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Key Points:
- We use a large field data set to quantitatively estimate floodplain soil organic carbon stock along the Yukon River
- The stock is ~68% higher than that estimated by the Northern Circumpolar Soil Carbon Database
- Dating of organics in floodplain sediment indicates that floodplains can store sediment and OC for thousands of years

Supporting Information:
- Supporting Information S1

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Significant Floodplain Soil Organic Carbon Storage Along a Large High-Latitude River and its Tributaries

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Abstract High-latitude permafrost regions store large stocks of soil organic carbon (OC), which 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 estimate floodplain soil OC stocks within the active layer (seasonally thawed layer) and to a maximum depth of 1 m from a large field data set in the Yukon Flats region of interior Alaska. We compare our estimated stocks to a previously published data set and find that the OC stock estimate using our field data could be as much as 68% higher than the published data set. Radiocarbon measurements indicate that sediment and associated OC can be stored for thousands of years before erosion and transport. Our results indicate the importance of floodplains as areas of underestimated carbon storage, particularly because climate change may modify geomorphic processes in permafrost regions.

Plain Language Summary Large amounts of organic carbon (OC) are stored in the northern permafrost (perennially frozen) soils. Accurately estimating the amount of carbon is important for understanding the movement of carbon between the land, the ocean, and the atmosphere. Soil OC in northern regions may be released to the atmosphere with future warming and permafrost thaw, further indicating the need to accurately understand how much OC is stored in soils. Floodplains, as sites of sediment and nutrient deposition, store significant amounts of soil OC and to date have not been adequately characterized. We estimate the amount of OC in floodplain soils in the Yukon Flats region in interior Alaska, finding that there may be significantly more soil OC in northern floodplains than previously thought.

1. Introduction

Boreal and arctic regions are experiencing increased temperatures due to anthropogenic climate change (Arctic Climate Impact Assessment, 2005; Intergovernmental Panel on Climate Change, 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 flow paths (O'Donnell et al., 2014; Toohey et al., 2016; Walvoord & Kurylyk, 2016; Walvoord & Striegl, 2007), changed the exports of nutrients to the Arctic Ocean (Frey & 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 changes in lateral channel migration due to permafrost thaw and subsequent 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 & 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 indicate 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 & Aalto, 2013; Dunne et al., 1998; 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 are 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 & Marín-Spiotta, 2014; Doetterl et al., 2016). In permafrost regions, previously frozen OC from upstream in a river network can be mineralized and released or buried before mineralization occurs (Vonk & Gustafsson, 2013). Thus, transient storage and burial of OC complicate estimates of greenhouse gas emissions from permafrost thaw. In addition, large river floodplains can store sediment and associated carbon for long periods of time before erosion and further transport downstream (Dunne & Aalto, 2013; Dunne et al., 1998; Torres et al., 2017). Thus, constraining the carbon content and residence time of floodplain sediment could inform the character and type of nutrient fluxes from rivers to oceans as well as help link OC stocks and fluxes.

We estimate soil OC stocks in the active layer (seasonally thawed layer) and top 1 m of floodplains in the Yukon Flats (YF) region in interior Alaska, a large inland alluvial basin. Our study includes the Yukon River 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 (YFNWR) 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 remobilization by fluvial erosion using radiocarbon activity measurements taken from cut banks 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.

2. Materials and Methods

The YF region is located in the discontinuous permafrost zone in interior Alaska (Figure 1). We sampled floodplain sediments over two field seasons (Summer 2014 and 2015) along five rivers within the YF with varying drainage areas (Text S1 in the supporting information). 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 or a soil corer, stopping when we reached 1 m in depth or point of refusal. 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. Detailed descriptions of geomorphic units and planform types at sampled locations are included in supporting information (Text S1). We sampled at 311 locations along study rivers; Table S1 shows the number of sampled locations, and Table S2 reports the depths reached at sampled locations by river, vegetation type, and geomorphic unit. We also took core samples into the face of cut banks at a few locations to assess the range of OC concentrations below 1 m in depth. For further description of sampling methodology and fieldwork, see Lininger et al. (2018) and supporting information Text S1.

We obtained measured or estimated OC concentrations, bulk density, texture, and OC stock for all samples (Text S2). 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 (in addition to measured stocks within the sampled depth). Estimating the 1-m stock is necessary to compare stocks to other data sets. 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. Similarly, we did not extrapolate down to 1 m if we did not reach the mineral soil (i.e., we did not extrapolate the OL down to 1 m in depth). Although we did not sample permafrost, if stopping due to frozen ground, we captured some of the unfrozen/frozen transition. There are uncertainties associated with extrapolation, but samples taken deeper than 1 m into cut banks to constrain permafrost OC content contained similar OC% values,

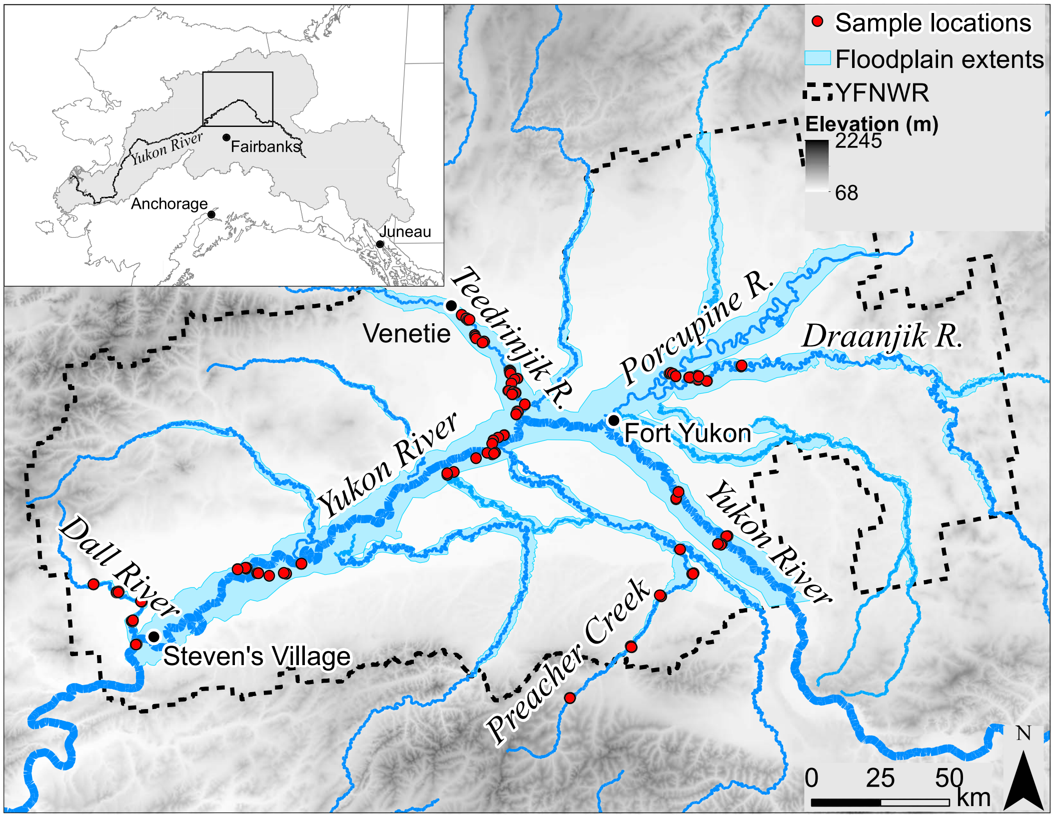

Figure 1. Study area, showing soil sample locations, the extent of the Yukon Flats National Wildlife Refuge, and delineated floodplain extents used for analyses in light blue bands. YFNWR = Yukon Flats National Wildlife Refuge.

indicating that extrapolating mineral samples down to 1 m in depth is a justifiable approach. 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 >2-mm fraction within the active layer. See supporting information (Text S2) for detailed description of laboratory methods.

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 digital elevation model from the Polar Geospatial Center (Noh & Howat, 2015). We also delineated the floodplain extent along all major rivers within the boundary of the YFNWR and below 375-m elevation, which is representative of our sampling locations (Figure 1; see Table S3 for a list of rivers along which floodplains were delineated and Text S3 for further details on methods).

Using the 2011 National Land Cover Data Set (Homer et al., 2015) to weight the areas of vegetation types, we calculated the total OC stock across the YF floodplains using the median values of the 1-m carbon stock for each vegetation type. For the floodplain region in the YFNWR below 375 m in elevation, we also computed the range in total OC stock estimate using the upper and lower bounds on the 95% confidence interval for the median OC stock per area for each vegetation type. See Text S3 for descriptions of calculating total OC stocks. We then compared this estimated total stock to the 1-m total 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 cut banks 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 cut banks 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

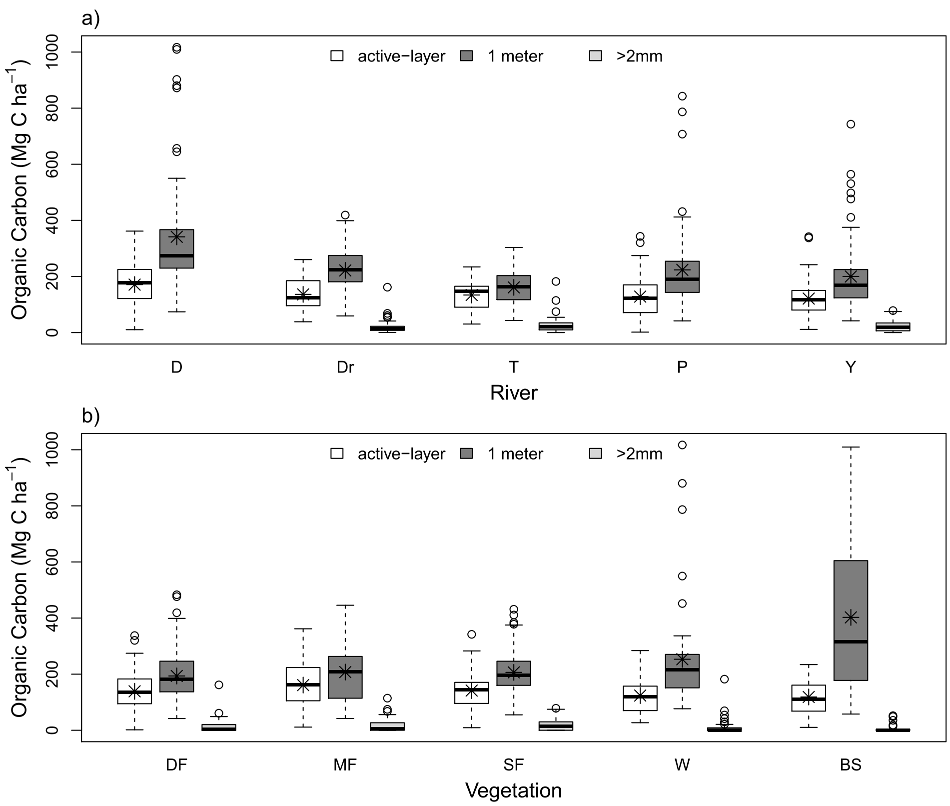

Figure 2. Carbon stocks per area by river (a) and vegetation type (b), in the active layer (white) and extrapolated to 1 m in depth (dark gray). The additional stock from >2-m fraction in the active layer was estimated for three of the rivers and is shown in light gray. For boxplots, the star within 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 percentiles. 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.

transported longer distances, and large wood recruited from river banks likely has a shorter transport distance from the source. Recruitment of wood from cut banks 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 cut bank samples, we also dated wood pieces in sediment samples and the humin fraction (the fraction that is insoluble in water, acid, and base and may be less mobile) of floodplain sediment in sediment samples that we took from the core farthest from the river channel in selected transects near the base of the active layer. We dated these samples to constrain the maximum age of carbon within the active layer in the distal, and presumably oldest, floodplain surfaces.

3. Carbon Stocks in the YF

For the entire data set, the mean and standard error for stocks are 137.8 ± 3.8 Mg C/ha (median = 137.0 Mg C/ha) within the active layer and 217.7 ± 8.8 Mg C/ha estimated within the top 1 m (median = 187.9 Mg C/ha). Measured stocks within the active layer vary in depth, with OC stocks averaging 121.2 ± 6.9 Mg C/ha in the Yukon floodplain (median = 117.5 Mg C/ha) and 171.0 ± 9.6 Mg C/ha on the Dall River (median = 177.4 Mg C/ha; Figure 2a). OC stocks within 1 m indicate that OC stocks could range from an average of 154.9 ± 8.25 Mg C/ha on the Teedrinjik River (median = 159.9 Mg C/ha), along which we reached gravel/cobbles/coarse sand at many sampled locations, to 341.4 ± 25.7 Mg C/ha on the Dall River (median = 273.5 Mg C/ha), along which coarse grains were not reached within 1 m. Adding the >2-mm fraction from the three rivers for which the data are available (Draanjik, Teedrinjik, and Yukon) increases the

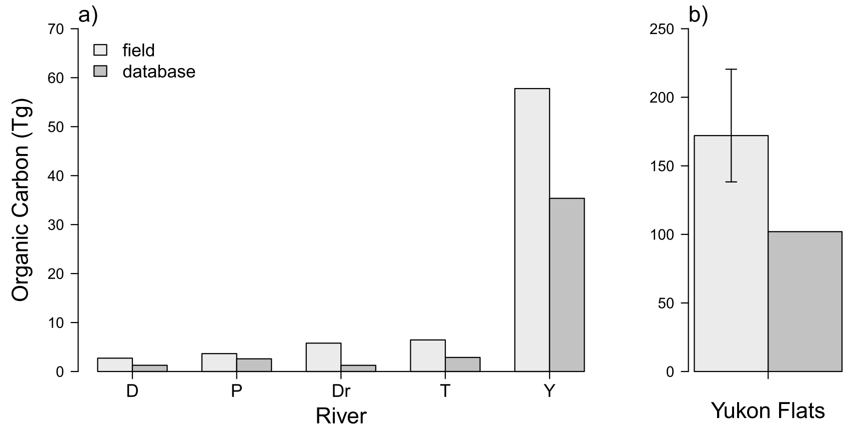

Figure 3. Total carbon stock in teragrams for each of the study river floodplains within the sampled extent (a) and for the YFNWR below 375 m in elevation (b). Light gray bars show estimates based on field measurements, and dark gray are estimates using the Northern Circumpolar Soil Carbon Database. The line on the light gray bar for the Yukon Flats estimate is the upper and lower bounds of the estimate at a 95% confidence interval, described in Text S3. Note the different scales for the axes in the two plots. D = Dall; Dr = Draanjik; T = Teedrinjik; P = Preacher, and Y = Yukon.

OC stock by an average of 21.6 to 26.5 Mg C/ha for the three rivers, which is a 15–20% increase in OC stock (Figure 2). This indicates that studies that do not account for the >2-mm fraction underestimate OC stock by 15–20%.

Active layer OC stocks vary by vegetation type (Figure 2b) and geomorphic unit (Figure S1), with a range of 118.7 to 161.2 Mg C/ha for mean stocks within vegetation types (medians range from 111.2 to 163.1 Mg C/ha) and 120.6 to 150.4 Mg C/ha for mean stocks within geomorphic units (medians range from 111.2 to 147.5 Mg C/ha). The estimated mean stocks for 1 m in depth range from 185.2 to 402.4 Mg C/ha across vegetation types (medians range from 170.3 to 315.5 Mg C/ha) and 152.8 to 393.5 Mg C/ha across geomorphic units (medians range from 140.0 to 289.3 Mg C/ha). Stocks within the OL (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. OL 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. Mean OL stocks ranged from 40.2 Mg C/ha in black spruce woody wetlands to 16.4 Mg C/ha in shrub/deciduous forest. The OL OC stock values are less than previously published OL OC stock values from the Yukon River Basin, with field estimates of ~110 Mg C/ha for woody wetlands and ~40–60 Mg C/ha for shrub/deciduous forest (Pastick et al., 2014). Summary statistics for stocks and sample depths (active layer, 1 m, and OL) for the entire data set and by river, geomorphic unit, and vegetation type are included in Tables S5–S7 in the supporting information.

Comparisons of stock measurements on a per area basis across other locations are 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 YF are similar to or higher than those reported for temperate floodplains and boreal floodplains, wetlands, and uplands (supporting information Text S4 and Table S8).

Our study indicates the need for extensive field data sets to improve upon the NCSCD, which uses limited soil profile data and is extrapolated based on soil information. Overall, the estimate for the total amount of OC within the top 1 m in the YFNWR floodplains below 375-m elevation increases by ~68% when comparing field estimates (172.1 Tg; range from 95% confidence interval on the median OC stock per area by vegetation type = 138.3–220.5 Tg) to NCSCD database estimates (102.0 Tg; Hugelius et al., 2013; Figure 3). The total carbon stock increases by approximately 40–360% across individual study river floodplains when estimating stocks using field data (Figure 3). These field estimates do not include the >2-mm fraction, which could add 15–20% to the calculated total. In contrast, previous comparisons with NCSCD have found that the NCSCD may overestimate stocks in some areas (Zubrzycki et al., 2013).

There is a potentially significant amount of OC stored in deeper alluvium that is difficult to quantify due to the great depth of alluvium and difficulty of sampling permafrost. Samples taken horizontally into cut banks ranged from 1 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 cut banks 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 cut bank 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 YF floodplains (Figure 3) can be compared with the export of dissolved organic carbon (DOC) and POC at Steven's Village (near the downstream end of the study area) to compare floodplain OC storage to fluxes. Because the Yukon River and its tributaries migrate through the floodplain via bank erosion, the source of some OC in transport is likely the floodplain OC stock. The export of POC per year was estimated to be 0.382 Tg/year from 2001 to 2005, with an annual DOC export of 0.781 Tg/year (Striegl et al., 2007). Thus, approximately 1.16 Tg of OC is exported each year from the outlet of the YF in the form of DOC and POC. Alluvium within the YF 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 YF outlet each year is equivalent to 53.05 km^2 of the top 1 m of floodplain sediment, which is 0.67% of the floodplain region delineated within the YFNWR in this study. This suggests the potential for large increases in OC fluxes if warming climate accelerates river erosion of cut banks 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. Constraining Floodplain Sediment and Active Layer Carbon Residence Time

Floodplains are transient storage sites of OC within the river corridor, and bank erosion of floodplains can contribute both DOC and POC to the river network. Constraining floodplain residence time helps in understanding the age and history of OC flux and the details of all aspects of the carbon cycle (e.g., stocks, transport, and transient storage). The results of radiocarbon dating indicate that the age of sediment deposition in the floodplain ranges from modern to over 7,000 calendar years before present (Figure 4a). These dates constrain the residence time of floodplain sediment, although we lack sufficient spatial extent of dated materials to calculate an average floodplain residence time or half-life. Reported ages of POC along the Draanjik (Black) River (1576 and 2585 years BP; Aiken et al., 2014) are similar to the median ages of large wood in cut banks along the Draanjik (1521–1408 years BP; Figure 4a). This 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 large wood within cut banks. Patterns in the age of sediment deposition may vary according to planform type within the YF, as described in Text S5.

Dating of OC in the humin fraction of sediment near the base of the active layer indicates that OC in the active layer can be up to 7,000 calendar years BP, although multiple dates in the active layer are relatively young or modern (Figure 4b).

5. Implications

Permafrost regions are already experiencing changes in hydrology and flow paths, permafrost degradation and warming, deepening active layers, and modified fluxes of nutrients to the Arctic Ocean (Rawlins

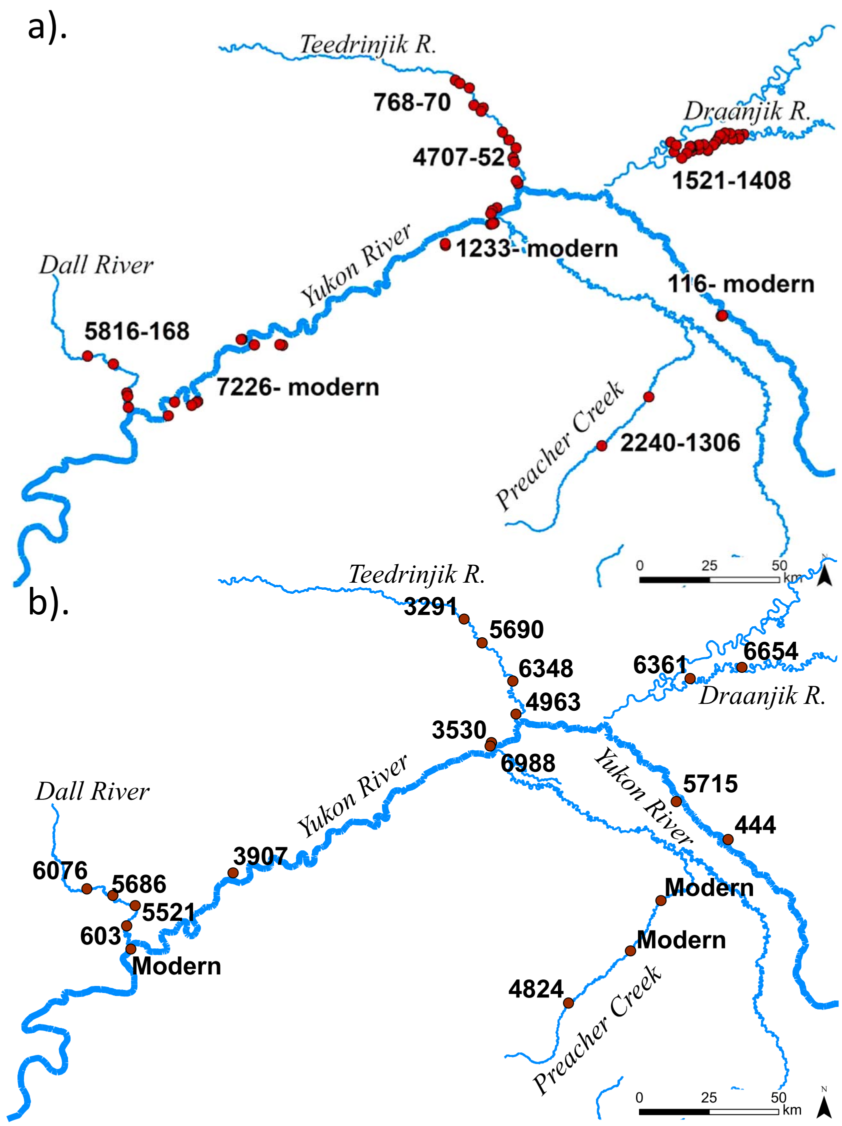

Figure 4. (a) Range of the oldest median age and youngest median age of large wood in cut banks in each sampling block along different sections of the studied rivers, showing age in calendar years BP. (b) Age of organic carbon from the humin fraction of sediment deep within the active layer, taken from sediment samples furthest from the active channel.

et al., 2010; Romanovsky et al., 2013; Striegl et al., 2005; Walvoord & Kurylyk, 2016). Understanding OC storage within floodplains 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. Permafrost degradation will likely change many geomorphic processes, including rates of channel migration and mobilization of floodplain sediments into river networks. Thus, establishing accurate baseline information and understanding floodplain OC stocks are integral to accurately constraining the carbon cycle and informing future changes to riverine fluxes in permafrost regions.

Many questions remain unanswered regarding linking stocks of OC in floodplains with exports and fluxes of OC, including whether mobilized OC from floodplains gets redeposited or buried and whether that OC is mineralized and released to the atmosphere. However, our results indicate that there is a larger amount of OC in the floodplains of the YF than previously estimated. There are extensive lowland, high-latitude floodplains in boreal and Arctic regions, indicating that the importance of floodplains as sites of OC storage over timespans of 10^2–10^3 years may be underestimated globally.

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