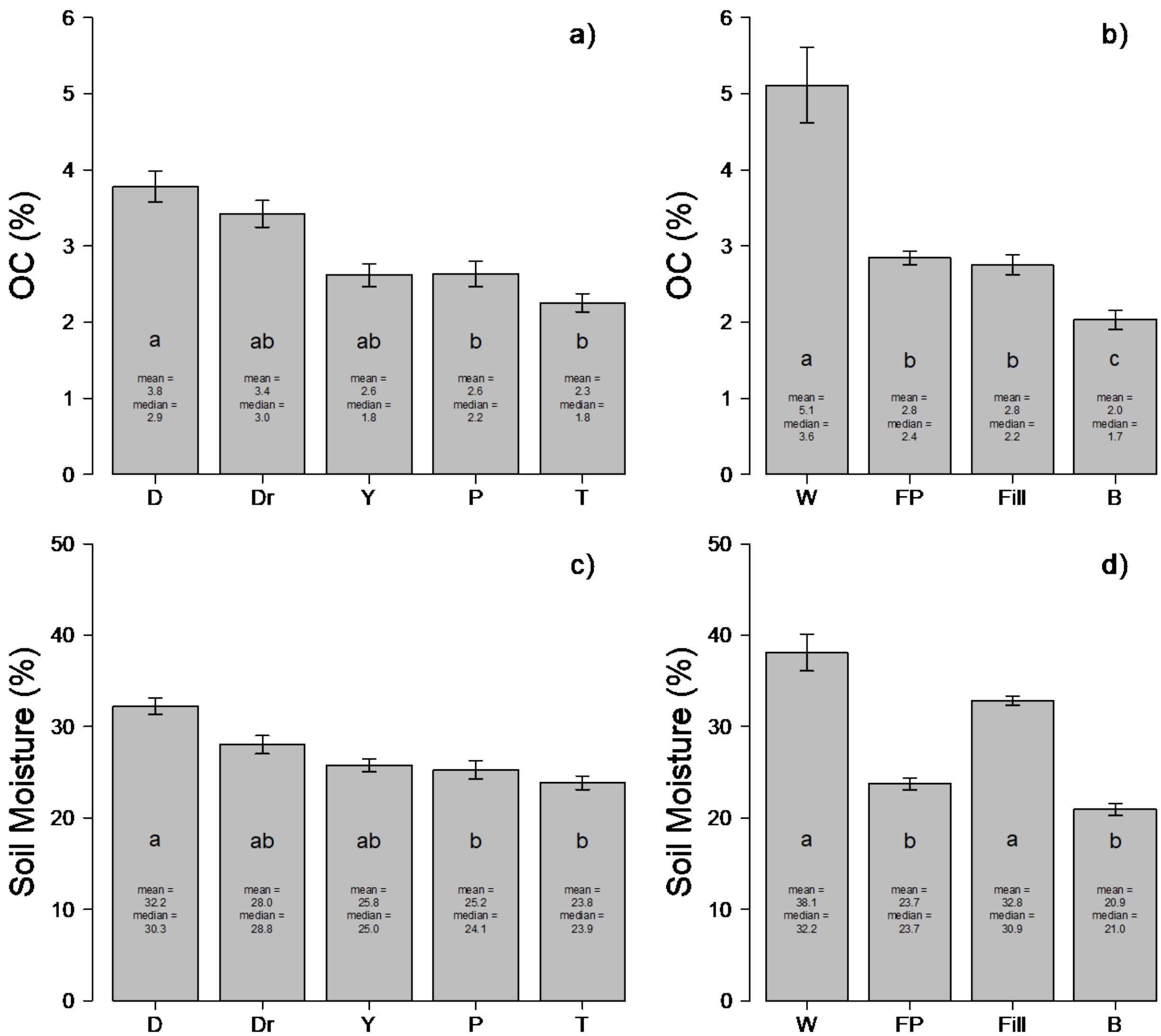

Figure 3.3. OC concentration (%) (a) and soil moisture (%) (c) for rivers across all geomorphic units. D = Dall, Dr = Draanjik, Y = Yukon, P = Preacher, T = Teedrinjik. OC concentration (b) and soil moisture (d) for geomorphic units across all rivers. W = wetland, FP = floodplain, B = bar. Letters in bars indicate significant differences at $\alpha = 0.05$. Bars containing the same letter have no significant differences, while bars that do not share a letter indicate significant differences. Bars show the mean ± the standard error. Values of means and medians are shown within bars.

In order to determine whether different rivers or different geomorphic units have significantly different grain sizes, we modeled the % fines (silt + clay) using river, geomorphic unit, the interaction between river and geomorphic unit, the middle depth of each sample (cm), and the distance from the channel (m). As the middle depth of each sample increases, the % fines decreases ($p < 0.0001$), although the effect is relatively small relative to the magnitude of changes in % fines ($\beta = -0.185$; Table B.7), indicating that a unit increase in depth has a relatively small unit decrease in % fines. Due to the significant interaction term of river x geomorphic unit, the differences in % fines among geomorphic units depend on the river sampled, and the differences found in % fines among rivers depend on the geomorphic unit. Table 3.1 shows the significant differences among geomorphic units given each river and the significant differences among rivers given each geomorphic unit. Although the interaction term creates difficulties in interpretation, in general, Preacher Creek has coarser sediment than the other sampled rivers, except in the wetland geomorphic unit. In addition, except for the Draanjik River, bars have coarser sediment compared to other geomorphic units.

Table 3.1. Summary of significant pairwise comparisons ($p < 0.05$) for model of % fines for river given each geomorphic unit and for geomorphic unit given each river.

Geomorphic unit	*Significant differences among rivers in % fines*
Bar	Preacher < Yukon = Teedrinjik = Dall = Draanjik
Floodplain	Preacher = Teedrinjik < Draanjik
Fill	Preacher < Teedrinjik = Draanjik
Wetland	None
River	*Significant differences among geomorphic units*
Dall	Bar = Floodplain < Wetland
Draanjik	None
Yukon	Bar < Fill
Preacher	Bar < Floodplain = Fill < Wetland
Teedrinjik	Bar = Floodplain < Fill

River, geomorphic unit, and the middle depth of the sample are significant predictors of % soil moisture (Table B.7). As the sample depth increases, soil moisture decreases ($p<0.0001$). The Dall has significantly higher soil moisture in samples compared to Preacher Creek and the Teedrinjik River, and wetland and fill geomorphic units are significantly higher in soil moisture compared to floodplain surfaces and bars (Figure 3.3). Summary statistics for % fines and soil moisture are included in Tables B.3, B.8, and B.9. As soil moisture and % fines increase, OC concentrations of samples generally increase (Figure B.3).

3.4 Discussion

Returning to the research objectives, 1) there are differences in floodplain soil OC concentration among river basins in the YF, 2) river planform exerts some influence on OC concentration along the Yukon River in some geomorphic units, but not along the Teedrinjik River, 3) there are differences in OC concentration among geomorphic units (e.g., bars, fills, higher floodplain surfaces, or wetlands) at the reach scale, and 4) the magnitude of difference in mean OC concentration is greatest among geomorphic units as opposed to among study rivers (Figure 3.3), indicating that the magnitude of variation in OC concentration differs among scales. In addition, our analyses indicate that OC concentration decreases with depth but does not vary with distance from the channel (Table B.7).

3.4.1 OC in floodplain soil may be mostly due to inputs from surface vegetation, with different starting points depending on river basin

The reduction of OC concentrations with depth suggests that much of the OC inputs to floodplain soil, across all geomorphic units, come from surface vegetation (i.e., autochthonous inputs) with little evidence for substantial buried organic horizons. Peaks of OC at depth relative to overlying samples occur only in 4-10% of all samples across study rivers. These few peaks may be buried forest floors or carbon-rich lenses from overbank flooding (Appling et al., 2014; Blazejewski et al., 2009). However, other studies have found stronger evidence of buried OC layers within floodplain soils (e.g., Blazejewski et al., 2009). OC concentrations in bar environments on the Dall and Draanjik Rivers (3.1% and 2.9%) are higher than OC concentrations in bars on Preacher Creek and the Teedrinjik River (1.7% and 1.4%), indicating that freshly deposited sediment on bars varies with river basin. Thus, although much of subsequent OC accumulation may come from surface vegetation, the starting concentration may depend on the river basin characteristics that influence the OC concentration in freshly deposited sediment.

The slight upward fining in the floodplain (Table B.7) may also influence the decrease of OC concentration with depth, as finer grain sizes are associated with more OC because finer grains better stabilize OC (Jobbágy and Jackson, 2000; Pinay et al., 1992). The upward fining indicates some signature of overbank flooding delivering fines to the floodplain over time, but the effect of increasing depth on % fines is relatively small. Because our measurement of % fines is based on texture classes, detections of upward fining in the floodplain may be limited, but we did not see strong upward fining in the field or with statistical modeling. Due to our samples being restricted to the active-layer, we did not frequently reach coarse gravel layers that could be interpreted as coarse laterally accreted or channel fill deposits deep within the floodplains. Bars, which are lateral accretions, are sometimes coarser than other geomorphic units, although this depends on the river (Table 3.1). The relatively weak upward fining in floodplain soil supports the idea that OC accumulation results from vegetation inputs (indicated by a relatively strong decrease of OC with depth) and is not strongly controlled by upward fining.

The YF may be similar to the Tanana River floodplain, located in the boreal zone in interior Alaska, where soil carbon stocks increase with successional age of the floodplain surface and vegetation (Van Cleve et al., 1993). This suggests that river migration and erosion, as opposed to overbank flooding, are the dominant geomorphic controls on sedimentation, surface creation, and associated OC increases in the subsurface, at least within the active-layer sediment. Distance from the channel does not significantly influence OC concentration, which may reflect the fact that these floodplains are complex, with avulsions, secondary channels, and bars being accreted to the floodplain (Clement, 1999), resulting in floodplains with a patchwork of geomorphic units.

3.4.2 Planform variations along rivers is not strongly correlated with OC concentrations

The mixed results for the influence of planform on OC concentration (no difference among planform types on the Teedrinjik, and some differences on the Yukon depending on geomorphic unit) could indicate that planform categories are actually on a continuum in terms of fluvial process and form. The lower OC concentration on bars in the braided segment compared to the wandering segment on the Yukon could be partially explained by differences in grain size, as bed sediment fines slightly from the entrance to the YF to the end of the sampled extent (Clement, 1999). In addition, Clement (1999) found that migration rates decreased from the braided segment to the wandering segment within the Flats, and more frequent erosion of bars in the braided segment could result in less time for OC to accumulate from vegetation. The higher OC concentration in wetlands in the braided segment could be a result of the river in the braided segment migrating in a narrower band, with wetland geomorphic units occurring on slightly higher elevational surfaces that are more stable compared to those surfaces in the wandering segment, although this is speculative.

3.4.3 Basin-scale differences in OC among river basins

Because rivers are integrators of their upstream contributing area, the differences among study rivers could result from many factors. The Dall River has a higher OC concentration compared to Preacher Creek and the Teedrinjik River, and although the difference is not significant at a significance level of 0.05, the Draanjik River may have higher OC concentration compared to the Teedrinjik River ($p = 0.072$; Figure 3.3). Grain size and soil moisture may play a role in these differences. Our results demonstrate that Preacher Creek generally has coarser sediment compared to the other study rivers, although the significant interaction between river and geomorphic unit makes these results somewhat difficult to generalize (Table 3.1). Difference in grain size has been an influencing factor for other studies of floodplain OC, with coarser sediment containing lower OC concentrations (Appling et al., 2014; Pinay et al., 1992; Sutfin and Wohl, 2017). The Dall River samples also have higher soil moisture than Preacher Creek and the Teedrinjik River, which could also influence OC concentration (Figure 3.3). Wetter soils tend to have higher OC concentrations until soils are fully saturated (Chapin III et al., 2012; Jobbágy and Jackson, 2000). The associations between grain size and OC concentration and soil moisture and OC concentration are also shown in our sample data (Figure B.3). In addition, soil moisture and grain size are related, as finer grain sizes are better able to retain moisture (Dingman, 2008).

Although planform does not influence OC concentration on the Teedrinjik River and partly influences OC concentrations on the Yukon River, planform may influence the differences among rivers. The Dall and Draanijik Rivers are single-thread meandering, whereas Preacher Creek and the Teedrinjik River are wandering rivers for at least some portion of the sampled extent. If much of the OC inputs into the floodplain come from autochthonous vegetation growing on the floodplain surface, the greater lateral mobility of Preacher Creek and the Teedrinjik River compared to the meandering Dall and Draanjik Rivers could result in less time for OC accumulation before river migration erodes the floodplain (Lininger et al., 2016).

Another difference among river basins that could influence floodplain OC concentrations is the DOC concentration of the study rivers. River samples from 2002 indicate that the Draanjik and Dall Rivers have high DOC concentrations (12.0-15.0 and 12.2 mg C L^{-1}, respectively) (Dornblaser and Halm, 2006). In contrast, the DOC concentrations on the Teedrinjik River have been measured at 1.6-2.5 mg C L^{-1} (Dornblaser and Halm, 2006), and concentrations in Preacher Creek have been reported as 8.9 mg C L^{-1} (O'Donnell et al., 2012). The DOC of the Yukon River throughout the study region ranges from 5.6-6.9 (Dornblaser and Halm, 2006). High concentrations of DOC could result in adsorption of DOC onto mineral grains in transport (McKnight et al., 2002) that are then deposited on the floodplain in bars or via overbank flow. Because floodplain soil OC concentrations may be influenced by DOC concentrations within the river, the baseline concentration of OC within floodplain sediments may depend on differences in freshly deposited sediment, while the subsequent accumulation of more carbon in the floodplain could be the result of autochthonous inputs. The differences in bar OC among rivers support this inference.

The lack of significant difference between the Yukon River and the other study rivers could reflect its large drainage area. The Yukon River integrates sediment inputs and water fluxes from a large number of tributaries with varying characteristics, including the four tributary rivers in this study. Thus, the lack of statistically significant differences indicates that OC concentrations on the Yukon are influenced by the tributary contributions and by upstream inputs.

3.4.4 Reach-scale differences in OC among geomorphic units

At the reach scale, wetlands have higher OC concentrations than bar environments (Figure 3.3). Bars have coarser sediment and lower soil moisture compared to wetlands on most rivers (Table 3.1; Figure 3.3), which likely contributes to this difference. In addition, wetlands in boreal floodplains of interior Alaska tend to be older surfaces, either with black spruce and a higher permafrost table (woody wetlands) or with herbaceous vegetation in thaw ponds or bogs. These older surfaces likely have had more time for OC to accumulate in the subsurface (Van Cleve et al., 1993). In addition, wetland environments in high latitude regions have reduced OC respiration rates due to wet and cold conditions, which inhibit mineralization and release of OC (Davidson and Janssens, 2006; Douglas et al., 2014). Floodplain primary succession in interior Alaska supports the assertion that wetlands are older surfaces. Surfaces with bar vegetation (shrubs and deciduous vegetation) develop after approximately 1-100 years depending on the type of vegetation, and woody wetlands with black spruce and bog vegetation may not develop for over 500 years after a surface is first created by river deposition (Chapin III et al., 2006; Viereck et al., 1993).

The lack of difference in OC concentrations between fills and floodplain surfaces may also be informed by the time since deposition and creation. Fills have higher soil moisture compared to floodplain surfaces and bars (Figure 3.3), potentially reflecting a lower topographic position on the landscape. This suggests that these environments would have higher OC concentrations due to the association between soil moisture and OC. But, floodplain surfaces, which contain white spruce stands, are likely older than fills, which have a mixture of deciduous, shrub, and wetland herbaceous vegetation (Table B.2). White spruce stands commonly do not develop on floodplains for 200-500 years (Chapin III et al., 2006; Viereck et al., 1993), indicating that they may be older than filled secondary channels and have been able to accumulate higher concentrations of OC. In the Rhine River basin, channel fill environments have higher OC concentrations when compared to other types of overbank deposits, which contrasts with the results of this study (Hoffmann et al., 2009).

3.4.5 Conceptual model of geomorphic influences on floodplain soil OC

Figure 3.4 summarizes the main processes occurring in the Yukon Flats that contribute to OC concentrations in floodplain soil. Figure 3.4a demonstrates the two main pathways for OC to accumulate within the floodplain. Rivers deposit sediment and organics directly onto the floodplain, either via lateral accretion and bar deposition or via vertical accretion of finer sediments with overbank flooding (dark grey arrow). This direct river deposition contributes a certain amount of OC within the soil (dark grey OC bar), and this amount varies depending on river basin characteristics such as the grain size of sediment in transport and the DOC concentration within river water. Also shown in Figure 3.4a, vegetation provides inputs of OC into the soil (light grey arrow and OC bar). Vegetation inputs are likely the primary input of OC relative to either lateral accretion deposition in bars or overbank flooding, and this assumption is supported by the lack of peaks of OC at depth and the decrease of OC with depth within the samples. With channel migration and erosion of the floodplain, OC re-enters the river network and is carried downstream. Figure 3.4a does not include mineralization of OC and the release of carbon into the atmosphere via microbial respiration because our focus is on the geomorphic processes occurring within the floodplain.

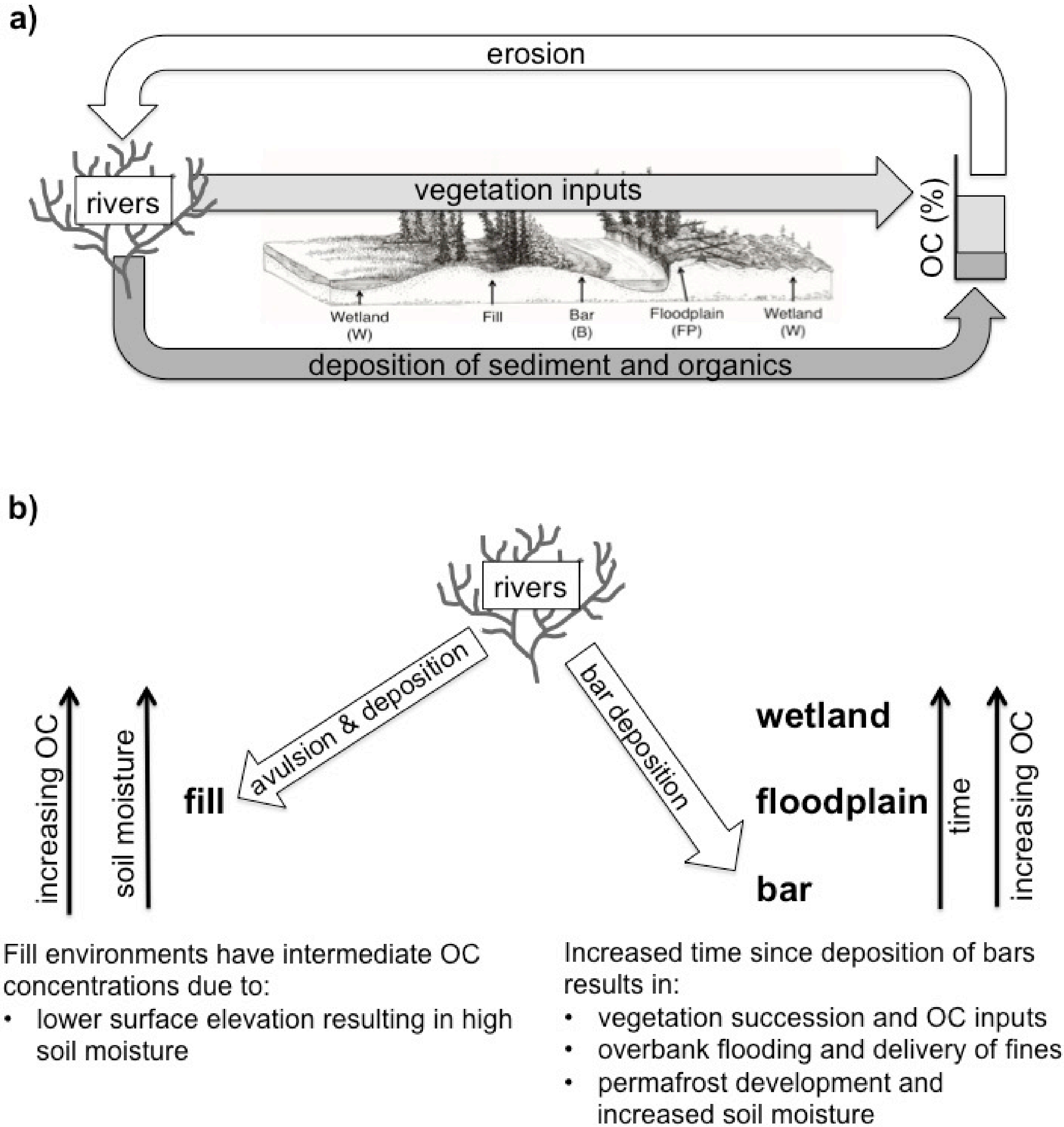

Figure 3.4. Conceptual models demonstrating the controls on OC within the floodplain in the Yukon Flats. A). The primary ways in which OC is delivered to floodplain soil include direct deposition of sediment and organics by the river via lateral and vertical accretion (dark grey arrow and associated dark grey OC) and the creation of floodplain surfaces, vegetation growth, and the delivery of OC via vegetation inputs (light grey arrow and associated light grey OC). B) Two scenarios demonstrate the mechanisms for OC accumulation within geomorphic units in relation to other factors that influence OC in the subsurface. See text for additional details.

Figure 3.4b demonstrates some of the influences on OC accumulation within different geomorphic units. Through lateral accretion and river migration, rivers deposit bars (right side of Figure 3.4b), which are coarser, drier, and contain less OC compared to other geomorphic units. The river slowly migrates away from the bars, which develop into other geomorphic units (floodplain and wetland). Over time, vegetation succession occurs, contributing more OC to the soil; overbank flooding may contribute fines to the soil, which help stabilize OC; and the permafrost table may rise, impeding soil drainage and reducing mineralization rates due to wet conditions. Channel migration rates, which differ among planform types, likely influence this process, because migration rates determine how long the surface will be stable before being re-eroded by the river. All of these factors likely influence the increase of OC in the subsurface. Rivers also avulse, creating filled secondary channels, or scour low points on bars that are then filled (left side of Figure 3.4b). These fills are frequently at a lower elevation in the landscape, and have higher soil moisture, which contributes to the OC contained in the soil.

3.4.7 Comparison of OC concentration values with other environments

The YF OC concentrations have a larger range (<0.5-14.96%) for mineral sediment compared to OC concentrations reported from non-floodplain locations in interior Alaska (Figure 3.5). Ping et al. (1997) report the percentage of OC in upland environments in interior Alaska, including a hillslope bog, glaciated upland forest, and forested outwash plain. Their values for mineral soil horizons range from 0.5-4.2%, with the highest in the hillslope bog location with mineral horizon OC concentrations of 1.9 and 4.2%, and the lowest OC% in a forested outwash plain with 0.05- 2.8% in mineral horizons (Ping et al., 1997). The highest OC concentrations in our study were from wetland environments, with a mean of 5.1 ± 0.5% and a median of 3.6%. O’Donnell et al. (2011) report a mean and standard error of 3.4 ± 0.7% for mineral soil in black spruce stands from burned and unburned upland slopes in interior Alaska. These sites from the uplands may be most comparable to wetlands in our study, as both sites have permafrost and impeded drainage. Thus, wetlands with black spruce may have higher concentrations of OC compared to upland black spruce sites. However, the similarity between the OC concentrations in upland environments and the floodplains in the YF also provides support for the assertion that much of the OC in the subsurface in floodplains comes from surface vegetation inputs. For example, if vegetation is similar in upland and floodplain environments, the OC concentrations may also be similar. The larger range in OC in floodplains could reflect the diversity of geomorphic units (reflecting both river processes and differences in time since deposition) within the floodplains relative to upland locations or the different starting points of OC concentration. In the Tanana River floodplain, also located in boreal interior Alaska, OC concentration values range from <0.5% in early successional vegetation to 8% in older, white spruce vegetation (Van Cleve et al., 1993), and these results are similar to this study. Floodplain lowlands in the boreal zone may have higher OC concentrations than mountainous rivers in the boreal zone, with 1.3-1.5% OC in floodplains of mountains in Alberta, Canada (Hoffmann et al., 2014).

Comparing the YF to floodplains in other regions, YF may have lower OC concentrations than semi-arid mountain environments but may have similar or higher OC concentrations compared to other locations (Figure 3.5). Sutfin and Wohl (2017) report a mean OC concentration of 6.3% for floodplains in the eastern side of the Rocky Mountains, which is higher than the mean OC concentration of our study (2.8%). However, the median OC % from their study (3.7%) is more similar to the median in the YF (2.2%). The higher OC concentrations in the Rocky Mountains could be due to higher primary productivity in the warmer climate compared to the boreal zone (Bradford et al., 2008). A comparison with temperate lowland

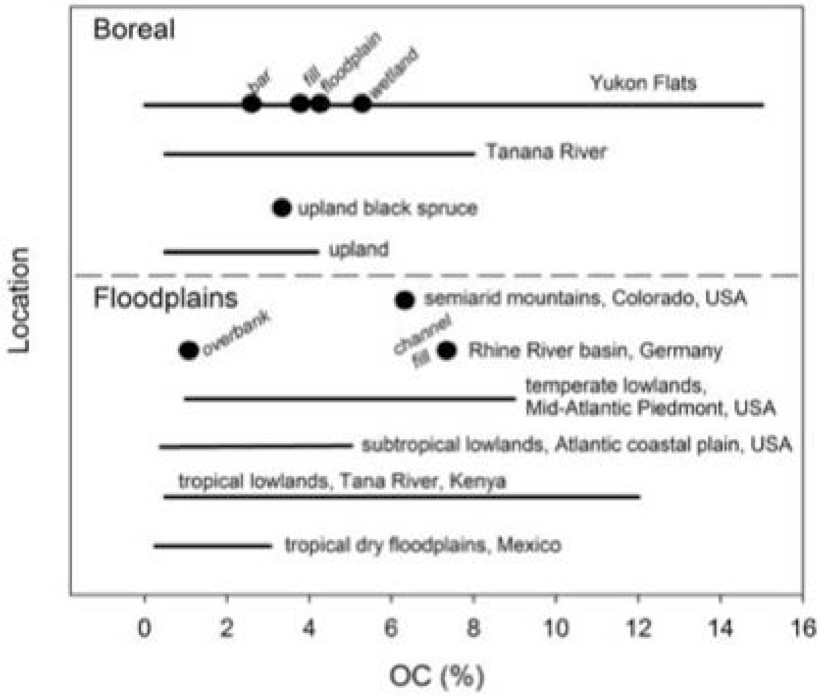

Figure 3.5. OC concentrations in boreal regions and in floodplains in other climatic zones. Black dots indicate means, and lines indicate ranges. References for values are cited in the text and include: Yukon Flats (this study), Tanana River (Van Cleve et al., 1993), upland black spruce (O'Donnell et al., 2011), upland (Ping et al., 1997), semiarid mountains, Colorado, USA (Sutfin and Wohl, 2017), Rhine River Basin, Germany (Hoffmann et al., 2009), temperate lowlands, mid-Atlantic piedmont, USA (Walter and Merritts, 2008), subtropical lowlands, Atlantic coastal plain, USA (Ricker and Lockaby, 2015), tropical lowlands, Tana River, Kenya (Omengo et al., 2016), and tropical dry floodplains, Mexico (Jaramillo et al., 2003).

floodplains such as the Rhine River Basin (Hoffmann et al., 2009) or the Mid-Atlantic Piedmont (Walter and Merritts, 2008) indicates that the YF may have higher OC concentrations (Figure 3.5). YF floodplains also contain higher or a larger range of OC concentrations than subtropical and tropical floodplains (Figure 3.5), which may reflect higher decomposition rates in warmer climates that enhance carbon mineralization in tropical and subtropical floodplains compared to boreal floodplains (Chapin III et al., 2012; Jobbágy and Jackson, 2000).

3.4.8 Implications

Our results indicate that it is important to consider both large-scale differences among river basins and small-scale differences among geomorphic units when assessing floodplain soil OC concentrations. The patterns in OC concentration among geomorphic units are similar across study rivers, but different baselines of OC concentrations occur for separate river basins. In addition, the larger differences in OC concentration among geomorphic units (between wetlands and bars) compared to among study rivers (between the Dall River and the Teedrinjik River) indicate that reach scale controls may have a stronger overall influence on the spatial distribution of OC within the floodplain. Segment scale differences in planform may be important to consider depending on the river studied, but are also dependent on geomorphic unit. Our results suggest that most of the OC accumulated in floodplain soil in the YF comes from autochthonous inputs of vegetation, although freshly deposited floodplain differs in OC concentration among rivers. Because vegetation reflects geomorphic processes and time since surface creation (Table B.2) (Chapin III et al., 2006; Viereck et al., 1993; Whited et al., 2007), fluvial processes exert a strong control on OC concentrations within floodplains. The dominant influence of geomorphic units on OC concentrations also points to the opportunity to utilize high-resolution topography and remote imagery when assessing OC distribution and stocks within floodplain landscapes.

3.5 Conclusions

Floodplains act as sites of OC accumulation and storage, and as a source of OC to river networks. Determining the geomorphic controls on floodplain soil OC is important for assessing the spatial distribution of carbon in the high latitudes as permafrost warms and temperatures continue to increase (IPCC, 2014; Romanovsky et al., 2010). In addition, climate change and associated permafrost degradation will likely influence riverine fluxes of OC and geomorphic processes (Frey and McClelland, 2009; Rowland et al., 2010), highlighting the importance of understanding floodplain soil OC dynamics in the context of geomorphology. Studies suggest that flowpaths, the relative contributions of groundwater vs. surface water, and nutrient fluxes from the YF may be already changing due to anthropogenic climate change (O'Donnell et al., 2014; Striegl et al., 2005; Walvoord and Striegl, 2007), and the location of the YF in the discontinuous permafrost zone may make it highly sensitive to future changes.

We initially asked how differences in the spatial scale of analysis influence quantification of OC concentrations across large floodplains and how differences in the spatial scale of analysis inform our understanding of the controls on OC concentrations in the mineral soil of floodplains. We assessed OC concentrations at the scale of drainage basins, river segments, and river reaches. We find that there are few significant differences at the segment scale. There are differences among drainage basins, but the greatest differences in OC concentrations occur among geomorphic units within a river reach. This suggests that the most accurate way to quantitatively estimate floodplain OC concentrations across large floodplains is a bottom-up approach in which the distribution of individual units is mapped and the cumulative spatial extent of each unit is used with a median or mean value for OC concentration. We also infer that OC in floodplain mineral sediment results primarily from autochthonous inputs of floodplain vegetation, so that time over which the surface has been stable and type of vegetation, as these influence OC inputs, and grain size and soil moisture, as these influence OC retention within soil, all control OC concentration. This implies that the history of river erosion and deposition within a reach ultimately controls the spatial distribution and concentration of organic carbon in floodplain soils, even though direct riverine deposition of organic carbon may not exert the primary control on floodplain OC concentrations.

Data Availability

The data analyzed in this publication are available online through the Colorado State University Digital Repository at https://hdl.handle.net/10217/185889.

Chapter 4 Significant floodplain soil organic carbon storage along a large high-latitude river and its tributaries[3]

Summary

High-latitude permafrost regions store large amounts of organic carbon (OC) in soils, and these stocks are vulnerable to climate warming. Estimates of subsurface carbon stocks do not take into account floodplains as unique landscape units that mediate and influence the delivery of materials into river networks. We present estimated floodplain soil OC stocks within the active layer (seasonally thawed layer) and within the top 1 m of the subsurface from a large field dataset in the Yukon Flats region of interior Alaska. We compare our estimated stocks to a previously published dataset, and find that the OC stock estimate using our field data is approximately 80% higher than the published dataset. We constrain the residence time of floodplain sediment and OC using radiocarbon dating. Our results indicate the importance of floodplains as areas of underestimated carbon storage, particularly because climate change may modify geomorphic processes in permafrost regions.

4.1 Introduction

Boreal and arctic regions are experiencing increased temperatures due to anthropogenic climate change (ACIA, 2005; IPCC, 2014; U.S. Environmental Protection Agency, 2016). Ongoing climate disruption has caused permafrost warming and thaw (Jorgenson et al., 2006; Romanovsky et al., 2010, 2013), intensified the hydrologic cycle (Rawlins et al., 2010), modified hydrologic flowpaths (O'Donnell et al., 2014; Toohey et al., 2016; Walvoord and Kurylyk, 2016; Walvoord and Striegl, 2007), changed the exports of nutrients to the Arctic Ocean (Frey and

[3] Chapter in review as Lininger, K.B., E. Wohl, J.R. Rose, and S.J. Leisz, in review. Significant floodplain soil organic carbon storage along a large high-latitude river and its tributaries.

McClelland, 2009; Striegl et al., 2005; Toohey et al., 2016), and will likely cause many changes to geomorphic processes (Rowland et al., 2010), including the potential for accelerated lateral channel migration and mobilization of floodplain soil carbon stock.

The amount of organic carbon (OC) stored in the subsurface in permafrost regions is approximately half of global subsurface OC (Hugelius et al., 2014; Jobbágy and Jackson, 2000), and permafrost warming and thaw, along with accelerated river erosion and transport of floodplain soil carbon, could release large amounts of carbon into the atmosphere, causing further climatic changes (Koven et al., 2015; Schädel et al., 2016; Schuur et al., 2008, 2015). The amount and vulnerability of soil OC indicates the need to accurately estimate OC stocks in high latitude regions, and previous studies have highlighted uncertainties in estimated OC stocks in available databases and between databases and field measurements (Tifafi et al., 2018; Zubrzycki et al., 2013).

Floodplains, which are sites of sediment and carbon storage and accumulation (Dunne et al., 1998; Dunne and Aalto, 2013; Lininger et al., 2018; Sutfin et al., 2016), have not been explicitly considered in estimates of OC stocks and fluxes in the high latitudes (e.g., Stackpoole et al., 2017), and carbon burial and storage in floodplain sediments is poorly constrained at the global scale (Regnier et al., 2013). Some attention has been given to estimating carbon stocks in Arctic river deltas and lowland environments, (Hugelius et al., 2014; Johnson et al., 2011; Schuur et al., 2008; Zubrzycki et al., 2013), but floodplains have not been treated as distinct portions of the landscape even though they can retain large deposits of alluvium, similar to deltas. Floodplains are also regions of OC burial, which can protect OC from decomposition (Chaopricha and Marín-Spiotta, 2014; Doetterl et al., 2016). In permafrost regions, previously frozen OC from upstream in a river network can be buried before mineralization occurs, which could complicate estimates of greenhouse gas emissions from permafrost thaw (Vonk and Gustafsson, 2013). In addition, large river floodplains can store sediment and associated carbon for long periods of time before erosion and further transport downstream (Dunne et al., 1998; Dunne and Aalto, 2013). Thus, constraining the carbon content and residence time of floodplain sediment could inform the character and type of nutrient fluxes from rivers to oceans.

We estimate soil OC stocks in the active layer (seasonally thawed layer) and top 1 meter of floodplains in the Yukon Flats (YF) region in interior Alaska, a large inland alluvial basin. Our study includes the Yukon River mainstem and four tributaries, resulting in OC stock estimates from numerous samples over a large area. We extrapolate our measurements to floodplains across the entire YF region within the Yukon Flats National Wildlife Refuge and put the estimate of floodplain soil stocks in context with published estimates of OC exports from the Yukon River. We also constrain the residence time of floodplain sediment before re-mobilization by fluvial erosion using radiocarbon dates taken from cutbanks along the study rivers and estimate the maximum age of soil OC through radiocarbon dating of sediment at the base of the active layer within the floodplain.

4.2 Materials and Methods

The YF region is located in the discontinuous permafrost zone in interior Alaska (Figure 4.1). We sampled floodplain sediments over two field seasons (Summer 2014 and 2015) along five rivers within the YF with varying drainage areas: the Dall River (3,700 km^2), Preacher Creek (4,000 km^2), the Draanjik (Black) River (16,500 km^2), the Teedrinjik (Chandalar) River (29,000 km^2), and the Yukon River (508,000 km^2 at Steven's Village, the downstream end of the study region). We sampled the organic layer (OL), which includes moss, litter, peat, and organic soil horizons above the boundary with mineral sediment, cutting out blocks with knives to estimate the bulk density of the OL. We sampled mineral sediment in increments of approximately 18 cm with an auger (2014; Dall River and Preacher Creek) or a soil corer (2015; Draanjik, Teedrinjik, and Yukon Rivers), stopping when we reached frozen soil (51.4% of locations), gravels/cobbles/coarse sand (24.4% of locations), 1 m in depth (18.0% of locations), or were unable to retrieve samples due to saturation or other sampling issues (6.1% of locations). At each sampled location, we noted the geomorphic unit, vegetation type (shrub/deciduous (*Salix spp., Alnus spp., Populus spp.*, and *Betula papyrifera*), mixed forest, white spruce (*Picea glauca*), black spruce woody wetlands (*Picea mariana),* or herbaceous wetland), and evidence of recent disturbance such as fire. We located our samples within reaches that reflect differing planform types, if planform changed along the sampled extent of each river. We sampled at 311 locations along study rivers; Table C.1 in appendix C shows the number of sampled locations, and Table C.2 reports the depths reached at sampled locations by river, vegetation type, and geomorphic unit. For further description of sampling methodology, see Lininger et al. (2018). We also took core samples from the face of cutbanks at a few locations to assess the range of OC concentrations below 1 m in depth.

We obtained measured or estimated OC concentrations, bulk density, texture, and OC stock for all samples. If we could not sample to 1 m due to frozen soil or inability to retrieve samples due to saturation, we extrapolated using measurements from the deepest sample down to a depth of 1 m = in order to estimate 1 m stocks. We did not extrapolate down to 1 m if we could not sample deeper due to gravel/cobbles/coarse sand in the subsurface, and considered the sampled depth the 1 m stock. Estimating the 1 m stock is necessary to compare stocks to other datasets. We also characterized the >2 mm fraction OC stock of each mineral sample for the 2015 samples (along the Yukon, Draanjik, and Teedrinjik Rivers) to determine stocks in the

>2mm fraction within the active layer. See appendix C (Text C.1) for detailed description of methods.

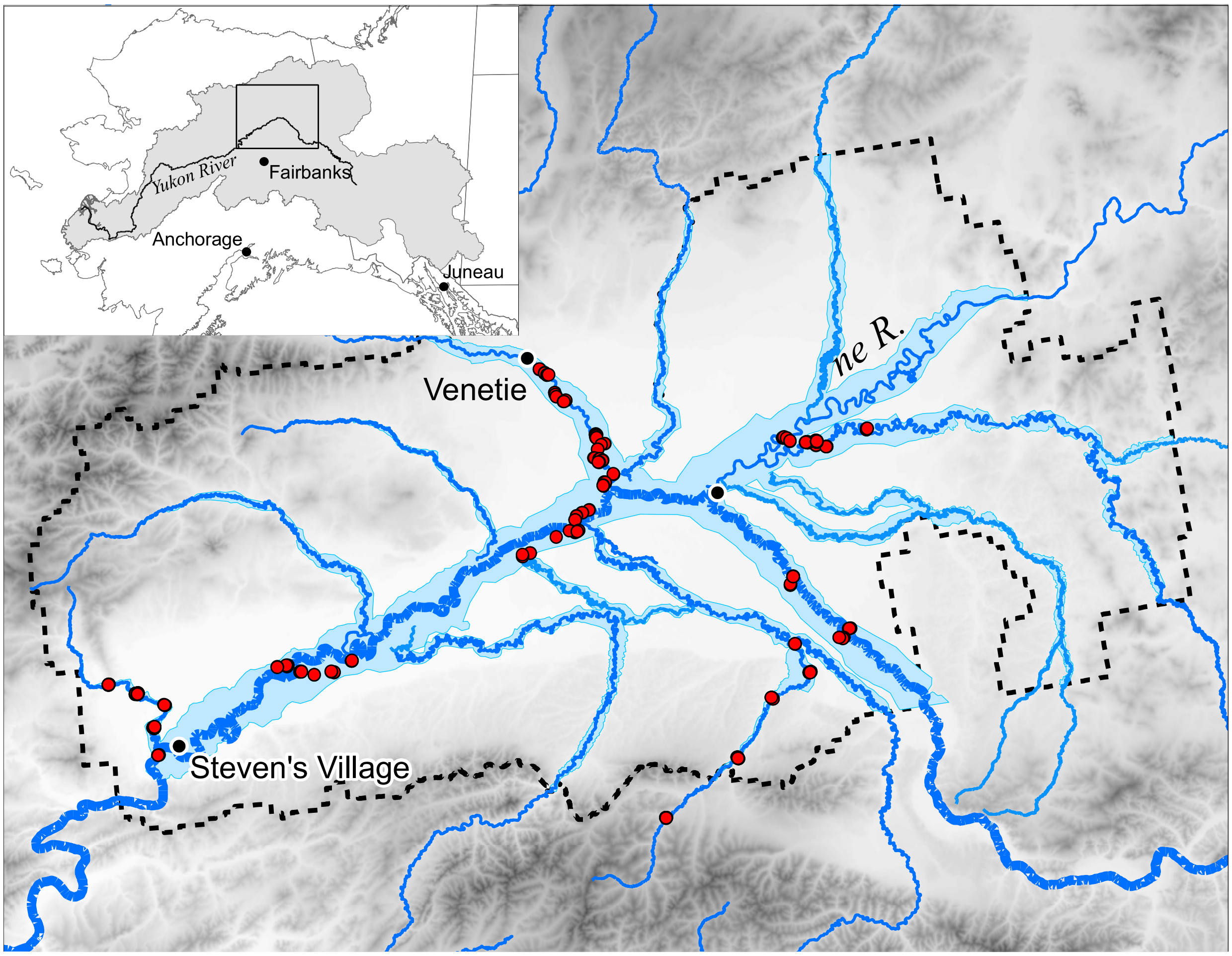

Figure 4.1. Study area, showing soil sample locations, the extent of the Yukon Flats National Wildlife Refuge, and delineated floodplain extents used for analyses in light blue bands.

We digitized the floodplain extent for each study river within furthest upstream and furthest downstream sampled locations in GIS software using aerial photography and a 2 m resolution Arctic DEM from the Polar Geospatial Center (Noh and Howat, 2015). The floodplain extent was informed by the width of meander belts, scrolls, and oxbow lakes seen within imagery, and any local topography indicating valley extent seen from the Arctic DEM. We also delineated the floodplain extent along all major rivers within the boundary of the Yukon Flats

National Wildlife Refuge (YFNWR) and below 375 m elevation, which is representative of our sampling locations, using the same methods (Figure 4.1; see Table C.3 for a list of rivers along which floodplains were delineated). There is very little relief within the central area of the Yukon Flats, preventing us from determining the floodplain extent using automated methods. We determined the area of different land cover types within each floodplain using the 2011 National Land Cover Dataset (NLCD) for Alaska (Homer et al., 2015). Land cover classes from the NLCD were collapsed into vegetation classes noted in the field (deciduous/shrub, white spruce forest, mixed forest, black spruce woody wetland, and herbaceous wetlands; Table C.4). The 2011 NLCD was not available when we began sampling in 2014, so we were unable to use the NLCD designations in our sampling design. We determined total carbon storage for each study river floodplain within the sampled extent by multiplying the average OC stock (within the top 1 m of the subsurface) of each collapsed land cover class for each river by the total area of that class. Along one study river, the Draanjik, we did not sample one vegetation class (black spruce woody wetland), so we used the average OC stock from all samples for black spruce woody wetland. We determined the standard error of our estimate of total OC stock using methods described in Text C.2 in appendix C. We then applied the average OC stock for each collapsed land cover class across all samples to the broader floodplain region within the YFNWR. We compared this estimated stock to the 1 m stock estimated with the Northern Circumpolar Soil Carbon Database (NCSCD) within the same floodplain extents (Hugelius et al., 2013).

In order to constrain floodplain residence times, we sampled large wood in cutbanks along the studied rivers for radiocarbon analysis. We chose large wood that appeared to have been deposited horizontally in the past and was currently being eroded out of cutbanks to estimate the time since deposition of the large wood, and thus floodplain sediment. At a few locations, we dated smaller pieces of organic matter. We recognize that large wood could have been stored upstream in the river network before being deposited at the sampled location, but we chose large wood instead of smaller particulate OC (POC) because smaller POC was likely transported longer distances, and large wood recruited from river banks likely has a shorter transport distance from the source. Recruitment of wood from cutbanks is a common occurrence within boreal river systems (e.g., Ott et al., 2001). Samples were sent to DirectAMS for processing, and we calibrated radiocarbon ages using OxCal software (Brook Ramsey, 2001) and the IntCal13 calibration curve (Reimer et al., 2004). In addition to constraining floodplain residence times with cutbank samples, we also dated wood pieces in sediment samples and the humin fraction (the fraction that is insoluble in water, acid, and base and less likely to be mobile) of floodplain sediment in sediment samples that we took from the core farthest from the river channel in select transects at the base of the active layer. We dated these samples to constrain the maximum age of carbon at the active layer-permafrost transition zone in the distal, and presumably oldest, floodplain surfaces.

4.3 Carbon stocks in the Yukon Flats

For the entire dataset, the mean and standard error for stocks are 137.8 ± 3.8 Mg C ha^{-1} within the active layer and 217.7 ± 8.8 Mg C ha^{-1} estimated within the top 1 m. The active layer varies in depth, with measured OC stocks ranging from 121.2 Mg C ha^{-1} in the Yukon floodplain to 171.0 Mg C ha^{-1} on the Dall River (Figure 4.2a). OC stocks within 1 m indicate that OC stocks could range from 154.9 Mg C ha^{-1} on the Teedrinjik River, along which we reached gravel/cobbles/coarse sand at many sampled locations, to 341.4 Mg C ha^{-1} on the Dall River, along which coarse grains were not reached within 1 m. Adding the >2mm fraction from the three rivers for which the data are available (Draanjik, Teedrinjik, and Yukon) increases the OC stock by an average of 21.6 to 26.5 Mg C ha^{-1} for the three rivers, which is a 15-20% increase in total OC stock (Figure 4.2). This indicates that studies that do not account for the >2mm fraction underestimate OC stock by 15-20%.

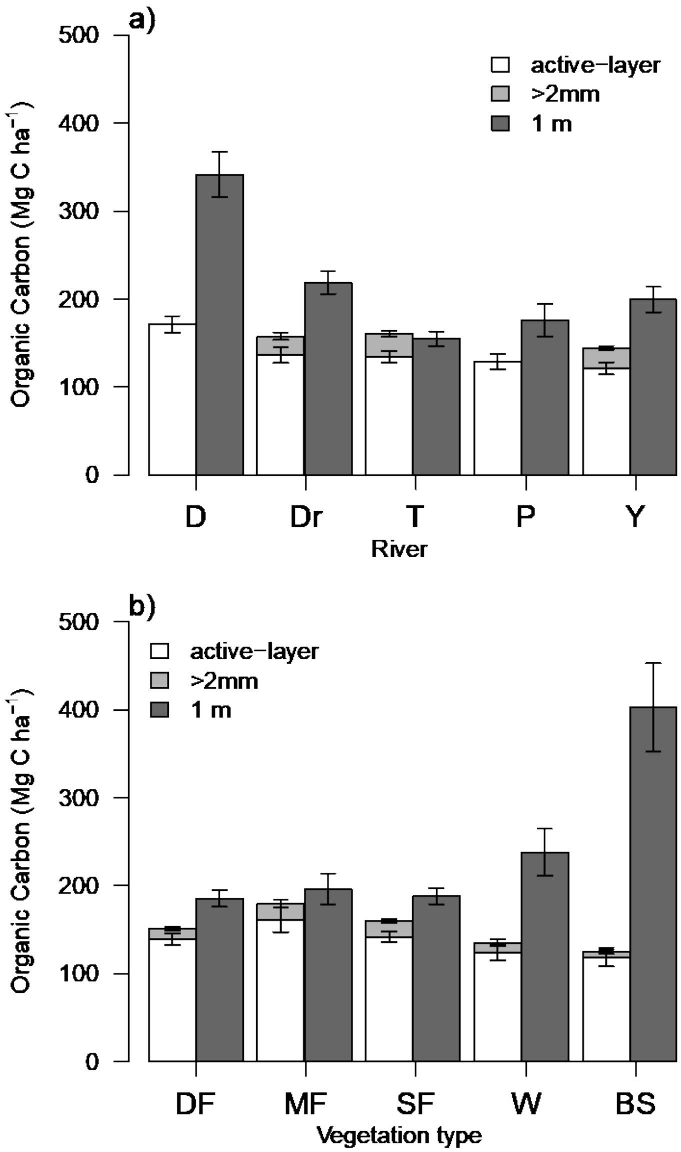

Figure 4.2. Average carbon stocks per area by river (a) and vegetation type (b), in the active layer (white bar) and extrapolated to 1 m in depth (dark grey bar). The additional stock from >2mm fraction in the active layer was estimated for three of the rivers, and is added to the active layer stocks (light grey bar). Bars show the mean ± standard error of the mean. D = Dall, Dr = Draanjik, T = Teedrinjik, P = Preacher, and Y = Yukon. DF = deciduous/shrub, MF = mixed forest, SF = white spruce forest, W = herbaceous wetland, BS = black spruce woody wetland.

Active layer OC stocks vary by vegetation type (Figure 4.2b) and geomorphic unit (Figure C.1 in appendix C), with a range of 118.7 to 161.2 Mg C ha^{-1} for mean stocks within vegetation types and 120.6 to 150.4 Mg C ha^{-1} for mean stocks within geomorphic units. The estimated mean stocks for 1 meter in depth range from 185.2 to 402.4 Mg C ha^{-1} across vegetation types and 152.8 to 393.5 Mg C ha^{-1} across geomorphic units.

Stocks within the organic layer (above the boundary of mineral sediment) comprise 11-34 % of the total stock in the active layer and 8-12% of the total stock in the top 1 m across study rivers. Organic layer depths averaged 4.2 cm for shrub/deciduous forest, 5.2 cm for mixed forests, 5.7 cm for herbaceous wetlands, 6.9 cm for white spruce forests, and 16.7 cm for black spruce woody wetlands. Summary statistics for stocks (active layer, 1 m, and organic layer) for the entire dataset and by river, geomorphic unit, and vegetation type are included in Tables C.5-C.7 in appendix C.

Comparisons of stock measurements on a per area basis across other locations is complicated by the variable depths reported in different studies, as stock estimates depend greatly on the depth of the sampled location. With that caveat, OC stock estimates for the top 1 m from diverse environments indicate that stocks in the Yukon Flats are similar to or higher than those reported for temperate and most other boreal environments (Text C.3 and Table C.8 in appendix C).

Overall, the estimate for the total amount of OC within the top 1 m in the YFNWR increases by 82.2% when comparing field (185.8 ± 8.7 Tg) to NCSCD database estimates (102.0 Tg) (Hugelius et al., 2013) (Figure 4.3). The total carbon stock increases by approximately 60-350% across individual study river floodplains when estimating stocks using field data (Figure 4.3). These field estimates do not include the >2mm fraction, which could add 15-20% to the calculated total. In contrast, previous comparisons with NCSCD have found the NCSCD may overestimate stocks in some areas (Zubrzycki et al., 2013).

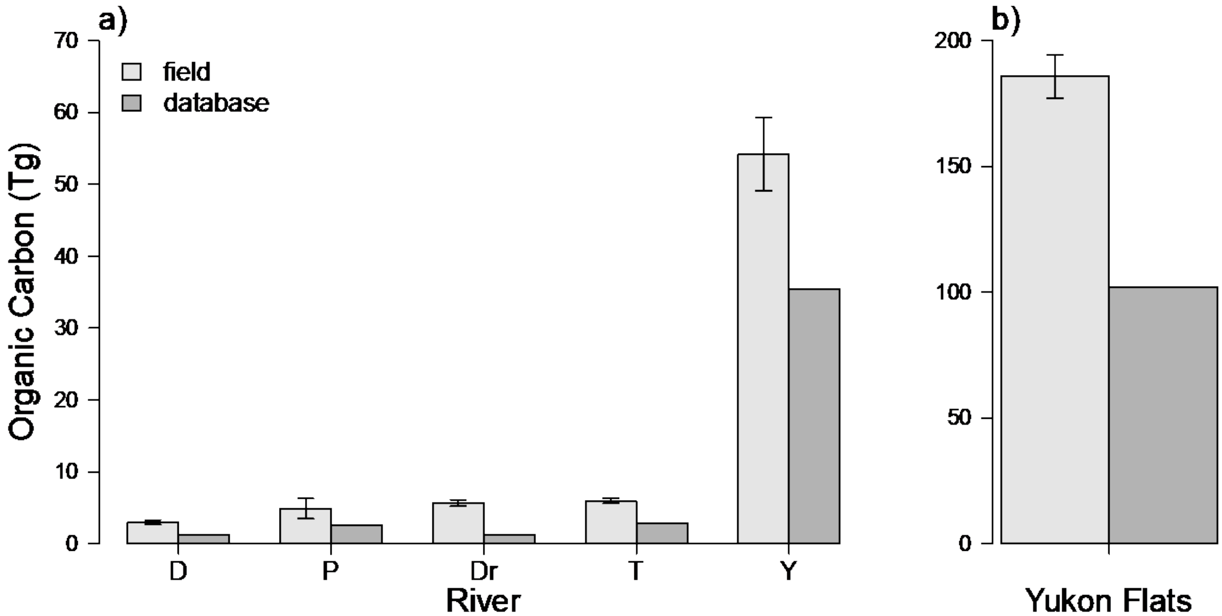

Figure 4.3. Total carbon stock in teragrams for each of the study river floodplains within the sampled extent (a) and for the YFNWR below 375 m in elevation (b). Light gray are estimates based on field measurements and dark grey are estimates using the NCSCD. Note the different scales for the axes in the two plots. D = Dall, Dr = Draanjik, T = Teedrinjik, P = Preacher, and Y = Yukon.

There is a potentially significant amount of OC stored in deeper alluvium that is difficult to quantify due to the great depth and difficulty of sampling permafrost. Samples taken horizontally into cutbanks ranged from 1 m to 4.2 m below the top of the bank, and the OC concentrations of these samples were similar to the OC concentrations of mineral sediment within the top 1 m (median = 2.1% OC from cutbanks compared to median = 2.2% OC in mineral sediment within top 1 m) (Lininger et al., 2018). Bank heights varied substantially throughout the study region, but many banks contained a gravel layer overlain by finer alluvial deposits. Because of the variability in the depth of fine alluvium across the floodplain, it is difficult to estimate stocks deeper than 1 m from cutbank samples. However, because the OC concentrations below 1 m are similar to samples within the top 1 m, stock estimates that include finer alluvium below 1 m to fluvial gravel layers at 2 or 3 m in depth would increase estimates of total floodplain OC stock by two to three times when compared to the 1 m stock estimates.

The total OC stock in the Yukon Flats floodplains (Figure 4.3) can be compared with the export of DOC and POC for the entire Yukon River Basin to put floodplain OC storage in a watershed context. The export of POC per year is 0.539 ± 0.026 Tg of OC (McClelland et al., 2016). The export of DOC per year has been estimated to be 1.472 Tg of OC (Holmes et al., 2012). Thus, approximately 2.01 Tg of OC is exported each year from the outlet in the form of DOC and POC. Alluvium within the Yukon Flats basin is deeper than 1 m, which complicates comparisons of fluxes and stocks of OC in the Yukon. However, the export of OC from the Yukon outlet each year is equivalent to 85.1 km^2 of the top 1 m of floodplain sediment, which is 1.1% of the floodplain region delineated within the YFNWR in this study. This suggests the potential for enormous increases in OC fluxes if warming climate accelerates river erosion of cutbanks and biogeochemical processes in a deepening active layer.

Erosion of banks and the floodplain contributes to the DOC and POC within the Yukon River, although the fate of this eroded carbon and whether it is mineralized and released to the atmosphere is somewhat uncertain. Evidence suggests that ancient DOC from within permafrost is rapidly mineralized and used by microbes (Spencer et al., 2015; Vonk et al., 2013), and most DOC exported from the Yukon River and tributaries such as the Draanjik (Black) is relatively young (Aiken et al., 2014). The fate of POC that enters the river network is not well-studied, but evidence from the Mackenzie River Basin indicates that POC may be efficiently buried offshore in the Arctic Ocean and suggests that POC can be preserved in marine environments (Hilton et al., 2015).

4.4 Constraining floodplain sediment and active layer carbon residence time

The results of radiocarbon dating indicate that the age of sediment deposition in the floodplain (via age of deposited large wood) ranges from modern to over 7000 calendar years before present (Figure 4.4a; Tables C.9 and C.10 provides information on all dated samples). These dates constrain the residence time of floodplain sediment, although we are not able to calculate an average floodplain residence time or half-life due to the inability to find large wood for dating across all locations and depths along the study rivers. Ages of POC along the Draanjik (Black) River have been reported as 1576 and 2585 years BP (Aiken et al., 2014), which are similar to the median ages of large wood in cutbanks along the Draanjik (Figure 4.4a). This similarity lends support to the use of large wood age as an indicator of sedimentation, as POC in transport is a similar age and may have been deposited along with large wood. In addition, POC may be sourced from degraded and broken down large wood within cutbanks.

Patterns in the ages of large wood may reflect planform characteristics, although more ages are needed to confirm potential patterns. For example, there is a relatively young maximum date (median age of 768 cal yr BP) in the upstream portions of the Teedrinjik River, which is wandering in planform (Figure 4.4a); we use the term wandering to indicate a laterally active anabranching river (Desloges and Church, 1989). The maximum date (median age of 4707 cal yr BP) in the downstream meandering portions of the Teedrinjik is older than the median age in the upstream portions by about 4,000 years. The Dall River is an incised, single-thread meandering river and has older dates than Preacher Creek, which is wandering in planform. Maximum ages from the upstream portion of the study area along the Yukon are younger (median age of 116 cal yr BP) and then become older downstream (median ages of 1233 and 7226 cal yr BP), where the Yukon displays a wandering morphology. The upstream portion has a braided planform, which

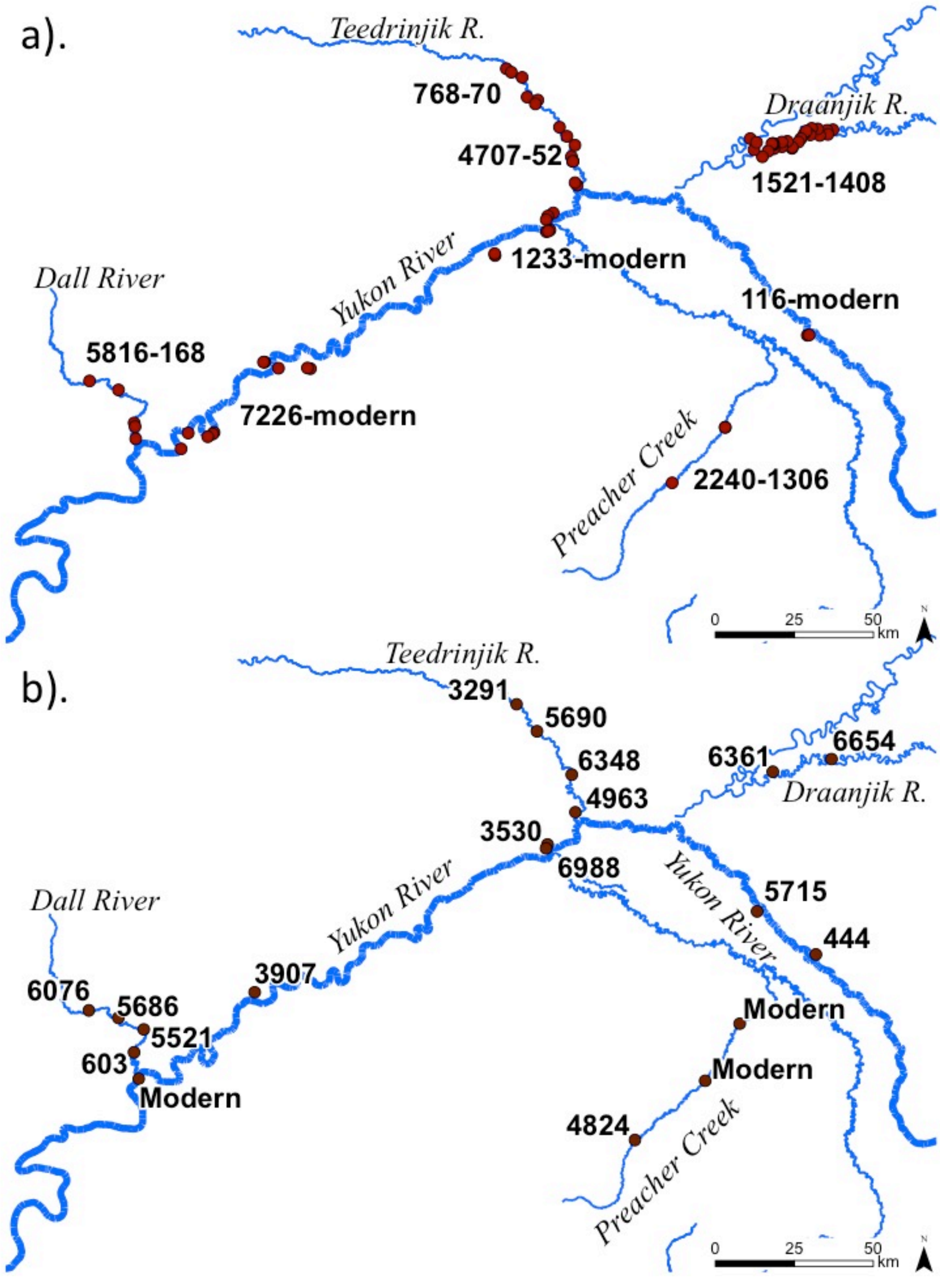

Figure 4.4. a) Range of oldest median age and youngest median age of large wood in cutbanks in each sampling block along different sections of the studied rivers, showing age in calendar years BP. b) Age of organic carbon at the base of the active layer taken from sediment samples furthest from the active channel.

transitions to a wandering morphology downstream (Clement, 1999). Braided planform can more frequently avulse and erode floodplain surfaces relative to meandering planforms (Kleinhans, 2010),although sometimes braided channels can remain relatively stable (Leopold and Wolman, 1957). However, the braided segment of the Yukon as it enters the Flats does not have a higher migration rate relative to other sections (Rowland, 2018). Migration rates peak in the transitional region between braided and wandering (up to approximately 3 m yr^{-1} when measuring all banks) (Rowland, 2018), where the oldest median age is 1233 cal yr BP. More ages from cutbanks along the Yukon are likely needed to accurately constrain floodplain residence time and link those measurements to planform characteristics.

Dating of sediment at the base of the active layer indicates that OC in the active layer-permafrost transition zone can be up to 7000 calendar years BP (Figure 4.4b). However, two modern samples along Preacher Creek and one relatively young sample in the upstream portion of the Yukon (Figure 4.4b) indicate that wandering or braided reaches may contain younger OC in the active layer, although more samples are needed to support this suggestion.

4.5 Implications

Permafrost regions are already experiencing changes in hydrology and flowpaths, permafrost degradation and warming, deepening active layers, and modified fluxes of nutrients to the Arctic Ocean (Rawlins et al., 2010; Romanovsky et al., 2013; Striegl et al., 2005; Walvoord and Kurylyk, 2016). Understanding OC storage within and the dynamics of floodplains, as transitional zones between terrestrial and aquatic ecosystems, will be integral to understanding changing flows and fluxes of sediment and nutrients. In addition, permafrost degradation will likely change many geomorphic processes, including potentially influencing rates of channel migration and mobilization of floodplain sediments into river networks. Thus, establishing accurate baseline information and understanding floodplain OC stocks is integral to accurately constraining the carbon cycle and informing future changes to riverine fluxes in permafrost regions.

Many questions remain unanswered in order to link the stocks of OC in floodplains with exports and fluxes of OC, including whether mobilized OC from floodplains gets re-deposited or buried and whether that OC is mineralized and released to the atmosphere. However, our results indicate that there is a great deal more OC in the floodplains of the Yukon Flats than previously estimated. There is no reason to think that the Yukon Flats floodplains are different than other lowland, high latitude floodplains in boreal and arctic regions (e.g., along large rivers in Siberia), indicating that floodplains may be underestimated in terms of OC stock across a large region.

Data Availability

DEMs were provided by the Polar Geospatial Center under NSF OPP awards 1043681, 1559691 and 1542736. The datasets discussed in this paper are available online at https://hdl.handle.net/10217/187212 through the Colorado State University Digital Repository. Data on delineated floodplain areas and estimated organic carbon amount within the sampled extents along the study rivers and in the Yukon Flats within the Yukon Flats National Wildlife Refuge and below 375 m elevation are included in Table C.11 in appendix C.

Chapter 5 Conclusion

As fluxes of water, sediment, nutrients, and organic carbon (OC) in soil and downed large wood (LW) move from the land to the ocean, those fluxes pass through and are stored in floodplains for varying lengths of time. As such, it is important that floodplains are recognized as distinct landscape units within which unique geomorphic processes occur (e.g., erosion, sedimentation, overbank flooding, and vegetation succession). It is particularly important to investigate floodplain OC storage and dynamics in high latitude river corridors, where permafrost is present, climate is warming, and changes in permafrost extent and depth, hydrology, and river ice may occur (Beltaos and Prowse, 2009; IPCC, 2014; Rawlins et al., 2010; Romanovsky et al., 2013).

In this dissertation, I evaluate 3 aspects of OC storage in floodplains: OC in downed LW, geomorphic controls on spatial variations in OC concentrations at differing scales, and floodplain OC stocks. Comparisons of LW loads on floodplains in semiarid boreal (Yukon Flats region), subtropical, and semiarid temperate sites indicate that the largest loads occur at the semiarid temperate site (116.3 $m^3 ha^{-1}$). I interpret this pattern as reflecting the combined effects of moderate-to-high net primary productivity, temperature-limited decomposition rate, and resulting slow wood turnover time. LW loads at the semiarid boreal site are approximately a third as large compared to semiarid temperate sites (42.3 $m^3 ha^{-1}$), disturbances such as wildfire increases LW loads at the boreal site. This is important for understanding likely trajectories of change as climate warms and fires become more frequent and widespread in boreal regions (Rupp and Springsteen, 2009). Spatial variations in OC concentrations occur at reach and river basin scales, within geomorphic factors influencing these variations. The dissolved OC concentration within river water, variations in planform, and floodplain soil moisture may influence variations in OC concentration among rivers. Grain size, soil moisture, and time since the deposition of the floodplain surface likely influence variations among geomorphic units. Greater variation in soil OC among small-scale geomorphic units compared to among river basins indicates that estimation of OC in floodplains should take a bottom-up approach, scaling up from small-scale units. Floodplain soil OC stocks are likely underestimated relative to currently available databases and floodplain sediment can be stored for long periods of time before being re-eroded by the river channel.

There are some limitations to the research presented here. For example, there are temporal components of the research that remain uncertain. Due to the difficulty of determining the time of disturbances in the three biomes with downed LW measurements (Chapter 2), I have little information on how long disturbance influences floodplain LW loads. There is no information regarding LW decay rates in the Yukon Flats region, limiting comparisons across biomes. Spatial limitations include the inability of sample soils to 1 m in depth at every sample location due to the presence of permafrost. This means that OC stocks calculated to 1 m in depth in order to make comparisons to other datasets are extrapolated and have greater uncertainty. In addition, I am unable to calculate floodplain turnover time due to the inability to sample for radiocarbon dates consistently along the river and at specific locations throughout the study region (Chapter 4). Finally, the investigations into floodplain soil OC (Chapters 3 & 4) do not account for the biogeochemical cycling of soil OC. For example, I did not investigate the bioavailability of OC to microbial respiration within my soil samples or whether the characteristics of different geomorphic units (e.g., soil moisture, grain size) influence bioavailability. Despite these limitations, the work summarized here provides important insights into processes influencing OC stocks, partitioning of OC among LW and soil, and spatial patterns of OC stock.

There is a great deal more work that could be done in the Yukon Flats region in regards to floodplain OC storage, floodplain dynamics, and other topics with the data presented in this dissertation. For example, I could use the data on radiocarbon dates presented in Chapter 4 to determine long-term floodplain sedimentation (and associated OC accumulation) rates within the Yukon Flats. Because my soil samples are within basins of varying drainage areas, resulting in floodplains of differing sizes, I could assess the ability to estimate OC stocks using landscape units determined from remote imagery of differing resolutions (e.g., Landsat, 30 m resolution; DigitalGlobe imagery, sub-decimeter imagery) on floodplains of differing scales. I could also relate metrics or assessments of floodplain physical complexity, such as the number of geomorphic units within a certain floodplain area, to floodplain soil OC storage. Using high-resolution satellite imagery from DigitalGlobe, I could estimate the amount of LW that is stored in channel-margin jams in the transition from the channel to the floodplain.

Another avenue of research that would contribute to understanding the role of rivers in the carbon cycle in high latitude systems is to better link river migration and floodplain erosion of soil OC with fluxes of particulate OC (POC) and dissolved OC (DOC). This would involve quantifying rates of bank erosion and the contributions of bank erosion to POC and DOC concentrations within river water. The results in Chapter 3 demonstrated that different geomorphic units have differing OC concentrations. Linking stocks and fluxes of OC within river corridors would have to account for processes of bank erosion and point bar deposition and link the sediment budget to the OC budget. For example, a net gain or loss of sediment resulting from bank erosion and point bar deposition at the reach scale might not equate to an analogous net gain or loss of OC because of differences in OC concentration among geomorphic units (e.g., bars vs. other geomorphic units that may be eroded from banks). Finally, the Yukon Flats is a region with discontinuous permafrost, and may be particularly sensitive to permafrost degradation and thaw with anthropogenic warming. The effects of climate change on geomorphic processes and floodplain OC storage are uncertain, but data from this dissertation could be used to inform attempts to conceptualize or model changes in floodplain OC due to climate change.

Going beyond the Yukon Flats region, more work is needed to investigate the role of rivers corridors in the carbon cycle. There are very few studies of floodplain soil OC storage outside of temperate regions, for example. As discussed above, linking OC stocks within river corridors to OC fluxes from rivers will help integrate river corridors into the carbon cycle and account for transient storage in floodplains. Fully linking stocks and fluxes of OC will necessitate collaborations between biogeochemists and geomorphologists, as carbon is transported and deposited but also respired and transformed by organisms. In addition, the influence of human alterations of river corridors on OC storage has not been adequately explored, although a few studies do exist (e.g., Hanberry et al., 2015). In high latitude permafrost regions, the impacts of hydrologic and geomorphic changes due to warming and permafrost degradation and thaw will modify channel and floodplain processes, affecting OC stocks within floodplains and fluxes of OC to the Arctic Ocean. In order to understand future changes in floodplain OC stocks and floodplain dynamics under a warming climate, more work linking geomorphic and OC dynamics is needed.

In summary, there remains much work to be done to quantitatively describe the geomorphic controls on OC in floodplains over varying timescales and the manner in which warming climate will affect these processes and rates of carbon dynamics. The research presented in this dissertation clearly indicates the vital importance of this continuing work by demonstrating that high latitude floodplains can store significant quantities of OC and that geomorphic processes influence the spatial distribution of OC on the landscape.

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Appendix A: Supplemental information for Chapter 2: Floodplain downed wood volumes: a comparison across three biomes

In 3 out of 5 study rivers in Alaska (the Yukon River, the Dall River, and the Black River), only the diameter that was the best representation of a downed log as a cylinder (off-tape diameter) was recorded in the field along transect lines. The line-intersect method relies on measuring the diameter of the wood piece along the transect itself (i.e., the tape diameter), and not the off-tape diameter of the wood piece. For 2 rivers in Alaska (the Chandalar River and Preacher Creek), both the off-tape and the tape diameter of the wood piece were recorded. Thus, we used a log transformed regression model (to satisfy the requirements of a linear regression model) with a forced zero intercept to determine the relationship between the LW volume estimated using off-tape diameter in the line-intersect equation and the LW volume estimated using the tape diameter in the line-intersect equation for data from these two rivers. The R^2 value for the relationship between untransformed LW volume using off-tape diameter and LW volume using tape diameter is 0.94, indicating a strong relationship between the two ways of using the line-intersect equation (Figure A.1).

The regression model for wood volume using off-tape diameter predicted by wood volume via tape diameter has an R^2 value of 0.99 (p<2.23-16), and a slope parameter of 1.07237. We then inverted and back-transformed the regression equation to calculate a wood volume via tape diameter for the rivers in which only off-tape diameter measurements are available.

The regression equation is:

$$log(Wood\ volume\ via\ offtape\ diameter + 1)$$
$$= 1.07237(\log(Wood\ volume\ via\ tape\ diameter + 1))$$

The inverted and back-transformed regression equation used to calculate wood volumes for rivers in which only off-tape diameter was available is:

$$Wood\ volume\ via\ tape\ diameter = e^{\left(\left(\frac{\log(Wood\ volume\ via\ off tape\ diameter+1)}{1.07237}\right)\right)} - 1$$

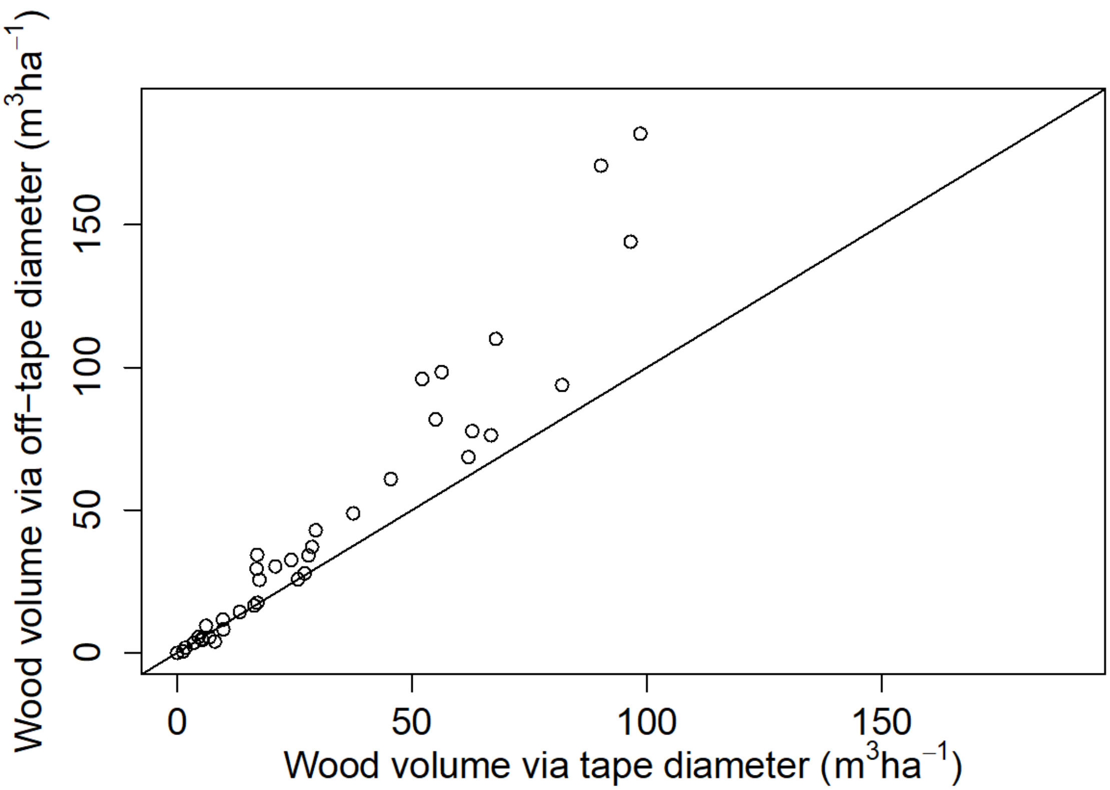

Figure A.1. Wood load calculated using the off-tape diameter of the downed wood vs. wood load calculated using the tape diameter of the downed wood for 2 of the 5 study rivers in Alaska. The line in the plot is the 1:1 line.

Table A.1. Dataset used for analyses in chapter 2, showing measurements in each biome.

Biome	**Large wood load ($m^3 ha^{-1}$)**	**Organic carbon in wood (Mg ha^{-1})**	**Average DBH (cm)**	**Average piece length (cm)**	**Basal area ($m^2 ha^{-1}$)**
subtropical lowlands	54.3	14.4	20.1	257.7	19.6
subtropical lowlands	54.9	14.6	17.7	377.1	23.2
subtropical lowlands	71.2	18.9	21.3	432.2	26.3
subtropical lowlands	3.5	0.9	11.7	240.0	32.6
subtropical lowlands	42.1	11.1	19.4	342.5	24.8
subtropical lowlands	21.1	5.6	19.0	293.9	23.6
subtropical lowlands	18.7	5.0	13.4	483.0	30.4
subtropical lowlands	72.7	19.3	30.5	358.6	51.8
subtropical lowlands	45.2	12.0	19.8	271.4	31.5
subtropical lowlands	111.2	29.5	22.0	374.8	22.5
subtropical lowlands	23.3	6.2	22.4	335.0	20.3
subtropical lowlands	107.2	28.4	23.6	477.1	28.1
subtropical lowlands	75.0	19.9	24.8	306.3	31.5
subtropical lowlands	7.1	1.9	14.9	202.1	50.0
subtropical lowlands	43.1	11.4	31.7	301.3	50.2
subtropical lowlands	41.6	11.0	16.5	305.9	55.6
subtropical lowlands	33.9	9.0	22.7	394.7	36.7
subtropical lowlands	12.5	3.3	14.6	184.5	23.6
subtropical lowlands	84.4	22.4	19.0	424.8	30.4
subtropical lowlands	80.2	21.3	21.2	272.0	32.6
subtropical	23.6	6.2	19.4	338.9	29.3

lowlands					
subtropical lowlands	91.4	24.2	21.9	423.7	37.1
subtropical lowlands	108.6	28.8	24.0	349.1	28.1
subtropical lowlands	29.8	7.9	19.2	343.0	38.3
subtropical lowlands	62.5	16.6	18.5	387.0	30.4
subtropical lowlands	49.8	13.2	21.1	347.0	29.3
subtropical lowlands	56.4	15.0	25.1	349.3	10.1
subtropical lowlands	23.5	6.2	19.5	364.7	47.3
subtropical lowlands	58.5	15.5	20.6	476.7	45.0
subtropical lowlands	42.3	11.2	20.1	214.0	16.9
subtropical lowlands	15.0	4.0	17.2	292.4	39.4
subtropical lowlands	39.0	10.3	22.9	266.1	52.9
subtropical lowlands	55.9	14.8	24.6	370.8	63.0
subtropical lowlands	54.3	14.4	28.7	420.0	38.3
semi-arid mountains-subalpine	70.4	14.1	16.0	268.1	NA
semi-arid mountains-subalpine	22.8	4.6	45.0	1200.0	NA
semi-arid mountains-subalpine	227.5	45.5	31.5	476.8	NA
semi-arid mountains-subalpine	106.9	21.4	26.3	486.0	NA
semi-arid mountains-subalpine	23.5	4.7	21.8	312.5	NA
semi-arid mountains-subalpine	33.4	6.7	25.5	504.3	NA

semi-arid mountains-subalpine	39.7	7.9	29.8	578.5	NA
semi-arid mountains-subalpine	2.9	0.6	17.6	283.0	NA
semi-arid mountains-montane	182.4	36.5	27.3	747.7	NA
semi-arid mountains-subalpine	73.4	14.7	22.6	504.3	NA
semi-arid mountains-montane	19.0	3.8	16.4	296.3	NA
semi-arid mountains-subalpine	210.0	42.0	28.7	634.6	NA
semi-arid mountains-montane	57.7	11.5	28.9	731.7	NA
semi-arid mountains-montane	13.3	2.7	17.3	429.3	NA
semi-arid mountains-subalpine	41.5	8.3	22.1	659.6	NA
semi-arid mountains-subalpine	267.0	53.4	29.6	735.8	16.8
semi-arid mountains-subalpine	308.6	61.7	25.0	317.9	17.6
semi-arid mountains-subalpine	199.6	39.9	26.9	601.1	45.9
semi-arid mountains-subalpine	277.7	55.5	23.5	565.2	26.8
semi-arid mountains-subalpine	138.8	27.8	32.5	602.4	49.7
semi-arid mountains-subalpine	5.0	1.0	20.3	345.8	NA
semi-arid	211.2	42.2	26.5	570.3	52.0

mountains-subalpine					
semi-arid mountains-subalpine	35.4	7.1	22.8	588.4	34.4
semi-arid mountains-subalpine	0.0	0.0			0.0
semi-arid mountains-subalpine	126.4	25.3	20.9	331.7	20.0
semi-arid mountains-subalpine	328.8	65.8	22.7	418.5	39.0
semi-arid mountains-subalpine	0.0	0.0			0.0
semi-arid mountains-subalpine	315.4	63.1	26.7	461.5	41.0
semi-arid mountains-subalpine	184.4	36.9	21.5	243.3	23.0
semi-arid mountains-subalpine	33.9	6.8	21.7	313.9	18.0
semi-arid mountains-montane	171.2	34.2	NA	NA	NA
semi-arid mountains-montane	23.5	4.7	NA	NA	NA
semi-arid mountains-montane	95.6	19.1	NA	NA	NA
semi-arid mountains-montane	151.2	30.2	NA	NA	NA
semi-arid mountains-montane	89.4	17.9	NA	NA	NA
semi-arid mountains-montane	288.1	57.6	NA	NA	NA
semi-arid mountains-	6.2	1.2	NA	NA	NA

montane					
semi-arid mountains-montane	95.6	19.1	NA	NA	NA
semi-arid mountains-montane	98.7	19.7	NA	NA	NA
semi-arid mountains-montane	74.4	14.9	NA	NA	NA
boreal lowlands	8.1	1.6	13.8	355.0	4.6
boreal lowlands	4.7	0.9	21.0	260.0	10.3
boreal lowlands	0.0	0.0			0.0
boreal lowlands	13.7	2.7	14.7	655.0	8.0
boreal lowlands	27.1	5.4	16.9	411.4	10.3
boreal lowlands	0.0	0.0			0.0
boreal lowlands	17.1	3.4	12.0	266.7	21.8
boreal lowlands	62.0	12.4	16.9	666.7	14.9
boreal lowlands	4.6	0.9	15.0	435.0	2.3
boreal lowlands	28.0	5.6	14.3	338.3	14.9
boreal lowlands	5.4	1.1	13.5	303.3	6.9
boreal lowlands	0.0	0.0	NA	NA	0.0
boreal lowlands	9.8	2.0	12.8	187.5	9.2
boreal lowlands	8.0	1.6	9.0	100.0	16.1
boreal lowlands	96.5	19.3	18.7	941.6	24.1
boreal lowlands	6.2	1.2	19.0	600.0	0.0
boreal lowlands	37.5	7.5	13.4	619.1	28.7
boreal lowlands	24.3	4.9	14.5	783.3	18.4

boreal lowlands	1.2	0.2	6.0	40.0	6.9
boreal lowlands	66.8	13.4	15.3	514.0	13.8
boreal lowlands	0.0	0.0	NA	NA	5.7
boreal lowlands	13.4	2.7	13.8	273.3	6.9
boreal lowlands	55.0	11.0	20.2	746.7	11.5
boreal lowlands	0.0	0.0	NA	NA	0.0
boreal lowlands	0.0	0.0	NA	NA	0.0
boreal lowlands	3.6	0.7	17.0	190.0	0.0
boreal lowlands	20.9	4.2	16.9	761.3	12.6
boreal lowlands	16.4	3.3	13.6	235.7	2.3
boreal lowlands	25.7	5.1	14.3	367.8	6.9
boreal lowlands	1.8	0.4	12.0	130.0	6.9
boreal lowlands	1.8	0.4	12.0	130.0	0.0
boreal lowlands	29.5	5.9	16.6	705.8	11.5
boreal lowlands	28.7	5.7	16.1	701.8	27.5
boreal lowlands	0.0	0.0	NA	NA	12.6
boreal lowlands	0.0	0.0	NA	NA	6.9
boreal lowlands	0.0	0.0	NA	NA	0.0
boreal lowlands	0.0	0.0	NA	NA	3.4
boreal lowlands	17.0	3.4	14.8	430.0	16.1
boreal lowlands	52.2	10.4	20.5	661.3	0.0
boreal lowlands	81.9	16.4	15.1	538.0	4.6
boreal lowlands	62.8	12.6	16.9	789.5	23.0

boreal lowlands	98.6	19.7	21.1	890.0	28.7
boreal lowlands	5.2	1.0	14.0	470.0	5.7
boreal lowlands	90.2	18.0	26.2	1545.2	21.1
boreal lowlands	16.9	3.4	20.4	890.6	7.9
boreal lowlands	6.9	1.4	14.3	341.7	4.6
boreal lowlands	67.9	13.6	23.0	1464.0	2.3
boreal lowlands	45.5	9.1	17.1	740.7	5.8
boreal lowlands	56.3	11.3	19.8	875.5	3.8
boreal lowlands	17.5	3.5	16.4	888.6	0.0
boreal lowlands	9.7	1.9	13.3	941.1	7.1
boreal lowlands	52.7	10.5	20.7	674.1	6.5
boreal lowlands	310.7	62.1	19.3	893.9	0.0
boreal lowlands	15.0	3.0	18.3	738.8	2.7
boreal lowlands	46.8	9.4	16.9	684.6	0.0
boreal lowlands	44.1	8.8	15.9	468.1	1.5
boreal lowlands	122.9	24.6	17.8	551.6	3.4
boreal lowlands	43.3	8.7	18.1	351.2	3.4
boreal lowlands	13.9	2.8	16.6	478.9	2.5
boreal lowlands	13.9	2.8	15.6	564.4	3.3
boreal lowlands	14.5	2.9	15.0	290.0	1.5
boreal lowlands	18.2	3.6	10.7	406.9	8.0
boreal lowlands	53.4	10.7	16.7	599.4	11.5
boreal lowlands	96.7	19.3	19.5	818.8	10.3

boreal lowlands	5.8	1.2	16.5	490.0	3.4
boreal lowlands	36.3	7.3	21.6	471.4	1.1
boreal lowlands	2.7	0.5	11.0	505.0	0.0
boreal lowlands	42.7	8.5	13.0	374.0	0.0
boreal lowlands	26.5	5.3	12.6	251.3	3.4
boreal lowlands	62.6	12.5	14.7	442.9	23.0
boreal lowlands	35.5	7.1	12.5	317.3	5.7
boreal lowlands	106.5	21.3	19.6	862.9	17.2
boreal lowlands	46.9	9.4	13.5	315.2	2.3
boreal lowlands	120.4	24.1	16.6	473.1	5.7
boreal lowlands	149.4	29.9	18.5	630.3	6.9
boreal lowlands	204.8	41.0	16.8	736.3	12.6
boreal lowlands	1.1	0.2	10.0	370.0	19.5
boreal lowlands	15.8	3.2	11.9	244.5	10.3
boreal lowlands	0.0	0.0		NA	0.0
boreal lowlands	155.9	31.2	20.4	917.9	5.7
boreal lowlands	16.3	3.3	14.7	302.9	10.3
boreal lowlands	67.9	13.6	14.9	507.1	12.6
boreal lowlands	105.9	21.2	14.9	494.7	4.6
boreal lowlands	75.0	15.0	12.8	615.0	11.5
boreal lowlands	18.5	3.7	18.0	742.0	6.9
boreal lowlands	6.0	1.2	24.0	820.0	0.0
boreal lowlands	27.6	5.5	11.3	469.5	6.9

boreal lowlands	31.7	6.3	13.6	467.5	0.0
boreal lowlands	50.5	10.1	14.6	610.0	3.4
boreal lowlands	70.3	14.1	13.8	380.8	5.7
boreal lowlands	29.1	5.8	15.1	425.8	9.2
boreal lowlands	35.0	7.0	16.0	435.0	NA
boreal lowlands	201.0	40.2	15.9	957.7	2.3
boreal lowlands	16.7	3.3	14.0	638.8	25.3
boreal lowlands	45.8	9.2	13.3	395.0	1.1
boreal lowlands	28.6	5.7	13.7	301.3	12.6
boreal lowlands	0.0	0.0	NA	NA	0.0
boreal lowlands	126.2	25.2	12.9	396.7	1.1
boreal lowlands	24.6	4.9	11.7	573.9	6.9
boreal lowlands	46.2	9.2	12.8	397.5	0.0
boreal lowlands	142.9	28.6	15.8	989.3	16.1
boreal lowlands	167.8	33.6	17.8	964.7	0.0
boreal lowlands	108.4	21.7	17.6	916.1	17.2
boreal lowlands	17.7	3.5	12.4	306.4	2.3
boreal lowlands	9.1	1.8	12.0	285.0	0.0
boreal lowlands	6.5	1.3	12.3	622.5	13.8
boreal lowlands	13.1	2.6	10.4	327.5	3.4
boreal lowlands	3.5	0.7	12.5	235.0	8.0
boreal lowlands	37.7	7.5	12.4	582.8	1.1
boreal lowlands	10.8	2.2	10.3	330.0	0.0

boreal lowlands	0.0	0.0	NA	NA	0.0
boreal lowlands	19.5	3.9	11.3	310.0	18.4
boreal lowlands	20.5	4.1	11.0	321.2	9.2
boreal lowlands	18.5	3.7	12.3	464.2	3.4
boreal lowlands	47.2	9.4	12.6	358.3	3.4
boreal lowlands	0.0	0.0	NA	NA	0.0
boreal lowlands	74.8	15.0	12.5	372.2	1.1
boreal lowlands	58.1	11.6	14.1	759.0	16.1
boreal lowlands	34.8	7.0	12.3	402.2	0.0
boreal lowlands	57.4	11.5	12.6	525.1	3.4
boreal lowlands	131.7	26.3	16.4	1000.4	13.8
boreal lowlands	48.7	9.7	12.9	659.0	0.0

Appendix B: Supplemental information for Chapter 3: Geomorphic Controls on Floodplain Soil Organic Carbon in the Yukon Flats, Interior Alaska, From Reach to River Basin Scales

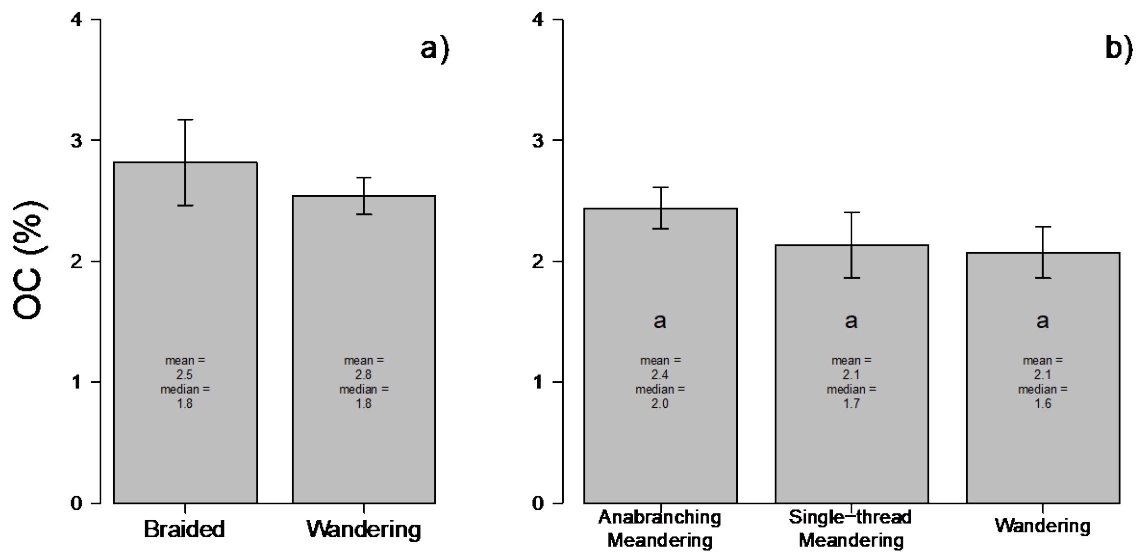

Figure B.1. OC concentration among planform types on the Yukon River (a) and Teedrinjik River (b) with letters showing no statistical difference among planforms at α = 0.05 (letters are the same for all bars, indicating no significant differences). Lack of letters in bars for Yukon plot indicates that significant differences exist only in bar and wetland geomorphic units. Bars show the mean ± the standard error.

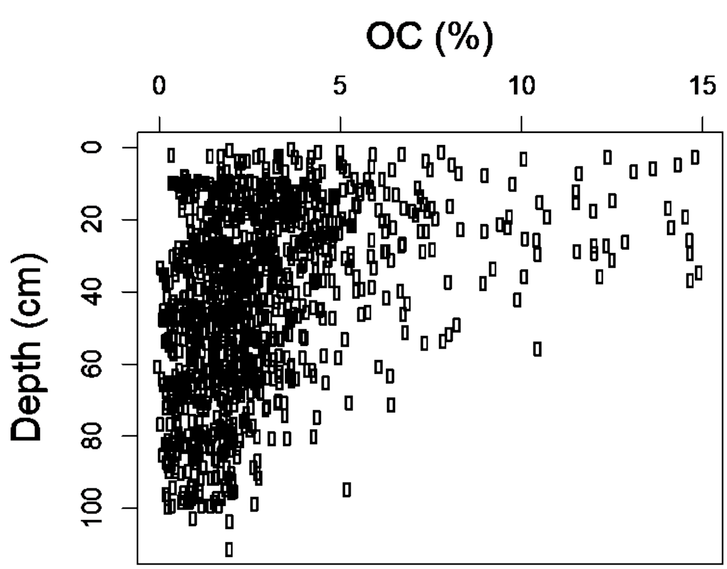

Figure B.2. The middle depth of each sample (cm) vs. OC concentration (%) for all samples, demonstrating that OC generally decreases with depth.

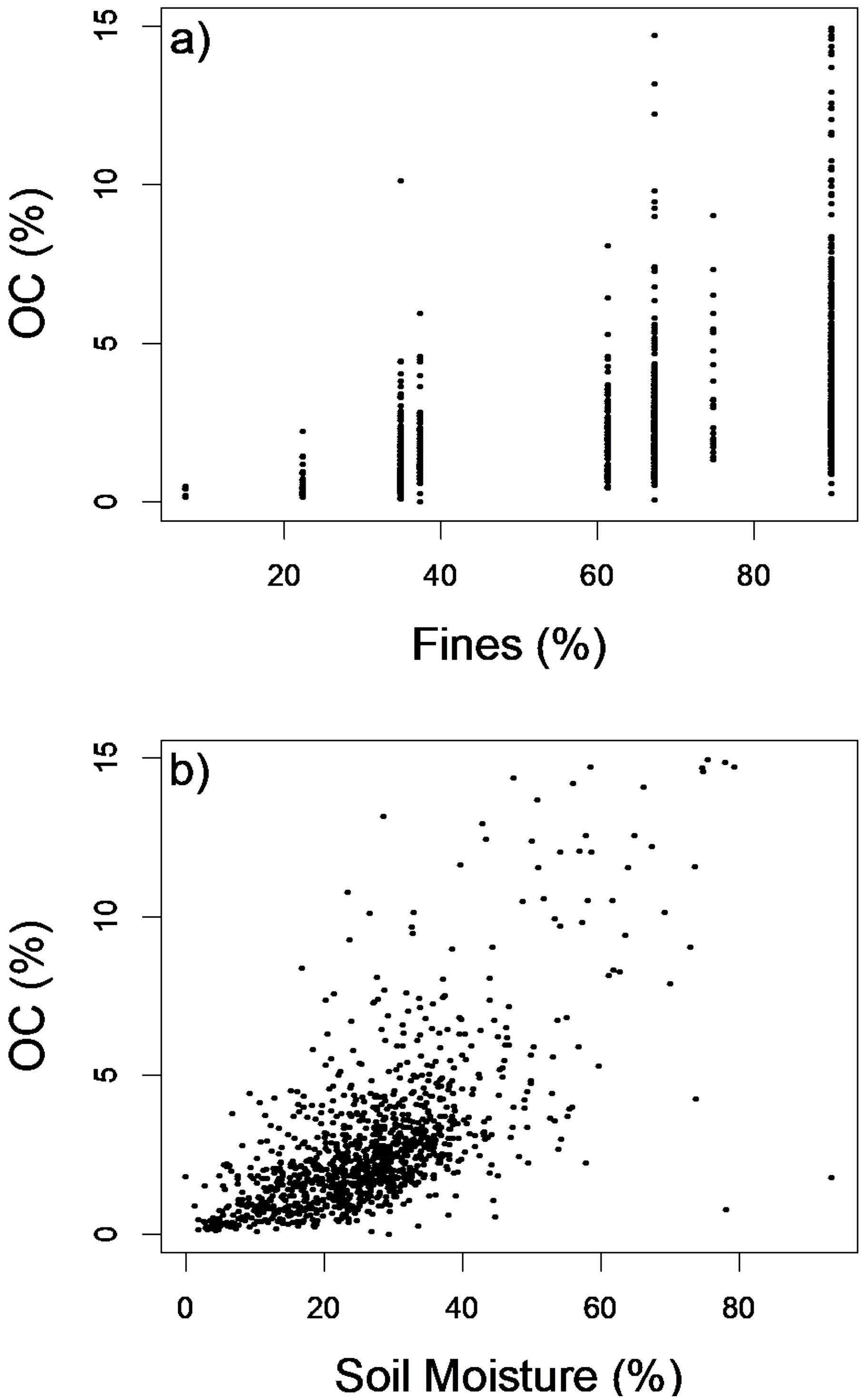

Figure B.3. OC concentration (%) vs. % fines (silt + clay) (a) and soil moisture (%) (b).

Table B.1. The number of sampled locations within each geomorphic unit by river basin.

Geomorphic unit	River				
	Dall	Draanjik	Yukon	Preacher	Teedrinjik
Bar	11	3	11	12	10
Fill	7	14	27	13	19
Floodplain	27	24	30	34	24
Wetland	17	2	6	6	6

Table B.2. Summary of overlap in vegetation and geomorphic units of sampled locations.

Geomorphic unit	Vegetation type				
	Black Spruce	Deciduous/Shrub	Mixed Forest	White Spruce	Wetland
Bar	0	45	2	0	0
Fill	0	33	5	0	42
Floodplain	0	23	30	90	0
Wetland	27	2	0	0	8

Table B.3. Summary statistics for OC%, % fines, and % soil moisture of entire dataset

	OC (%)	Fines (%)	Soil moisture (%)
n	1082	1078	1082
Minimum	0.01	7.5	0.11
Maximum	14.96	90	93.42
Median	2.22	67.5	26.01
Mean	2.84	66.88	26.59
Standard deviation	2.43	22.92	12.64
Standard error of the mean	0.07	0.70	0.38

Table B.4. Summary statistics for the maximum depths reached at sampled locations for the entire dataset and by river and geomorphic unit.

	Min (cm)	Max (cm)	Median (cm)	Mean (cm)	Standard deviation (cm)	Standard error of the mean (cm)
All sampled locations	4	118	67	66.63	26.31	1.50
By river						
Dall River	14	118	53.00	57.92	27.62	3.43
Draanjik River	22	100	56.00	60.54	19.30	2.94
Yukon River	20	108	67.00	67.51	25.54	2.97
Preacher Creek	4	110	57.00	59.35	29.23	3.60
Teedrinjik River	30	107	88.00	82.90	20.61	2.60
By geomorphic unit						
Wetland	14	105	36.00	42.96	22.76	3.47
Floodplain	4	110	68.50	69.32	22.39	1.88
Fill	15	108	66.00	64.89	28.87	3.23
Bar	4	118	84.00	78.71	25.95	3.83

Table B.5. Model summary for OC (%) for planform analyses for the Teedrinjik River

	p value (*F* statistic) [coefficient]
Planform	0.29702 (1.6)
Geomorphic unit	0.05056 (2.9)
Planform x Geomorphic unit	0.3589 (1.1)
Middle depth of sample (cm)	<0.0001 (63.0) [-0.01354]
Distance from channel (m)	0.55279 (0.4) [-0.00039]

Table B.6. Model summary for OC (%) for planform analyses for the Yukon River.

	p value (*F* statistic) [coefficient]
Planform	0.44275 (0.6)
Geomorphic unit	<0.0001 (10.0)
Planform x Geomorphic unit	0.03327 (3.2)
Middle depth of sample (cm)	<0.0001 (90.7) [-0.01208]
Distance from channel (m)	0.27111 (1.2) [.0007215]

Table B.7. Model summary for response variables OC (%), fines (%), and soil moisture (%) for entire dataset. Table shows *p* value (*F* statistic) [coefficient β; effect of a unit increase in the predictor on the response]. Bolded values are statistically significant at alpha = 0.05. The response variables OC (%) and soil moisture (%) were log-transformed to meet model assumptions.

	OC (%)	Fines (%)	Soil moisture (%)
River	**0.003 (5.3)**	0.065 (2.6)	**0.023 (3.4)**
Geomorphic unit	**<0.0001 (11.2)**	**<0.0001 (22.7)**	**<0.0001 (22.3)**
River x Geomorphic unit	0.137 (1.5)	**0.005 (2.4)**	0.466 (1.0)
Middle depth of sample (cm)	**<0.0001 (301.7) [-0.0135]**	**<0.0001 (84.3) [-0.185]**	**<0.0001 (55.4) [-0.0037]**
Distance from channel (m)	0.278 (1.2) [-0.0003]	0.643 (0.2) [-0.004]	0.559 (0.4) [-0.00014]

Table B.8. Summary statistics for OC%, % fines, and % soil moisture by river

River		OC (%)	Fines (%)	Soil moisture (%)
Dall (n = 188)	Minimum	0.40	35.00	7.76
	Maximum	14.90	90.00	93.42
	Median	2.93	67.50	30.27
	Mean	3.78	67.05	32.24
	Standard deviation	2.83	21.67	12.56
	Standard error of the mean	0.21	1.58	0.92
Draanjik (n = 146)	Minimum	0.15	7.50	1.50
	Maximum	12.40	90.00	73.78
	Median	3.02	90.00	28.76
	Mean	3.42	80.84	28.00
	Standard deviation	2.12	18.39	12.08
	Standard error of the mean	0.18	1.53	1.00
Yukon (n = 276)	Minimum	0.17	35.00	2.89
	Maximum	14.72	90.00	74.77
	Median	1.80	67.50	25.02
	Mean	2.62	69.75	25.76
	Standard deviation	2.48	18.89	11.01
	Standard error of the mean	0.15	1.14	0.66
Preacher (n = 191)	Minimum	0.15	7.50	0.11
	Maximum	14.96	90.00	75.66
	Median	2.17	61.50	24.08
	Mean	2.63	54.15	25.23
	Standard deviation	2.34	25.62	13.72
	Standard error of the mean	0.17	1.87	0.99
Teedrinjik (n = 281)	Minimum	0.01	22.50	4.13
	Maximum	12.93	90.00	78.23
	Median	1.79	67.50	23.88
	Mean	2.25	65.28	23.83
	Standard deviation	2.02	22.88	12.54
	Standard error of the mean	0.12	1.37	0.75

Table B.9. Summary statistics for OC%, % fines, and % soil moisture by geomorphic unit

Geomorphic unit		OC (%)	Fines (%)	Soil moisture (%)
Wetland (n = 78)	Minimum	0.37	35.00	0.11
	Maximum	14.96	90.00	79.49
	Median	3.58	90.00	32.17
	Mean	5.11	78.44	38.08
	Standard deviation	4.39	17.62	17.79
	Standard error of the mean	0.50	2.00	2.01
Floodplain (n = 534)	Minimum	0.13	7.50	1.50
	Maximum	14.38	90.00	93.42
	Median	2.35	67.50	23.67
	Mean	2.84	64.36	23.73
	Standard deviation	2.13	22.90	11.07
	Standard error of the mean	0.09	0.99	0.48
Fill (n = 276)	Minimum	0.01	7.50	8.29
	Maximum	14.86	90.00	78.19
	Median	2.21	90.00	30.93
	Mean	2.75	77.65	32.86
	Standard deviation	2.20	17.56	11.24
	Standard error of the mean	0.13	1.06	0.67
Bar (n = 194)	Minimum	0.09	7.50	3.10
	Maximum	13.70	90.00	51.00
	Median	1.72	37.50	20.97
	Mean	2.03	53.85	20.94
	Standard deviation	1.77	22.88	9.27
	Standard error of the mean	0.13	1.65	0.67

Appendix C: Supplemental information for Chapter 4: Significant floodplain soil organic carbon along a large high-latitude river and its tributaries

Text C.1. Description of methods to determine OC stock

The Soil, Water, and Plant testing lab at Colorado State University conducted analyses of carbon concentration in the <2mm fraction for all mineral samples with a LECO TruSpec CN furnace (Nelson and Sommers, 1982), adjusting for inorganic carbon content through measuring CO_2 loss gravimetrically (Soil Survey Laboratory, 1996) to obtain organic carbon (OC) concentration (%).To determine OC concentration for organic layer (OL) samples, we used loss-on-ignition and a conversion factor of 0.58 (De Vos et al., 2005) to convert organic matter lost after burning for 15 hours at 550 degrees C to OC. Bulk density of each OL sample was determined through volume measurements in the field during sampling and the dry weight of each OL sample. Bulk density of 2015 mineral samples, for which a soil corer was used, was found via drying the <2mm fraction of mineral samples for 24 hours at 105 degrees C. We determined soil texture classes for each mineral sample following USDA Natural Resources Conservation Service guidelines (Thein, 1979). An average bulk density for each texture class was found for the 2015 samples and was applied was to the 2014 samples taken with an auger by texture class. To convert OC concentration (%) to OC stock (Mg C ha^{-1}), we used the following equation: $OC * Bulk\ density * Depth\ of\ sample\ increment * 100$, where OC is a proportion, bulk density is in g cm^{-3}, the depth of each sample increment is in cm, and 100 is a conversion factor to obtain stock in Mg C ha^{-1}. We summed the OC stock for each depth increment to determine an OC stock per area at each sampled location for the active layer.

To extrapolate the estimated stock to 1 m in depth if 1 m was not reached due to frozen ground or saturation, we used OC concentration value (%) and bulk density measurement for the deepest sampling increment and calculated a stock to a depth of 1 m. We did not extrapolate to 1 m if sampled depth did not reach 1 m due to gravel/cobbles/coarse sand.

To obtain OC stock in the >2 mm fraction for samples from 2015, we dried the >2mm fraction for 24 hours at 105 degrees C and determining the dried mass of the organic pieces in the >2 mm fraction. We then used a conversion factor of 0.58 (De Vos et al., 2005) to convert the mass of the organics into OC mass. This OC mass was divided by the volume of the corer (cm^3) and multiplied by the depth increment of the sample to determine OC stock per unit area of the >2 mm fraction.

Text C.2. Calculation of standard error for total OC stock in floodplains

In order to determine the standard error for the estimate of the total stock across the entire floodplain for floodplains within the sampled extent on the study rivers and across the Yukon Flats floodplains, we used the equation in Appling et al. (2014): $SE(OC_{tot}) = [\sum A_v^2 \, SE(OC_v)^2]^{1/2}$, where OC_{tot} is the total OC stock in the floodplain, A_v is the area covered by land cover type v, and $SE(OC_v)$ is the standard error of the mean OC stock per area for land cover type v. Because we did not sample in black spruce woody wetland on the Draanjik River, we applied the highest standard error from all of the study rivers for black spruce woody wetland, which was from Preacher Creek, as the standard error for black spruce woody wetland on the Draanjik River.

Text C.3. Comparison of OC stock in the Yukon Flats to different environments

Table C.7 provides stocks within the top 1 m in different environments, unless otherwise noted. The mean stock estimated in for the Yukon Flats in the top 1 m of soil is 217.7 Mg C ha^{-1}, which is higher than stocks within the top 1 m in a floodplain in western Montana and floodplains in tropical dry floodplains in Mexico (Appling et al., 2014; Jaramillo et al., 2003). Estimated stocks within the Yukon Flats are similar to those in the Lena River Delta (Zubrzycki et al., 2013) and in multiple temperate floodplains (Ricker et al., 2012; Sutfin, 2015). However, Yukon Flats stocks are higher than those estimate in the Tanana River floodplain, although stocks within the Tanana River floodplain are calculated to a depth of 60 cm (Van Cleve et al., 1993). Johnson et al. (2011) use data from government and academic sources to determine average stocks according to different landscape units throughout Alaska, including lowlands and uplands, but do not distinguish floodplains separately from lowlands in general. However, the range of values for lowland environments in the intermontane boreal region, in which the Yukon Flats is located, is somewhat similar to the range in stock values among different vegetation types in this study, but potentially less. Wetland environments in the intermontane boreal were estimated at 381 Mg C ha^{-1} (Johnson et al., 2011), and this value is similar to the black spruce woody wetland (402.2 Mg C ha^{-1}) and herbaceous wetland (238.0 Mg C ha^{-1}) values in the Yukon Flats floodplains.

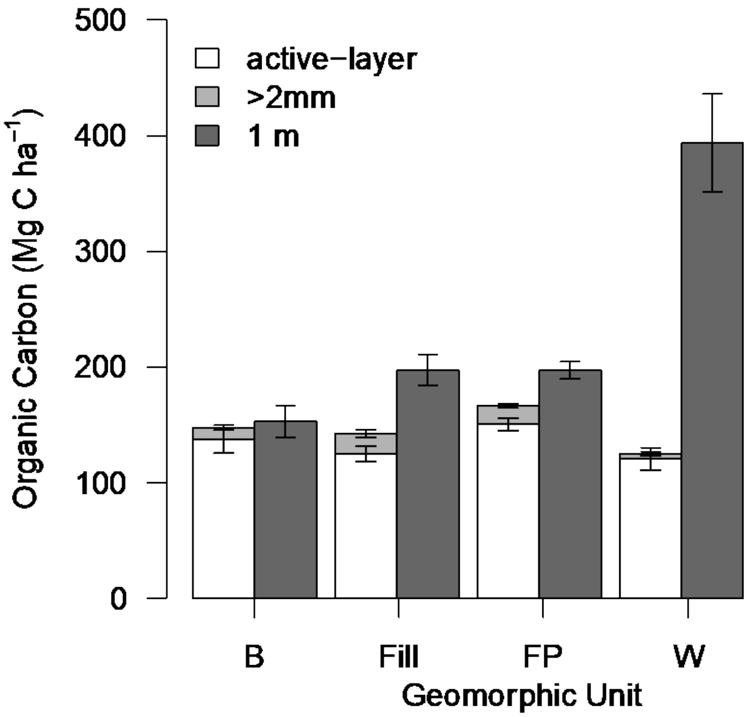

Figure C.1. Average carbon stocks per area by geomorphic unit, in the active layer (white bar) and extrapolated to 1 m in depth (dark grey bar). The additional stock from >2mm fraction in the active layer was estimated for three of the rivers, and is added to the active layer stocks (light grey bar). Bars show the mean ± standard error of the mean. B = Bar, FP = Floodplain, W = Wetland

Table C.1. Number of sampled locations by river, geomorphic unit, and vegetation type.

By river	Number of sampling locations
Draanjik River	43
Teedrinjik River	63
Dall River	65
Preacher Creek	66
Yukon River	74

By geomorphic unit	Number of sampling locations
Bar	46
Fill	80
Floodplain	142
Wetland	43

By vegetation type	Number of sampling locations
Black spruce woody wetland	31
Deciduous/shrub	102
Mixed Forest	37
White spruce forest	89
Herbaceous wetland	52

Table C.2. Summary statistics for the maximum depths reached at sampled locations for the entire dataset and by river and geomorphic unit.

	Min (cm)	Max (cm)	Median (cm)	Mean (cm)	Standard deviation (cm)	Standard error of the mean (cm)
All sampled locations	4	118	67	65.9	26.7	1.5
By river						
Draanjik River	22	100	56	60.55	19.30	2.94
Teedrinjik River	30	107	88	82.90	20.61	2.60
Dall River	14	118	53	57.92	27.62	3.43
Preacher Creek	4	110	57	59.35	29.23	3.60
Yukon River	20	108	67	67.51	25.54	2.97
By geomorphic unit						
Bar	4	118	84	78.72	25.95	3.83
Fill	15	108	66	64.89	28.87	3.23
Floodplain	4	110	68.5	69.32	22.39	1.88
Wetland	14	105	36	42.97	22.76	3.47
By vegetation type						
Black spruce woody wetland	14	105	36	43.50	25.35	4.55
Deciduous/shrub	4	118	70.75	71.93	25.67	2.54
Mixed Forest	24	107	72	70.74	24.14	3.97
White spruce forest	4	107	67	68.92	22.91	2.43
Herbaceous wetland	17	107	55	58.98	29.39	4.08

Table C.3. List of rivers along which floodplains were delineated within the Yukon Flats. Floodplains were delineated below 375 m elevation and within the Yukon Flats National Wildlife Refuge boundary.

River
Dall River
Hodzana River
Hadweenzic River
Teedrinjik (Chandalar) River
Christian River
Sheenjek River
Porcupine River
Draanjik (Black) River
Grass River
Little Black River
Paddle Creek
Sucker River
Yukon River
Birch Creek
Lower Mouth Birch Creek
Preacher Creek
Beaver Creek

Table C.4. NLCD land cover class and converted vegetation type identified in the field.

NLCD land cover class	Applied field vegetation type
evergreen Forest	white spruce forest
grassland/herbaceous	herbaceous wetland
shrub/scrub	shrub/deciduous forest
emergent herbaceous wetland	herbaceous wetland
mixed forest	mixed forest
woody wetlands	black spruce woody wetland
dwarf shrub	shrub/deciduous forest
sedge/herbaceous	herbaceous wetland

Table C.5. Summary statistics for OC stocks in the active layer for entire dataset and by river, geomorphic unit, and vegetation type.

	Minimum (Mg C ha^{-1})	Maximum (Mg C ha^{-1})	Median (Mg C ha^{-1})	Mean (Mg C ha^{-1})	Standard deviation (Mg C ha^{-1})	Standard error of the mean (Mg C ha^{-1})
All sampled locations	1.7	361.8	137.0	137.8	67.1	3.8
By river						
Draanjik River	38.61	260.12	123.38	136.19	59.34	9.05
Teedrinjik River	30.52	234.19	147.85	134.00	52.58	6.62
Dall River	10.38	361.81	177.35	171.03	77.54	9.62
Preacher Creek	1.67	343.31	123.05	128.33	71.67	8.82
Yukon River	11.35	342.21	117.54	121.23	59.60	6.93
By geomorphic unit						
Bar	1.67	337.87	117.91	137.49	81.84	12.07
Fill	26.99	273.85	119.83	124.83	60.13	6.72
Floodplain	9.25	361.81	147.54	150.41	64.73	5.43
Wetland	10.38	284.10	111.19	120.59	63.56	9.69
By vegetation type						
Black spruce woody wetland	10.38	234.19	111.19	118.70	60.43	10.85
Deciduous/shrub	1.67	337.87	135.76	138.88	67.82	6.71
Mixed Forest	11.35	361.81	163.07	161.18	85.89	14.12
White spruce forest	9.25	342.21	143.72	141.65	59.38	6.29
Herbaceous wetland	26.99	284.10	119.83	123.85	63.13	8.75

Table C.6. Summary statistics for OC stocks extrapolated to 1 m for entire dataset and by river, geomorphic unit, and vegetation type.

	Minimum (Mg C ha^{-1})	Maximum (Mg C ha^{-1})	Median (Mg C ha^{-1})	Mean (Mg C ha^{-1})	Standard deviation (Mg C ha^{-1})	Standard error of the mean (Mg C ha^{-1})
All sampled locations	1.7	1017.3	187.9	217.7	154.7	8.8
By river						
Draanjik River	41.28	419.18	223.49	218.66	85.33	13.01
Teedrinjik River	37.73	303.43	159.88	154.88	65.51	8.25
Dall River	74.11	1017.27	273.46	341.43	207.52	25.74
Preacher Creek	1.67	843.07	146.64	175.90	154.62	19.03
Yukon River	11.35	743.14	168.35	199.41	125.58	14.60
By geomorphic unit						
Bar	1.67	371.03	138.98	152.85	92.17	13.59
Fill	28.22	786.95	167.00	197.29	116.72	13.05
Floodplain	9.25	483.36	190.07	197.05	88.56	7.43
Wetland	57.85	1017.27	289.32	393.54	277.57	42.33
By vegetation type						
Black spruce woody wetland	57.85	1009.59	315.54	402.40	278.76	50.07
Deciduous/shrub	1.67	483.36	170.26	185.21	95.95	9.50
Mixed Forest	11.35	445.65	208.44	196.13	106.56	17.52
White spruce forest	9.25	411.09	184.21	187.89	84.46	8.95
Herbaceous wetland	40.90	1017.27	184.97	237.96	189.78	26.32

Table C.7. Summary statistics for OC stocks in the organic layer for entire dataset and by river, geomorphic unit, and vegetation type.

	Minimum (Mg C ha^{-1})	Maximum (Mg C ha^{-1})	Median (Mg C ha^{-1})	Mean (Mg C ha^{-1})	Standard deviation (Mg C ha^{-1})	Standard error of the mean (Mg C ha^{-1})
All sampled locations	0.38	265.98	15.52	22.43	28.01	1.85
By river						
Draanjik River	5.85	124.00	15.28	21.35	23.23	1.53
Teedrinjik River	1.03	65.25	10.34	13.68	13.06	0.86
Dall River	1.11	143.65	22.98	34.23	32.86	2.17
Preacher Creek	0.49	51.94	16.48	18.18	12.02	0.79
Yukon River	0.38	265.98	17.42	22.58	38.31	2.53
By geomorphic unit						
Bar	0.48	103.85	3.68	11.04	20.14	1.33
Fill	0.91	124.00	13.50	20.15	25.47	1.68
Floodplain	0.38	265.98	14.85	20.05	27.96	1.84
Wetland	5.86	143.65	29.19	38.77	28.75	1.90
By vegetation type						
Black spruce woody wetland	5.86	143.65	30.79	40.15	30.44	2.01
Deciduous/shrub	0.48	124.00	8.68	16.41	22.65	1.49
Mixed Forest	1.29	62.88	15.15	17.85	13.63	0.90
White spruce forest	0.38	265.98	13.00	21.14	33.94	2.24
Herbaceous wetland	1.58	78.36	22.21	28.93	22.05	1.45

Table C.8. Published stock estimates for different environments.

Location	Stock (Mg C ha^{-1})[a]	Environment type	Reference[b]
Northwestern Montana, USA	54 ± 10	temperate mountain gravel-bed floodplain	(Appling et al., 2014)
Lena River Delta, Russia	290 ± 10[c]; 140 ± 7[d]	Arctic large river delta	(Zubrzycki et al., 2013)
Colorado Rockies, Colorado, USA	102-464[e]; 23-58[f]	temperate semi-arid mountain river floodplains	(Sutfin, 2015)
Southern New England, USA	262	temperate headwater floodplains	(Ricker et al., 2012)
Jalisco, Mexico	113.8 ± 32.9[g]	floodplains in tropical dry forest	(Jaramillo et al., 2003)
Tanana River floodplain, boreal region, interior Alaska	4.56 ± 1.58 – 102.1 ± 17.9[h]	lowland boreal floodplain	(Van Cleve et al., 1993)
Lowland intermontane boreal, Alaska	113 (98)[i]; 152 (88)[j]; 194 (79)[k];	boreal lowlands	(Johnson et al., 2011)
Upland intermontane boreal, Alaska	86 (45)	boreal upland	(Johnson et al., 2011)
Wetland, intermontane boreal, Alaska	381 (207)	boreal wetland	(Johnson et al., 2011)

[a]Numbers are the mean stock ± the standard error of the mean or with standard deviation in parentheses to 1 m in depth on a per area basis, unless otherwise noted
[b]References included supporting information reference list, above
[c]Holocene river terrace
[d]active floodplain
[e]mean values for soil organic carbon, with low mean value in single thread confined valleys and high mean value in single thread unconfined valley segments.
[f]mean values for litter and duff, with low mean value in single thread partly confined valley segments and high mean value in old-growth multithread segments.
[g]mean value for soil organic carbon to a depth of 120 cm
[h]mean values for mineral soils to a depth of 60cm, with low mean value for bare alluvial surfaces and high mean value of white spruce stands that were 184 years old.
[i]mean value for sandy lowland

[j]mean value for silty lowland
[k]mean values for lowland

Table C.9. Information on all radiocarbon dates taken from cutbanks. Calibrated ages are reported as calendar years before present, relative to 1950. Y = Yukon, T = Teedrinjik, Dr = Draanjik, D = Dall, and P = Preacher.

River	**Planform type**	**Depth of sample (cm)**	**GPS_ID**	**Material type**	**Sample name**	**Uncalibrated radiocarbon age ± 1σ error (yr BP)**	**Calibrated 95.4% age range (cal yr BP)**	**Calibrated average age (cal yr BP)**	**Calibrated standard deviation (cal yr BP)**	**Calibrated median age (cal yr BP)**
Y	Braided	300	E1	wood	Yuk2 CB1 11June 2015 14C	128 ± 20	270-11	137	79	116
Y	Braided	140	E2	wood	Yuk2 CB2 11June 2015 14C	modern	modern	modern	modern	modern
Dr	Meandering	355	K37	wood	BL1-CB1-355cm 14C	643 ± 22	665-557	608	35	592
Dr	Meandering	385	K52	wood	BL1-CB2-385cm	3659 ± 22	4083-3903	3991	52	3980
Dr	Meandering	350	K53	wood	BL1-68km-3.5m 14C	817 ± 21	769-686	722	21	720
Dr	Meandering	400	K54	wood	BL-km66-4m 14C	2988 ± 33	3326-3062	3163	60	3166
Dr	Meandering	343	K55	wood	BL57.5km CB3-343cm 14C	206 ± 22	301-modern	175	94	171
Dr	Meandering	275	K58	wood	BL-53.5km-275 cm 14C	356 ± 21	494-317	404	55	410
Dr	Meandering	260	K59	wood	BL-49km-260cm 14C	107 ± 25	268-18	131	77	112
Dr	Meandering	310	K60	wood	BL46.5km-310cm 14C	2910 ± 27	3156-2963	3050	51	3046
Dr	Meandering	200	K61	wood	BL-44.5-200cm 14C	28 ± 25	254-32	86	66	53
Dr	Meandering	260	K62	wood	BL42.5-2.6m	922 ± 23	916-788	850	39	854
Dr	Meandering	290	K63	wood	BL36km-2.9m 14C	2004 ± 31	2039-1880	1953	38	1953
Dr	Meandering	230	K64	wood	BL33.5km-230cm 14C	2414 ± 25	2680-2353	2452	87	2429
Dr	Meandering	330	K74	wood	BL2-P15-CB6 330cm 14C	5808 ± 30	6675-6500	6609	45	6612
Dr	Meandering	200	K72	wood	BL2-P16-200cm 14C	487 ± 32	550-496	523	18	522
Dr	Meandering	260	K75	wood	BL25.5km-	1485 ± 25	1409-1313	1367	28	1367

					260cm					
Dr	Meandering	410	K103	wood	BL3-P24-CB-410cm 14C	1200 ± 27	1230-1057	1126	44	1125
Dr	Meandering	370	K105	wood	BL3-P25-CB 370 cm 14C	6655 ± 40	7591-7460	7531	34	7532
Dr	Meandering	360	K107	organics	BL-15km-360cm	2731 ± 21	2866-2775	2819	25	2819
Dr	Meandering	430	K110	wood	BL4-P26-430cm 14C	4438 ± 33	5280-4878	5075	112	5039
Dr	Meandering	350	K113	wood	BL4-P27-350m CB 14C	96 ± 25	262-24	128	77	109
Dr	Meandering	215	K115	wood	BL4-P28-CB 215 cm 218	1000 ± 28	966-799	909	44	925
Dr	Meandering	270	K117	wood	BL4-P29-CB 270cm 14C	337 ± 28	476-310	393	49	388
Dr	Meandering	310	K118	wood	BL8km-310cm C14	140 ± 20	279-7	145	83	142
Dr	Meandering	260	K119	wood	BL5km-2.6m 14C	3889 ± 29	4416-4241	4329	54	4332
Dr	Meandering	280	K121	wood	BL1km-280cm 14C	1326 ± 24	1298-1185	1260	32	1273
Y	Wandering	260	K139	wood	Yuk4-P38-CB 260cm 14C	281 ± 25	435-286	360	55	378
Y	Wandering	210	K141	wood	Yuk4-P39-CB 210 cm 14C	525 ± 24	624-511	542	27	535
Y	Wandering	135	K143	wood	Yuk4-P40-CB 135cm 14C	483 ± 36	619-485	522	23	520
Y	Wandering	155	K145	wood	Yuk4-P41-CB 155cm 14C	modern	modern	modern	modern	modern
Y	Wandering	130	K150	wood	Yuk4-P43-CB 130cm 14C	1283 ± 29	1284-1179	1228	35	1233
Y	Wandering	190	K152	wood	Yuk4-P44-CB 190cm 14C	1076 ± 27	1055-931	987	36	978
Y	Wandering	90	K159	organics	Yuk4-P47-CB 90 cm 14C	1145 ± 24	1174-976	1052	52	1045
Y	Wandering	115	K160	wood	Yuk4-P48 CB 115cm	74 ± 20	255-31	115	77	79

					14C					
Y	Wandering	250	K171	wood	Yuk5-P51-CB 290cm 14C	4066 ± 28	4798-4438	4564	89	4550
Y	Wandering	280	K175	wood	Yuk5-P52-CB 280 cm	5719 ± 31	6631-6415	6512	50	6507
Y	Wandering	200	K183	wood	Yuk5-P55-CB 200cm 14C	188 ± 34	303-modern	165	91	178
Y	Wandering	230	K185	wood	Yuk5-P56-CB 230 cm 14C	99 ± 25	264-23	129	77	110
Y	Wandering	100	K189	wood	Yuk5-P58-CB 100cm 14C	124 ± 24	271-11	136	79	117
Y	Wandering	110	K193	wood	Yuk river km 56.5-CB 110 cm 14C	121 ± 19	269-14	133	77	112
Y	Wandering	410	K194	wood	Yuk56km-14C paleojam 4.1m	6304 ± 30	7290-7166	7226	35	7226
Y	Wandering	280	K195	organics	Yuk55km-CB 280cm 14C	2712 ± 24	2855-2761	2809	27	2808
Y	Wandering	270	K198	wood	Yuk42km-270cm CB 14C	315 ± 23	460-305	383	43	388
Y	Wandering	280	K203	wood	Yuk31km-CB-280cm 14C	modern	modern	modern	modern	modern
D	Meandering	150	K222	wood	Dall15-CB1 150cm 14C	2035 ± 20	2055-1926	1985	34	1983
D	Meandering	260	K223	organics	Dall15-CB2 260 cm 14C	5111 ± 27	5921-5752	5836	56	5816
D	Meandering	140	K227	wood	Dall15-CB6-140cm 14C	4374 ± 26	5036-4860	4932	45	4927
T	Wandering	120	K233	wood	Chan1-P60-CB-120cm C14	776 ± 24	730-674	701	17	698
T	Wandering	105	K242	wood	Chan1-P64-CB-105cm 14C	164 ± 27	287-modern	157	86	179
T	Wandering	110	K260	wood	Chan1-71km-CB	605 ± 20	652-547	602	30	603

					110cm					
T	Wandering	60	K268	wood	Chan2-P70-CB60cm	807 ± 19	745-682	714	17	713
T	Wandering	70	K277	wood	Chan2-P72-70cm	868 ± 21	899-728	775	39	768
T	Wandering	120	K289	wood	Chan2-P74-CB-120cm	74 ± 18	255-32	112	77	70
T	Wandering	85	K298	wood	Chan2-45km-85cm 14C	99 ± 18	259-28	129	76	111
T	Meandering	190		wood	Chan3-37km-190cm 14C	67 ± 18	254-32	102	74	58
T	Meandering	100	K303	wood	Chan3-P78-CB100cm C14	73 ± 24	257-31	118	77	94
T	Meandering	100	K317	wood	Chan3-P81-CB100 cm C14	1107 ± 23	1060-962	1012	30	1010
T	Meandering	310	K326	wood	Chan3-30km-310cm 14C	255 ± 17	313-153	288	47	298
T	Meandering	120	K343	wood	Chan4-P90-CB-120cm	46 ± 18	244-35	74	57	52
T	Meandering	125	K346	wood	Chan4-P91-CB-125 cm 14C	954 ± 25	928-796	859	40	853
T	Meandering	150	K357	wood	Chan5-7km-CB150cm	126 ± 18	270-12	135	79	112
T	Meandering	330	K361	organics	Chan5-6km-330cm 14C	4163 ± 31	4830-4581	4708	69	4707
D	Meandering	250	14	wood	Dall reach 1 bank wood	361 ± 19	495-319	410	56	435
D	Meandering	240	48	wood	Dall reach 3 bank wood	209 ± 21	302-modern	179	94	169
D	Meandering	350	48	wood	Dall reach 3 bank wood	213 ± 20	303-modern	186	92	168

P	Wandering	126	244	wood	Preacher 18 Jul-C14-1	1395 ± 28	1347-1281	1310	17	1306
P	Wandering	300	903	wood	Pr-20July-C14-3	2262 ± 32	2347-2158	2257	59	2240

Table C.10. Information on all radiocarbon dates taken from the active layer-permafrost transition. Y = Yukon, T = Teedrinjik, Dr = Draanjik, D = Dall, and P = Preacher.

River	**Planform type**	**Top depth of sample (cm)**	**Bottom depth of sample (cm)**	**Middle depth of sample (cm)**	**GPS ID**	**Material type**	**Sample name**	**Lab name**	**Uncalibrated radiocarbon age ± 1σ error (yr BP)**	**Calibrated 95.4% age range (cal yr BP)**	**Calibrated average age (cal yr BP)**	**Calibrated standard deviation (cal yr BP)**	**Calibrated median age (cal yr BP)**
Y	Braided	22	26	24	K14	wood	Yuk2-P6-2.3		370 ± 22	500-320	421	58	444
Y	Braided	87	107	97	K23	humins	Yuk3-P9-2.6		4992 ± 34	5888-5615	5731	67	5715
Y	Wandering	52	63	57.5	K140	humins	Yuk4-P39-2.4		6113 ± 31	7156-6895	7008	72	6988
Y	Wandering	32	48	40	K142	humins	Yuk4-P40-2.3		3312 ± 27	3610-3464	3534	38	3530
Y	Wandering	60	66	63	K190	humins	Yuk5-P59-2.6		3601 ± 29	3978-3839	3910	42	3907
T	Wandering	73	84	78.5	K248	humins	Chan1-P66-2.6		3078 ± 26	3363-3219	3292	41	3291
T	Wandering	92	107	99.5	K281	humins	Chan2-P73-1.7		4968 ± 27	5747-5611	5692	40	5690
T	Meandering	79	98	88.5	K318	humins	Chan3-P82-2.6		5557 ± 30	6401-6297	6349	32	6348
T	Meandering	56	65	60.5	K365	humins	Chan5-P97-1.5		4401 ± 28	5046-4868	4967	68	4963
Dr	Meandering	45.5	55.5	50.5	K42	humins	BL1-T1-2.5		5836 ± 30	6735-6560	6649	46	6654
Dr	Meandering	51	53	52	K114	humins	BL4-P28-2.5		5586 ± 37	6436-6300	6363	37	6361
Y	Wandering	31	31	31	164	wood	Yukon C14 sample 1	YY1	modern	modern	modern	modern	modern
Y	Wandering	44	44	44	164	wood	Yukon C14 sample 2	YY2	modern	modern	modern	modern	modern
D	Meandering	47	69	58	133	humins	Dall5-T10-RR-1.5	1	600 ± 27	652-543	600	31	603
D	Meandering	25	35	30	6	humins	Dall1-T10RR-1.3		5287 ± 36	6184-5945	6074	66	6076

D	Meandering	67	82	74.5	55	humins	Dall3-T6-RL-1.5		4948 ± 62	5891-5587	5699	79	5686
D	Meandering	17	39	28	101	humins	Dall4-T7-RL-1.4		4814 ± 35	5609-5470	5532	46	5521
P	Wandering	72	80	76	286	humins	P2-T8-RL-1.5	2	modern	modern	modern	modern	modern
P	Wandering	43	63	53	397	humins	P3-T8-RR-1.3	3	modern	modern	modern	modern	modern
P	Wandering	32	36	34	213	humins	P1-T10RL-1.4		4241 ± 37	4868-4645	4787	66	4824