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A first-order approximation of floodplain soil organic carbon stocks in a river network: The South Platte River, Colorado, USA as a case study

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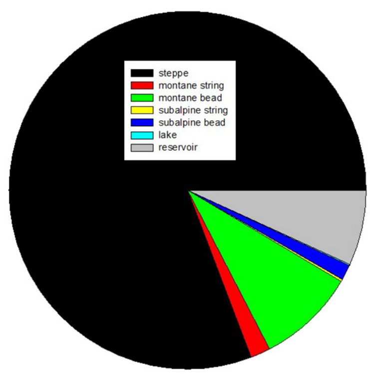
HIGHLIGHTS

- Floodplains cover 4 % of total watershed area.
- Floodplain soils store 11 % of total watershed organic carbon.
- Hydrologically connected floodplains are an important carbon sequestration site

GRAPHICAL ABSTRACT



Proportion of total carbon stock in different floodplain types using median channel widths adjusted for the South Platte River watershed.

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ABSTRACT

The lack of watershed-scale estimates of floodplain carbon stocks limits recognition of the important role of floodplains and river corridor restoration in efforts to enhance carbon sequestration. We use the South Platte River watershed of Colorado, USA as a case study to illustrate spatial patterns of, and controls on, floodplain carbon stocks at the watershed scale. This case study illustrates the disproportionate importance of floodplains for soil carbon stocks relative to adjacent uplands and provides an example of how spatially explicit data can be used to prioritize floodplain restoration with regard to carbon sequestration. We use the hydrogeomorphic floodplain tool GFPLAIN to delineate the extent of 100-year floodplains in the South Platte River watershed. We distinguish elevation bands for the steppe, montane, subalpine, and alpine zones. We also differentiate bead (floodplain width/channel width ≥ 5) and string (floodplain width/channel width < 5) reaches within the montane and subalpine zones. Drawing on prior, field-based measurements of organic carbon stock in downed, dead wood and soil in these floodplain types, we estimate total floodplain organic carbon stock based on median values of stock in different floodplain types and the spatial extent of these floodplain types. This estimate includes organic carbon stocks in lake and reservoir sediments in the watershed. Soil constitutes the greatest reservoir of floodplain carbon. The total estimated area of floodplain is 2916 km^2, which is 4.3 % of the total watershed area of the South Platte River. Our preferred estimate is 42.7 Tg C stock (likely range of 39.1–42.7 Tg). This equates to 11.1 % of a previously estimated overall carbon stock (above and belowground biomass and soil organic carbon) in the entire watershed of 384 Tg C. Floodplains are thus disproportionately important, relative to their surface area, in storing organic carbon in this semiarid watershed. Field measurements of floodplain soil organic carbon stocks from across the globe indicate that this finding is not unique to this watershed, with implications for prioritizing floodplain management and restoration as a means of enhancing carbon sequestration.

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1. Introduction

Quantifications of soil organic carbon stocks in river floodplains and adjacent uplands indicate that floodplains can contain disproportionately large carbon stocks relative to the proportion of total surface area that they occupy within a watershed (Wohl et al., 2012). This suggests that floodplains can be effective sites for management and restoration designed to enhance carbon sequestration. We use the phrase carbon stock to describe the mass of carbon stored in a carbon pool such as soil. We use sequestration to refer to the ability to capture and store carbon; sequestration can maintain or increase carbon stocks.

Existing studies have documented the disproportionately large carbon stocks of floodplains at limited spatial scales (e.g., Sutfin et al., 2016), but have not attempted to quantitatively estimate floodplain carbon stocks at the watershed scale. The concept of developing carbon markets in order to offset greenhouse gas emissions is applied to agriculture, forestry, and wetland restoration (Ribaudo et al., 2010; Paul et al., 2013; Sapkota and White, 2020) and practitioners of river restoration are now interested in the possibility of applying carbon credits to floodplain restoration (Matzek et al., 2015). Limited field-based measurements and resulting understanding of the spatial and temporal variations of floodplain carbon stocks within a watershed and between regions, however, can hamper prioritization of restoration sites and techniques in the context of maximizing carbon sequestration. Here, we present a watershed-scale estimate of floodplain carbon stocks and turnover times for an unusually well-constrained watershed as an illustration of how spatially and temporally explicit data can be used to prioritize floodplain restoration with regard to carbon sequestration.

Our primary objective is to quantitatively estimate soil organic carbon stocks and potential turnover times across the diversity of climate and valley geometry present in the South Platte River watershed of Colorado, USA. This estimate illustrates the importance of floodplain management in the context of carbon sequestration. This case study illustrates (i) the methods that can be used to quantify soil organic carbon stocks and turnover times in river corridors, (ii) the spatial variation in carbon stock and the sources of this variation within a watershed, and (iii) the potential for portions of a river network to have significant carbon sequestration potential relative to adjacent uplands. River network here refers to total extent of river corridor within a watershed. River corridor refers to the active channel(s), floodplain, and underlying hyporheic zone.

We first review understanding of organic carbon stocks in river corridors, then present the case study of the South Platte River, and finally discuss implications of this case study for efforts to enhance carbon sequestration. We use the South Platte River for our case study because we can draw on extensive field investigations of soil organic carbon conducted within this watershed during the past decade.

1.1. Organic carbon stocks and river corridors

A growing literature documents the concentrations (% soil carbon) and stocks (mass per area or volume) of organic carbon in diverse river corridors (Sutfin et al., 2016; Wohl et al., 2017; Dybala et al., 2019). Although living floodplain vegetation and living biomass in the active channel(s) contribute to carbon stock in river corridors (Jaramillo et al., 2003; Cierjacks et al., 2010; Hanberry et al., 2015), floodplain soil and downed, dead wood typically constitute the largest river-corridor carbon stocks in temperate and boreal latitude river networks (Wohl et al., 2012; Hanberry et al., 2015; Sutfin et al., 2016). Here, soil refers to all sediment within the river corridor.

Floodplain soil carbon concentration reflects the balance among (i) rates of organic matter input from litterfall on the floodplain and fluvial deposition, as well as dissolved carbon in surface and subsurface water fluxes into the floodplain; (ii) rates of carbon decomposition and soil respiration and release to the atmosphere; and (iii) sediment residence time in relation to fluvial erosion and transport downstream (Robertson et al., 1999; Wohl et al., 2017). Boreal river networks underlain by permafrost have some of the highest soil carbon concentrations in the world (Lininger et al., 2019) because of low rates of mineralization and long sediment residence times, but even tropical river corridors can have substantial soil carbon stocks (e.g., Shimada et al., 2001). In general and across diverse latitudes, organic carbon stock in floodplain soils is enhanced by a wide river corridor in which the active channel and floodplain are hydrologically connected; saturated, finely textured soils; high organic matter input; and long residence time for floodplain sediment (Sutfin et al., 2016; Hinshaw and Wohl, 2021).

River corridor carbon stocks in the form of downed, dead wood reflect inputs of dead wood from adjacent uplands, upstream portions of the river network, and tree mortality within the river corridor, as well as river corridor geometry that promotes wood trapping and retention (Scott and Wohl, 2018b; Hinshaw and Wohl, 2021). The volume of wood retained within a river corridor reflects the balance between wood trapping and retention, wood decay, and fluvial remobilization of stored wood (Benda and Sias, 2003). In watersheds with undisturbed forest (old-growth and naturally disturbed younger forest) and no history of wood removal from channels and floodplains, the carbon stock in downed, dead wood can be substantial and of comparable magnitude to carbon stock in floodplain soil (Wohl et al., 2012; Lininger et al., 2017; Scott and Wohl, 2020; Sutfin et al., 2021).

Soil and downed wood carbon stocks have different magnitudes, sequestration rates, and turnover times between river networks and within a river network. Within a river network, river-wetland corridors (Wohl et al., 2021) characterized by high primary productivity and saturated, reducing soils in the floodplain tend to have particularly large soil carbon stocks, for example. Wider valley floors are sometimes known as river beads (Wohl et al., 2018). When conditions such as beaver (*Castor* spp.) modifications within beads promote lateral and vertical hydrologic connectivity and limit longitudinal connectivity (Westbrook et al., 2006; Burchsted et al., 2010; Wegener et al., 2017; Larsen et al., 2021), a river-wetland corridor with high soil carbon stock is likely to be present (Johnston, 2014; Laurel and Wohl, 2019). In contrast, the intervening sections of laterally confined, commonly well-drained river corridor known as strings are likely to have lower soil carbon concentrations as well as smaller volumes of soil per unit length of valley (Wohl et al., 2012; Sutfin et al., 2021). Elevational differences in primary productivity and in disturbance regime (wildfire, mass movements, floods) that influence wood recruitment and transport, as well as floodplain erosion, can also create significant differences in river corridor carbon stock within downed wood and floodplain soil in mountainous river networks (Sutfin and Wohl, 2019).

Sequestration rates of floodplain soil organic carbon vary through space and time, depending in part on the primary source of organic matter to the soil. Floodplain surfaces that are relatively stable and have limited sediment connectivity with the active channel may receive organic matter primarily via litterfall and root exudates from floodplain vegetation (Wohl et al., 2017). These portions of a floodplain typically have the greatest organic carbon concentrations in the upper few tens of centimeters (Lininger et al., 2018; Scott and Wohl, 2018a). In contrast, floodplain surfaces that are frequently eroded and redeposited or characterized by high rates of sedimentation may receive organic matter primarily via fluvial deposition (Hupp et al., 2019). Depending on the source and organic content of the fluvially deposited sediments, these floodplains may also have high concentrations of carbon near the surface (Ricker et al., 2012) or may have buried carbon-rich layers (Walter and Merritts, 2008). Sequestration rates of floodplain soil organic carbon in the contiguous United States range over three orders of magnitude, from 0.03 to 8 Mg C/ha/y (Sutfin et al., 2016), but published rates come exclusively from the eastern half of the United States. We have been unable to find any published rates for the western USA or for the study area. Rates of large wood recruitment are also largely unknown for the study area, in part because wood recruitment is typically very episodic, with greater recruitment following forest disturbances (e.g., blowdowns, hillslope failures, wildfires, insect infestations) that have highly variable return intervals (Wohl, 2020).

Floodplain turnover time refers to the average residence time of soil (and soil organic carbon) in the floodplain and is commonly estimated from a population of ages of different portions of a floodplain using radiocarbon or other geochronological techniques (Wohl, 2015). A population of ages is used because different areas of a floodplain typically have different turnover times, with portions of the floodplain closest to the active channel likely to have shorter turnover times (Konrad, 2012). Lateral channel mobility, as a reflection of the ratio of erosive force to floodplain erosional resistance, largely determines floodplain turnover time. Published floodplain turnover times range from decades to thousands years on diverse rivers (Wohl, 2015).

Analogously, the residence time of large wood on a floodplain is commonly estimated from a combination of radiocarbon dates on wood and decay rates of downed wood (Wohl, 2020). Residence times vary widely as a function of the magnitude and frequency of fluvial transport and floodplain erosion that removes wood from floodplain storage (Benda and Sias, 2003) and decay rates in relation to climate and tree species. Reported residence times range from >1400 years in the Pacific Northwest region of the US (Hyatt and Naiman, 2001) to less than a decade in tropical regions (Clark et al., 2002).

2. Case study: The South Platte River, Colorado

2.1. The watershed

The South Platte River drains ~67,500 km^2 in Colorado. Headwaters of the river network start above treeline near the continental divide. The river flows eastward onto the Great Plains, joining the North Platte River in Nebraska (Fig. 1). The watershed thus includes alpine tundra (above 3450 m elevation), subalpine conifer forests and lakes (2840–3450 m), montane conifer forests (1830–2840 m), and steppe vegetation of grasses and woody shrubs (below 1830 m elevation). The South Platte mainstem and its larger tributaries that head in the mountains are perennial. Smaller tributaries and those that originate on the Great Plains are ephemeral or intermittent. At elevations above approximately 2300 m, the flow regime reflects predominantly snowmelt and peak unit flow seldom exceeds 1.1 m^3/s/km^2 (Jarrett, 1990). At lower elevations below 2300 m, summer convective storms can produce flash floods with peak flows up to 40 m^3/s/km^2 (Jarrett, 1990). Naturally occurring lakes (rather than reservoirs) occur primarily in the alpine and subalpine portions of the watershed.

Subalpine conifer forests above 2300 m have a longer recurrence interval (~400 years) for stand-replacing wildfires and a lower frequency of landslides and debris flows than do montane conifer forests (~70–200 years) (Veblen and Donnegan, 2005). Portions of the river network above 2300 m thus have the potential for much longer floodplain soil residence times because of lower magnitude and frequency of disturbance (Sutfin and Wohl, 2019). A dataset of 52 floodplain soil radiocarbon ages from the subalpine and montane portions of the South Platte watershed suggests floodplain soil residence times of ~1500 years in the subalpine portion of the watershed and ~ 600 years in the montane portion (Sutfin and Wohl, 2019). Where organic matter accumulating in floodplain soil comes predominantly from floodplain litterfall, rather than fluvial transport and overbank deposition of organic matter (Lininger et al., 2018; Scott and Wohl, 2018a; Hupp et al., 2019), longer floodplain soil residence time equates to higher soil organic carbon concentration and stock. Decay rates for downed wood also vary between the subalpine and montane portions of the network. Downed wood can persist for >600 years on subalpine floodplains and ~350 years on montane floodplains (Kueppers et al., 2004). Decay rates and residence times of downed wood along rivers in the steppe portion of Colorado are poorly constrained.

Diverse human activities have altered river corridor characteristics in the South Platte River network since the start of commercial beaver trapping in

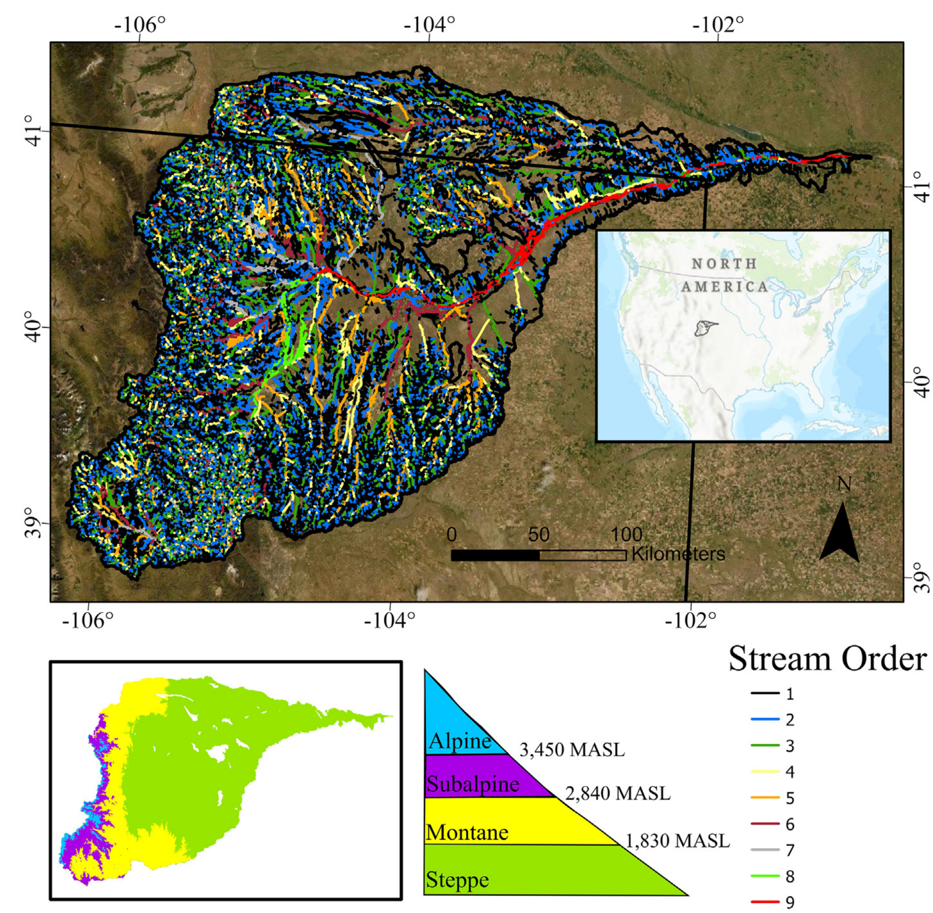

Fig. 1. Location map of the South Platte River watershed with stream orders color-coded and insets indicating location and elevation boundaries of the four zones within the watershed. The watershed lies mostly within Colorado (black lines in large map), but extends slightly northward into Wyoming. Inset map indicates the location of the South Platte watershed within the continental United States.

the first decade of the 19th century (Wohl, 2001). Over the intervening two centuries, the watershed has experienced placer mining, widespread deforestation, construction of roads and railroads along river corridors, log floating and instream wood removal, flow regulation, irrigated agriculture in the steppe portion of the watershed, and urbanization (Wohl, 2001). Numerous water-storage reservoirs are present within the montane and steppe portions of the watershed. All these activities directly and indirectly affect floodplain soil organic carbon stocks. Beaver trapping, log floating, and instream wood removal can result in drier floodplain soils with lower inputs of organic matter and greater rates of carbon loss to the atmosphere (Wohl, 2013; Laurel and Wohl, 2019). Flow regulation that reduces overbank flow can have similar effects (Lininger and Polvi, 2020). Placer mining, deforestation, and construction of transportation infrastructure in river corridors can reduce the residence time of floodplain soil and the inputs of organic matter via litterfall (Hilmes and Wohl, 1995; James, 1999; Blanton and Marcus, 2009; Hanberry et al., 2015). Agriculture and urbanization typically reduce floodplain soil organic carbon storage (e.g., Guo and Gifford, 2002). Although urbanization is present throughout the South Platte watershed, it is most spatially extensive in the steppe elevation band, as is agriculture. Reservoirs may store organic carbon in sediment but can also enhance methane emissions: the net effect of a reservoir on carbon stock within a watershed reflects multiple interacting processes and consequently varies among reservoirs (Clow et al., 2015; Wohl et al., 2017).

2.2. Methodology and data sources

We followed several steps in estimating soil carbon stock within the South Platte River network. Each of these steps is described in more detail below, but they are: (1) delineate the floodplain using GFPLAIN software with 30-m topography from the National Elevation Dataset (NED); (2) stratify river corridor segments by stream order and use representative values for bankfull channel width of each stream order to calculate the ratio of floodplain width to channel width at 500-m increments along the river corridor; (3) for the subalpine and montane zones, use these ratios to differentiate bead and string segments; (4) map the area of natural lakes and artificial reservoirs using the 2016 National Land Cover Database (Jin et al., 2019) and the delineated floodplain; and (5) assign a representative carbon stock (Mg C/ha) to floodplains in each elevation zone, to beads and strings in the subalpine and montane zone, and to lakes and reservoirs.

2.2.1. Watershed and floodplain delineation

The South Platte basin was delineated with the EPA WATERS GeoViewer (https://www.epa.gov/waterdata/waters-geoviewer) beginning from approximately 12 km west of North Platte, Nebraska (100.9095903°W, 41.1423038°N).

We delineated three 100-yr floodplains using the 1 arc-second (~ 30 m resolution) NED (Gesch et al., 2002) and hydrogeomorphic floodplain tool GFPLAIN (Nardi et al., 2019) in ArcGIS Pro (ESRI, 2020). Hydrogeomorphic floodplains are based on floodplain shape and the relationship between floodplain width and contributing area (Nardi et al., 2006). GFPLAIN uses three parameters to include the contributing area threshold for delineating streamflow, and two scaling parameters, a and b. Three sets of floodplains were delineated with contributing area thresholds of 50 km^2 (based on Annis et al., 2019; Knox et al., 2022b; Scheel et al., 2019), 25 km^2, and 10 km^2, respectively. We consider the 10 km^2 to be most appropriate for the study watershed and used the floodplain delineated with this contributing area for all analyses. We selected a value of 0.0035 for parameter a, and calibrated parameter b with FEMA special flood hazard areas A and AE on six streams varying from stream order one to six, resulting in the selection of the value 0.32 for b. More details on the calibration can be found in Knox et al. (2022b).

2.2.2. Stream order area analysis

We estimated floodplain area by associated stream order and altitude zone for each of the three floodplain sets using ArcGIS Pro (ESRI, 2020) and R Studio (RStudio Team, 2020). In ArcGIS Pro, each raster cell in the floodplain area was converted to a point, which was assigned the altitude of the NED and the stream order value of up to 10 stream segments within 500 m in the National Hydrography Dataset Plus HR (NHD Plus HR) (Buto and Anderson, 2020). We used R Studio to select the largest stream order value for each floodplain point and to estimate the floodplain area based on altitude and stream order.

2.2.3. Stream order and channel width

As a sensitivity analysis, we used two sets of values for channel width based on stream order: median values of channel width derived from the global dataset of Downing et al. (2012) and median values derived from our field data for sites in the South Platte watershed. The substantial geographic and climatic variability within the South Platte watershed likely creates different median values of channel width for a given stream order in the subalpine versus the steppe zone, for example, but we used the same median channel width value for each stream order across the elevation zones.

2.2.4. Beads and strings

In applying values for soil organic carbon stock, we distinguish beads and strings in the subalpine and montane zones. Beads have a floodplain width ≥ five times the width of the bankfull channel (Sutfin, 2016). Strings are narrower portions of the river corridor. We distinguish beads and strings because field-based quantification of soil organic carbon stocks in the subalpine and montane portions of the watershed indicate significant differences between beads and strings (Wohl et al., 2012; Sutfin, 2016). Beads are more likely to have high floodplain water tables that promote greater primary productivity of floodplain vegetation; saturated and reducing conditions that retard mineralization and decomposition of particulate organic matter; and longer residence time of floodplain sediment and organic matter (Wohl et al., 2018). Although floodplain wetlands associated with beads likely existed historically in parts of the steppe zone, these are now uncommon and we do not differentiate beads and strings in the steppe zone.

We estimated floodplain widths using the three GFPLAIN floodplain sets and streamlines in ArcGIS Pro. We segmented the streamlines into 1000 m lengths and assigned each length the average altitude of the NED along its length and the largest stream order value of the NHD Plus HR within 500 m. We then generated transects every 500 m along the streamlines and clipped the transects to the width of the floodplain. Each transect was measured and assigned the altitude and stream order of the intersecting streamline.

2.2.5. Lakes and reservoirs

We estimated lake and reservoir area using the 2016 National Land Cover Database (NLCD; Jin et al., 2019) in ArcGIS Pro. This database has 30 m resolution. We extracted NLCD values for open water within the GFPLAIN floodplain extent. These raster cells were converted to polygons, manually classified as a lake or reservoir, measured for area, and assigned an elevation value.

2.2.6. Representative carbon stock

We focus on floodplain soil organic carbon stocks, rather than carbon in living floodplain vegetation or in downed, dead wood within the river corridor. We chose the South Platte River watershed for this assessment because we can draw on numerous field-based quantifications of floodplain soil and dead wood carbon stock. These come primarily from the subalpine and montane zones, but we have some field data from the steppe portions of the watershed.

We used median values for carbon stocks in diverse portions of the river corridor (Table 1). Each of the field sites used to calculate median soil organic carbon values represents multiple samples from that site (typically, at least 11; Sutfin and Wohl, 2019) from a single reach, such as a subalpine bead or string. Sites were chosen to represent the least human alteration possible (e.g., old-growth or naturally disturbed forest along unregulated channels on national park or national forest lands). As described in the

Table 1
Values used to estimate floodplain, lake, and reservoir soil organic carbon (SOC) and downed, dead wood (LW) stocks.

Location	Median SOC stock[a] (Mg C/ha)	Standard deviation	Reference
Alpine	Unknown (6–244)	NA	Bockheim and Munroe, 2014
Subalpine bead	279.1 (109.7–595.7)	176.5	Sutfin et al., 2021
Subalpine string	118.4 (50.5–160)	34.6	
Montane bead	210 (94–379)	106	Sutfin, 2016; Sutfin and Wohl, 2019
Montane string	104 (40–170)	62	
Steppe floodplain	131 (4–326)	123.3	Wohl and Pfeiffer, 2018
	63		SSURGO data
Subalpine lake	211	NA	Dunnette et al., 2014; Pompeani et al., 2020
Reservoir	220	NA	J. Baron, USGS, pers. comm.
Location	**Median LW C stock[a] (Mg C/ha)**	**Standard deviation**	**Reference**
Subalpine bead	42 (6.7–1372)	447.3	Wohl et al., 2012; Sutfin, 2016
Subalpine string	14.7 (2.7–141)	44.8	
Montane bead	2.5 (0.6–16.7)	6.2	Jackson and Wohl, 2015; Sutfin, 2016
Montane string	11.5 (1.8–64.8)	15.5	

[a] Range in parentheses; NA – not available.

source references, the standard practice for estimating soil organic carbon stock is to sample soil from the upper 1 m of the floodplain below the litter and duff layer. Although exceptions exist, soil organic carbon concentration typically declines rapidly with depth and soil materials below 1 m depth contain minimal organic carbon. Organic carbon concentration is determined using loss on ignition or a CN furnace, typically by a commercial laboratory, and combined with soil bulk density to estimate carbon mass. All available field-based data for the watershed were used to calculate median values of soil organic carbon.

As a sensitivity analysis, we used two median values for the steppe floodplains. The first (131 Mg C/ha) comes from field sampling of floodplain sediment in eastern Colorado, as described in Wohl and Pfeiffer (2018). The second value (63 Mg C/ha) comes from NRCS SSURGO (US Natural Resources Conservation Service Soil Survey Geographic Database) soil map values of sites in eastern Colorado, as described in Wohl and Pfeiffer (2018).

Each of the samples used to calculate median organic carbon in large wood represents quantification of wood load (m^3/ha) based on several (typically, at least 5; Lininger et al., 2017) floodplain transects from a single reach. Downed wood is assumed to be half organic carbon and volume is converted to mass using published values of wood density for individual tree species (Lininger et al., 2017) to calculate Mg C/ha. All available field-based data for the watershed were used to calculate median values of organic carbon in downed, dead wood.

2.2.7. Sequestration rates and turnover times

Organic carbon stocks in floodplain soil and in downed wood have different sequestration rates and turnover times, and these are poorly constrained. Consequently, we make the simplifying assumption that the median values derived from published data are uniform through time and space within each elevation zone: we can use radiocarbon-based chronologies to estimate differences in floodplain soil and dead wood turnover times between the subalpine and montane zones.

2.2.8. Limitations and uncertainties

Each of the primary steps in this analysis includes uncertainties. (1–2) Floodplain delineation and stream order stratification: The contributing area threshold that we set for delineating floodplains influences our ability to detect floodplains on smaller channels. Global analyses suggest that first and second order streams dominate cumulative river length (Downing et al., 2012). Our use of a 10 km^2 threshold for delineating floodplains, along with our use of 30-m NED, likely causes us to miss most of the first and second order channels in the South Platte River watershed: prior work in the montane and subalpine zone indicates that first order channels in this watershed have a contributing area ranging from 0.01 to 0.06 km^2 (Henkle et al., 2011). We also know that there is likely to be lower accuracy when using GFPLAIN to delineate floodplains in topographically steep areas (Annis et al., 2022; Lindersson et al., 2021). Although narrow first and second order channels commonly have narrow floodplains, the numbers presented here likely underestimate total floodplain soil organic carbon stock. (3) Bead delineation: Floodplain width occurs along a continuum. Our designation of a floodplain width/channel width ratio of 5 for designating beads versus strings is informed by field experience in the study area but is nonetheless arbitrary. This threshold ratio does influence total carbon stock estimates, considering the substantially different median values of soil organic carbon stock assigned to beads versus strings. In addition, as noted previously, we are using a single value of channel width for each stream order across the entire watershed and this assumption introduces uncertainty. (5) Assigning a representative value of soil organic carbon stock: Field measurements indicate substantial spatial variability among values for soil organic carbon stock, as reflected in our previously published work. Use of a single median value for each elevation band and for beads and strings in the montane and subalpine zones thus introduces substantial uncertainty. In addition, floodplains within urban areas may contain substantially less soil carbon if the upper layer of soil was removed during construction of infrastructure. The Denver metropolitan area, which is within the steppe elevation band, includes 12,580 ha of floodplain, for example, and this area may have minimal soil organic carbon.

We attempt to partly constrain all of these uncertainties with sensitivity analyses, as described in the Methods section and in the Results section.

3. Results

The range of field-measured values for floodplain soil organic carbon stock in each type of floodplain includes substantial overlap between floodplain types (Fig. 2). Based on our field measurements of channel widths in diverse portions of the watershed, we consider the analysis using median carbon values and median channel widths adjusted for the South Platte River watershed to provide the most accurate estimation of total carbon stock. This analysis estimates 42,711,981 Mg C in floodplain soils and lake and reservoir sediments within the watershed. By comparison, using global median values of channel width, which alters only the proportion of beads and strings in the subalpine and montane zones, results in a total estimate of 41,759,379 Mg C. Fig. 3 and Table 2 show the distribution of carbon in different elevation zones using different assumed channel widths and Table 3 lists the distribution by stream order and elevation zone. In this context, it is worth noting that our field-based delineations of beads and strings in the montane and subalpine zones suggest that typically <25 % of total channel length is in beads (Wohl et al., 2012, 2022). Using the channel width values adjusted for the South Platte watershed, however, we estimated that 40 % and 43 % of total channel length is in beads in the montane and subalpine zones, respectively. Consequently, we may be

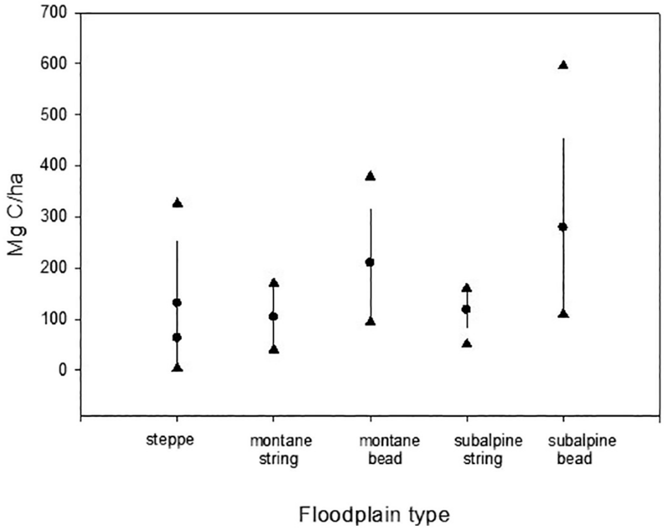

Fig. 2. Values of floodplain soil organic carbon stock in different types of floodplains within the South Platte River watershed. Solid circle indicates median value used in calculations. (Open circle for the steppe floodplains is an alternative median value.) Vertical line indicates standard deviation of values. Upper and lower triangles indicate range of values measured in field studies in the watershed.

overestimating bead extent and associated carbon storage. The use of a single median value for montane and subalpine floodplains, which results in total estimated stock of 39.1 Tg C, represents a reasonable lower bound for our preferred estimate.

The largest values of soil organic carbon per unit area are within the subalpine and montane bead floodplains (Fig. 2, Table 2). However, the great majority of the total floodplain area in the South Platte River watershed is within the steppe elevation zone (Table 2), so this zone also has the majority, although a slightly lesser proportion, of the total floodplain soil organic carbon stock (Fig. 3, Table 2).

3.1. Sensitivity analyses

Estimated total floodplain area ranges from 218,584 to 291,601 ha, depending on the contributing area threshold used (Table 4). Lowering the threshold from 50 to 25 km^2 increases the total floodplain area by 17 % and lowering the threshold to 10 km^2 increases total floodplain area by 33 % relative to the 50 km^2 area estimate. However, the total stream length in the South Platte River watershed estimated using this 10 km^2 threshold in GFPLAIN is only 12.8 % of the total stream length estimated in the NHD Plus database, largely because of differences in the estimated length of first and second order streams. Consequently, our approximation of total floodplain area within the watershed is likely an underestimate.

Using the 10 km^2 contributing area threshold and a single median value of carbon stock per elevation zone (i.e., ignoring beads and strings), total floodplain soil organic carbon stock is 39.1 Tg C (Table 4). Using the standard deviation values for carbon stock in subalpine and montane beads and strings with the 10 km^2 contributing area threshold, total floodplain soil organic carbon stock varies from 4.5 Tg (low value of carbon stock for each elevation band and floodplain configuration) to 75 Tg (high values) (Table 4). The sensitivity analyses indicate the substantial range in the value of estimated floodplain organic carbon stock that can result from assuming different representative values for Mg C/ha for each elevation zone and valley confinement category.

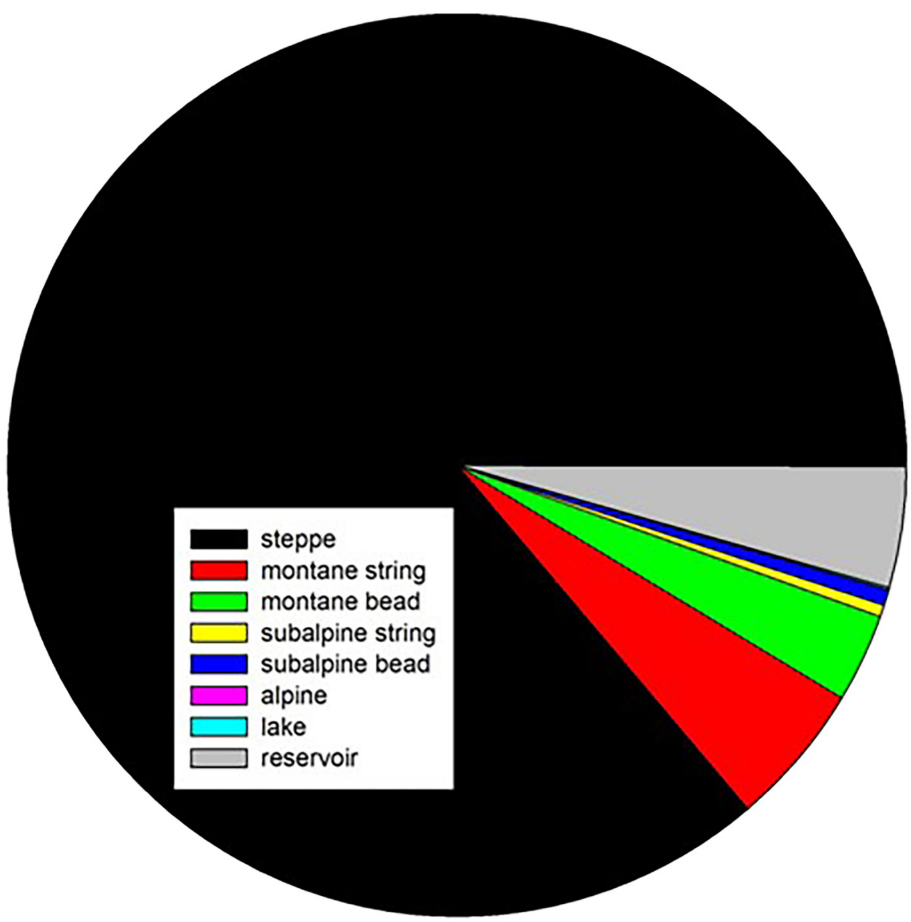

Fig. 3. Proportion of total carbon stock in different floodplain types using median channel widths adjusted for the South Platte River watershed.

Table 2
Distribution of organic carbon by environment in floodplains of the South Platte river watershed.

Environment	Area (ha)		Proportion of area		Mg C/ha	Mg C		Proportion total C	
	Global[1]	CO	Global	CO		Global	CO	Global	CO
Steppe		263,044		0.902	131 *63*[3]		34,458,830 *16,571,804*	0.825 *0.694*	0.807 *0.668*
Montane string	15,796	7434	0.0542	0.024	104	1,642,817	773,125	0.039 *0.069*	0.018 *0.031*
Montane bead	9731	18,094	0.032	0.059	210	2,043,589	3,799,699	0.049 *0.086*	0.089 *0.153*
Subalpine string	1309	897	0.004	0.003	118	155,118	106,283	0.004 *0.006*	0.002 *0.004*
Subalpine bead	1706	2118	0.006	0.007	279	476,018	591,038	0.011 *0.020*	0.014 *0.024*
Alpine[2]		14.5		0	–		0	0	0
Natural lakes		268		0.001	211		56,611	0.001 *0.002*	0.001 *0.002*
Reservoirs		13,302		0.044	220		2,926,396	0.070 *0.123*	0.068 *0.118*
Total		305,171		–	–	41,759,379 *23,872,353*	42,711,981 *24,824,955*		–

[1] Global refers to calculations using median channel width derived from a global dataset in Downing et al. (2012). CO refers to median channel widths adjusted to field measurements on channels within the South Platte River watershed.
[2] The area of alpine floodplain was so small that we did not include it in carbon stock calculations for the watershed.
[3] Italicized values are calculated using 63 Mg C/ha for steppe floodplains.

4. Discussion and conclusions

The total estimated area of floodplain is 2916 km^2. This is 4.3 % of the total watershed area of the South Platte River. Baron et al. (2006) estimated that total carbon stock (above and belowground biomass and soil organic carbon) in the South Platte River watershed was 407 Tg C prior to European settlement and is 384 Tg at present. Using the calculations from the global dataset of channel width, total soil carbon stock in the South Platte River watershed floodplains is 41.8 Tg; the value rises slightly to 42.7 Tg using the Colorado values for channel width (Table 2). These values are 10.9 % and 11.1 %, respectively, of the estimated contemporary total carbon stock in the watershed. Considering that our floodplain estimates include only soil organic carbon and not total biomass, these comparisons indicate the disproportionate importance of floodplain soil organic carbon on a per-unit-area basis. Across the contiguous United States, Knox et al. (2022a) estimate that floodplains occupy 966,024 km^2, or approximately 12 % of the total land area of 8,080,464 km^2. This suggests a substantial potential for enhancing organic carbon sequestration at the national scale as floodplains and floodplain wetlands are restored.

To put the floodplain soil organic carbon stocks in perspective with respect to potential floodplain carbon stocks in downed, dead wood, we used floodplain wood load and organic carbon stock data from montane and subalpine beads and strings (Wohl et al., 2012; Jackson and Wohl, 2015; Sutfin, 2016) (Table 1). Comparable data are not available for the steppe region, although steppe floodplains do contain downed wood, and alpine floodplains do not contain downed wood. Using the floodplain area in montane and subalpine beads and strings as estimated with channel width values adjusted for the South Platte watershed, along with the median values of large wood carbon stock in Table 1, the estimated total organic carbon in large wood is 0.2 Tg, whereas the estimated soil organic carbon in montane and subalpine beads and strings is 5.3 Tg. In other

Table 3
Distribution of Floodplain Area in Hectares by Stream Order and Elevation Zone.

Stream order	Steppe (ha)	Montane (ha)	Subalpine (ha)	Alpine (ha)
9	100,419		–	–
8	17,829	785	–	–
7	26,666	3738	–	–
6	26,598	6653	336	–
5	30,655	6136	598	–
4	23,025	4762	1335	8.5
3	20,056	2771	599	6
2	10,752	648	97	–
1	7045	33	50	–
Total	263,044	25,528	3015	14.5
Proportion[a]	0.902	0.088	0.010	0.000

[a] Proportion refers to proportion of total floodplain delineated in the South Platte River watershed.

Table 4
Sensitivity analyses.

Stream length in the South Platte River watershed

Stream length (km)	NHD plus	GFPLAIN with 10 km^2 threshold
1st & 2nd order	89,323 (73 % of total)	2300 (15 % of total)
Total	123,050	15,792

Floodplain area based on contributing area threshold

	Area (ha) for 50 km^2 threshold	Area (ha) for 25 km^2 threshold	Area (ha) for 10 km^2 threshold
Steppe	205,328	234,397	263,044
Montane	12,732	19,975	25,528
Subalpine	524	1607	3015
Alpine	0	0	15
Sum	*218,584*	*255,979*	*291,601*

Floodplain carbon stock using 10 km^2 threshold and single value per elevation band

	Mg C/ha	Total C (Tg)
Steppe	131	34.5
Montane	157	4.0
Subalpine	198.8	0.6
Sum		*39.1*

Floodplain carbon stock using upper and lower standard deviation per elevation type and valley category

	Mg C/ha high value	Mg C/ha low value	Total C high value (Mg)	Total C low value (Mg)
Steppe	254.3	7.7	66,892,089.2	2,025,439
Montane string	166	42	1,234,044	312,228
Montane bead	316	104	5,717,704	1,881,776
Subalpine string	153	83.8	137,241	75,168.6
Subalpine bead	455.6	102.6	964,960.8	217,306.8
Sum	–	–	*74,946,039 (75 Tg)*	*4,511,918 (4.5 Tg)*

words, despite the many vital geomorphic and ecological roles played by large wood on floodplains, it does not contribute substantially to total floodplain carbon stocks in the mountainous portion of the South Platte River watershed.

We present values for organic carbon in floodplain soils and downed, dead wood as though they reflect a steady-state reservoir, which is not the case. As noted earlier, extensive human alterations of portions of the watershed have likely reduced floodplain carbon stocks via timber harvest and wood removal from channels and floodplains, agricultural or urban uses of floodplains that reduce soil organic carbon, and hydrologic disconnection of floodplains via flow regulation. The data used for our quantitative estimates of the South Platte watershed come from the least human-altered sites in the watershed and thus reflect an upper bound that has likely changed during the two centuries since intensive human settlement and land use in the watershed. They may also represent an upper bound to future carbon stocks if riverine and watershed processes that influence carbon sequestration are restored as part of river and floodplain restoration.

In addition, sequestration rates and turnover times vary between locations on a single floodplain and between floodplains on different rivers, so the single median values used in our calculations are first-order approximations of carbon stock at a point in time. However, limited radiocarbon-based chronologies for floodplain soil and downed wood suggest that organic carbon can persist for centuries to millennia on floodplains in the South Platte River watershed that have a natural disturbance regime.

Recent studies have posited that anthropogenic alteration of channel-floodplain connectivity may enhance carbon sequestration by reducing carbon residence time in floodplain soils and expediting downstream transmission of carbon to marine sediments (Repasch, 2021; Shen et al., 2021). This approach seems to ignore both the potential for carbon sequestration in saturated, organic-rich floodplain soils over timespans of 10^2–10^3 years (Wohl et al., 2012; Sutfin and Wohl, 2019) and the potential for gaseous emissions of carbon during riverine transport (Raymond et al., 2013) to the oceans. Consequently, river management strategies focused on hydrologically reconnecting channels and floodplains are the most effective way to enhance carbon sequestration, as reflected in comparisons of floodplain soil organic carbon stock in managed versus unmanaged rivers (Hanberry et al., 2015; Lininger and Polvi, 2020). Just as it is important to consider both gaseous emissions and sedimentation when estimating the carbon balance of a lake or reservoir (Mendonça et al., 2012; Maavara et al., 2020), it is critical to consider all aspects of carbon dynamics in river corridors when evaluating potential effects of human alterations on riverine carbon balance (Wohl et al., 2017) and the implications for regional to global carbon dynamics. Restoration of floodplain hydrological connectivity also creates numerous additional benefits, including enhanced nutrient retention and denitrification (Appling et al., 2014; Hanrahan et al., 2018), increased habitat, biomass, and biodiversity (Bellmore and Baxter, 2014), and attenuation of downstream fluxes including flood peaks (Woltemade and Potter, 1994; Lininger and Latrubesse, 2016; Ahilan et al., 2018) and excess sediment (Kronvang et al., 2007; Noe et al., 2019).

Any resource management actions that protect or enhance organic carbon stocks in natural environments are helpful as we collectively face a future of increased climate warming resulting from excess emissions of greenhouse gases. The results presented here for a semiarid, mountainous watershed in Colorado indicate that focusing on protecting or restoring the river-wetland corridors (Wohl et al., 2021) historically characteristic of beads in the montane and subalpine elevation zones can be particularly important with respect to potential for carbon sequestration per unit area. Given the numerous other benefits that result from protection and restoration of these riverine segments, including enhanced attenuation of downstream fluxes of water, sediment, and solutes (Wegener et al., 2017; Sutfin et al., 2021), greater habitat abundance and diversity, and greater biomass and biodiversity (Bellmore and Baxter, 2014; Venarsky et al., 2018), a strong argument can be made for prioritizing management of these portions of the river network.

However, it is also important to emphasize the cumulative importance of the steppe floodplains. Although these portions of the river corridor have relatively low carbon stock per unit area and may not seem like obvious carbon-rich areas because of their relatively dry floodplains, their cumulative dominance of floodplain area and carbon stock suggests that even the floodplains of ephemeral channels in semiarid grasslands such as the U.S. Great Plains should not be ignored when thinking about potential carbon sequestration. Limited areas of steppe rivers such as transient and persistent floodplain wetlands can also have very high soil organic carbon stocks (e.g., values of 326 and 223 Mg C/ha; Wohl and Pfeiffer, 2018). Restoration of steppe floodplain wetlands may be more feasible where urban development is enhancing stormwater runoff that could be retained in wetlands constructed for this purpose (e.g., Rizzo et al., 2018).

The values presented in this analysis represent a first-order estimate of floodplain soil organic carbon stock in a single watershed. These values do, however, support prioritizing restoration of river corridors and floodplain wetlands to enhance carbon sequestration. The cumulative carbon sequestration achieved through such management could become significant for regional carbon dynamics.

Availability statement

Basic data in the form of the GFPLAIN outputs are publicly available through the Colorado State University Mountain Scholar Open Access Repository At http://dx.doi.org/10.25675/10217/235524.

CRediT authorship contribution statement

Ellen Wohl: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. **Richard L. Knox:** Data curation, Formal analysis, Methodology, Resources, Software, Writing – review & editing.

Data availability

We have uploaded data to a publicly available repository and provided a doi link in the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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