



Organic carbon storage in floodplain soils of the U.S. prairies

E. Wohl | A. Pfeiffer

Department of Geosciences, Colorado State University, Fort Collins, Colorado, USA

Correspondence

E. Wohl, Department of Geosciences, Colorado State University, Fort Collins, Colorado 80523-1482, USA.
Email: ellen.wohl@colostate.edu

Abstract

Two data sources, field-collected samples and values in the NRCS SSURGO database, were used to estimate organic carbon concentration (%) and stock (Mg C/ha) in floodplain soils along rivers of the tallgrass and shortgrass prairie within the United States. Field sampling of 6 sites in the tallgrass prairie and 6 sites in the shortgrass prairie (total sample size of 370 vertical cores) indicates that percent organic carbon within a planar cross section through floodplain sediment at a site is spatially heterogeneous and does not decline systematically with depth, but statistical analyses indicate that soil organic carbon is randomly distributed. The median values of organic carbon concentration at both field-sampled and sites remotely sampled based on soil maps in the tallgrass prairie are significantly higher than those of the shortgrass prairie. Median values of organic carbon stock are not significantly different between those obtained from forested sites for comparison and either shortgrass or tallgrass prairie sites but are significantly higher at tallgrass than at shortgrass prairie sites. These results are surprising because upland net primary productivity in prairies is lower than in forested sites. We infer that the historical abundance of floodplain wetlands in river corridors of the tallgrass prairie results in high organic carbon stocks in tallgrass prairie river corridors. This implies that management designed to enhance carbon sequestration should focus on floodplain soils, especially in the tallgrass prairie region, as well as on upland forests.

KEYWORDS

floodplain soil, organic carbon, prairie, river corridor, SSURGO

1 | INTRODUCTION

Investigations of sites from the North American arctic (Mann et al., 2015) to the Amazon lowlands (Sanders et al., 2017) and from the drylands of the Australian interior (Robertson, Bunn, Boon, & Walker, 1999) to subalpine lake deltas (Scott & Wohl, 2017) indicate that river corridors can store disproportionately large stocks of organic carbon relative to uplands. River corridor in this context refers to the active channel(s), floodplain, and other river depositional features such as deltas (Harvey and Gooseff, 2015), irrespective of the size of the channel. Dissolved and particulate organic carbon can be concentrated in river corridors via surface and subsurface transport from adjacent uplands and from upstream portions of the river network (Wohl, Hall, Llninger, Sutfin, & Walters, 2017). Organic carbon mobilized via

erosion of upland soils (Hilton, Meunier, Hovius, Bellingham, & Galy, 2011; Smith, Galy, Hovius, Tye, Turowski, & Schleppe, 2013) or groundwater fluxes through these soils (e.g., Johnson et al., 2008) is a particularly important carbon input to river corridors, although fossil organic carbon mobilized through landslide erosion of bedrock can also be a major contributor in high-relief river networks (e.g., Hilton, Galy, Hovius, Horng, & Chen, 2011). Organic carbon is stored predominantly within floodplain soil and in the form of downed, dead wood in the channel and floodplain (Sutfin, Wohl, & Dwire, 2016). Floodplain soil carbon can be mobilized and transported into the channel during the receding limb of overbank floods (Thoms, 2003).

Investigations of riverine carbon stocks have predominantly focused on forested river catchments, where upland soils receive organic matter from vegetation communities with higher levels of

aboveground biomass per unit of land surface than are present in grasslands (Ruesch & Gibbs, 2008). The accumulation of organic carbon within upland soils depends in part on net primary productivity (NPP) and decomposition rate as these processes influence the incorporation of plant litter into soil. Both primary productivity and decomposition vary in relation to climate, vegetation cover, soil texture and mineralogy, disturbance regime, and other factors (Buell & Markewich, 2004; Kirschbaum, 2000). Tallgrass prairie has continuous grass cover. Aboveground portions of the grasses reach heights greater than 2 m and depth of root penetration can exceed 2 m. Shortgrass prairie has spatially discontinuous vegetation cover, grasses seldom exceed 30 cm in height, and depth of root penetration is also less than in tallgrass prairies. Previous research indicates that soil organic carbon stocks generally increase from the shortgrass to the tallgrass prairies and tend to be higher in alluvial soils than in adjacent uplands (Buell & Markewich, 2004). Soil organic carbon stocks in tallgrass prairies can be comparable to those in temperate-latitude deciduous forests (Buell & Markewich, 2004). Relatively little attention has been paid, however, to how organic carbon content varies spatially within floodplain soils of prairie rivers or to how shortgrass and tallgrass prairie floodplain carbon stocks compare with one another. If prairie river floodplain soils have the potential to store more carbon than upland soils, this information could be useful in river and resource management that seeks to enhance carbon sequestration.

2 | OBJECTIVES AND HYPOTHESES

The primary objectives of this study are to (a) quantify organic carbon storage in floodplain sediment in representative river corridors of native prairies within the conterminous United States, (b) compare organic carbon stocks in shortgrass versus tallgrass prairie floodplains, and (c) compare organic carbon stocks in prairie and forested watersheds using published data for forested sites.

We hypothesize that organic carbon concentrations within floodplain soils of prairie river corridors are highly heterogeneous within the two-dimensional space of a valley-bottom cross section (H1); organic carbon stocks are significantly greater in floodplains of the tallgrass prairie than in floodplains of the shortgrass prairie (H2); and prairie floodplains generally contain lower stocks of soil organic carbon than those in forested watersheds of comparable size and latitude (H3).

We expect organic carbon concentrations in floodplain soils to be heterogeneous because of the relatively high lateral mobility of prairie river channels. Sinuous channels of the tallgrass prairies create oxbow lakes and other types of floodplain wetlands as they migrate laterally across the floodplain, and these wetlands accumulate higher concentrations of soil organic carbon (Bridgman, Megonigal, Keller, Bliss, & Trettin, 2006; Mitra, Wassmann, & Vloek, 2005). Braided channels of the shortgrass prairies are also laterally mobile and abandoned channels create depressions that can retain water and accumulate organic material. In both types of prairies, beavers (*Castor canadensis*) can create floodplain or instream ponded areas. Studies in forested environments indicate that beaver-created wetlands can contain especially high concentrations of organic carbon within sediments (Johnston, 2014; Wohl, 2013b). As a prairie channel migrates repeatedly across

its floodplain, it can thus create a three-dimensional mosaic of depositional units with locally higher concentrations of organic carbon where diverse types of floodplain wetlands are or were formerly present. Previous work on floodplain grain-size distribution (Southwell & Thoms, 2006) and organic carbon (Southwell & Thoms, 2011) in rivers of south-eastern Australia that share characteristics of process and form with the prairie rivers described here indicates that floodplain characteristics may best be described as a patch mosaic rather than a gradient with distance from the active channel.

We expect organic carbon stocks to be greater in floodplains of the tallgrass prairie because of the more continuous grass cover in tallgrass prairies and the associated greater NPP (NPP in tallgrass prairies is about twice that in shortgrass prairies; McGuire et al., 1992), as well as the more extensive floodplain wetlands present in tallgrass river corridors relative to river corridors in the shortgrass prairie. Floodplains of the tallgrass prairie are also more likely to have spatially extensive bottomland forests than are floodplains in the shortgrass prairie. Channels of the shortgrass prairie are more likely to be intermittent or ephemeral than those of the tallgrass prairie, and this may be important for three reasons. First, perennial channels have greater productivity than intermittent or ephemeral channels (Hill & Gardner, 1987) and thus have the potential to transport greater quantities of organic matter into overbank areas during floods. Second, perennial channels are likely to be associated with a higher riparian water table, which may correspond to saturated floodplain soils and a reducing environment that retains organic carbon. Third, climatic conditions that support perennial flow in the tallgrass prairies are likely to equate to greater primary productivity in riparian areas and thus greater quantities of organic matter added to floodplain soils via litterfall (Sims & Singh, 1978).

We expect prairie floodplains to contain lower organic carbon stocks than river floodplains of similar drainage area and latitude within forested watersheds for at least three reasons. The first involves upland fluxes to river corridors and the second and third involve organic carbon dynamics within river corridors. Watersheds that are primarily grasslands have lower NPP in upland sites and may have smaller carbon fluxes from uplands to river corridors than forested watersheds, although NPP values in tallgrass prairies are comparable to those in temperate coniferous forests. NPP values in deciduous and mixed forests are greater than those in tallgrass prairies and all temperate forest types have greater NPP than shortgrass prairies (McGuire et al., 1992). Although tallgrass prairies can have high rates of accumulation of plant detritus, periodic fires remove much of this material aboveground (Knapp & Seastedt, 1986). Schlesinger and Melack (1981) estimate that average rates of total organic carbon transport (particulate and dissolved organic carbon) in temperate latitude forested watersheds are about four times higher than rates from temperate grasslands, with rates from tallgrass prairies about double those of shortgrass prairies.

With respect to organic carbon dynamics within river corridors, prairie floodplains may contain lower soil organic carbon stocks than forested watersheds because instream wood loads can be much greater in forested catchments. Instream wood is effective at trapping particulate organic matter within the channel (Beckman & Wohl, 2014; Ehrman & Lamberti, 1992). Abundant instream wood also facilitates overbank flows that deposit particulate organic matter on floodplains

(Collins, Montgomery, Fetherston, & Abbe, 2012; Wohl, 2013a) and helps to maintain saturated soils that limit organic matter decomposition, potentially facilitating higher organic carbon stocks in floodplain soils of river corridors with more abundant instream wood.

Finally, beaver-created wetlands contain high carbon stocks (Johnston, 2014; Wohl, 2013b), as do other forms of floodplain wetlands (Bernal & Mitsch, 2012; Kayranli, Scholz, Mustafa, & Hedmark, 2010; Mitsch et al., 2013). Although beavers can build dams along prairie channels and floodplains that have only woody shrubs rather than trees, beaver population densities are likely to be higher along river corridors in forested watersheds.

We compare floodplain soils among prairie and forested watersheds of similar drainage area and latitude for two reasons. Spatial patterns of floodplain soil organic carbon with respect to drainage area and floodplain width relative to channel width remain largely unknown (Sutfin et al., 2016). There may be no consistent relation between drainage area and floodplain soil organic carbon concentrations, but we prefer to limit this source of potential variability among study sites. Concentrations of floodplain soil organic carbon are likely to vary with respect to latitude, as do concentrations of upland soil organic carbon (e.g., Post, Emanuel, Zinke, & Stangenberger, 1982). High-latitude soils, in particular, commonly have much greater organic carbon concentrations than low-latitude soils because of slow rates of organic matter decomposition (e.g., Tarnocai et al., 2009), so we limited the latitudinal range of sample sites in this study.

3 | STUDY AREAS

Data for this analysis come from two primary sources, field sampling and online NRCS (Natural Resources Conservation Service) soil databases. Field sites are segregated into tallgrass prairie river corridors in Kansas, Missouri, and Oklahoma and shortgrass prairie river corridors in eastern Colorado. We analyse five populations in this paper: field-sampled tallgrass prairie sites, field-sampled shortgrass prairie sites, remotely sampled (NRCS) tallgrass sites, remotely sampled shortgrass sites, and forested river corridors of comparable drainage area for which values are reported in published papers. All field sites are located between 36 and 39°N latitude and ~250 to 1,200 m elevation (Figure 1).

Tallgrass prairie is dominated by the grasses big bluestem (*Andropogon gerardii*), Indiangrass (*Sorghastrum nutans*), and switchgrass (*Panicum virgatum*) and the spatial distribution of species largely reflects topography and disturbance in the form of fire (Gibson & Hulbert, 1987). Grass cover is spatially continuous and, as the name implies, grasses extend well above the ground surface, reaching heights greater than 2 m (Knapp & Seastedt, 1986). Mean annual precipitation throughout the tallgrass prairie averages 80 to 100 cm. Riparian forest commonly surrounds even small channels (Figure 2).

Shortgrass prairie is dominated by grama grass (*Bouteloua* spp.) and mean annual precipitation averages 12 to 40 cm. Vegetation cover is spatially discontinuous, with patches of bare soil exposed between bunchgrasses, cacti, and small woody shrubs. Grasses seldom exceed 30 cm in height. Open riparian woodland can occur in large river corridors, but smaller channels commonly have minimal or no riparian

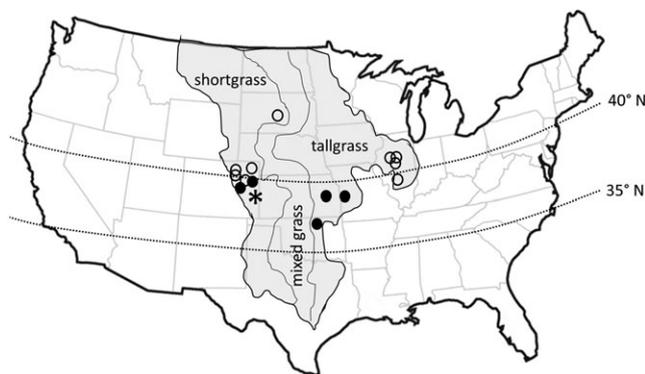


FIGURE 1 Location map showing the conterminous United States; the original extent of tallgrass, mixed grass, and shortgrass prairies in grey-shaded area; study areas with field sampling (solid black circles) and study areas with remote sampling (open black circles). The Arikaree River, which is featured in subsequent figures, is indicated by an asterisk. Extent of prairie from an online map by the Great Plains Nature Center (<http://www.gpnc.org/floraof.htm>)

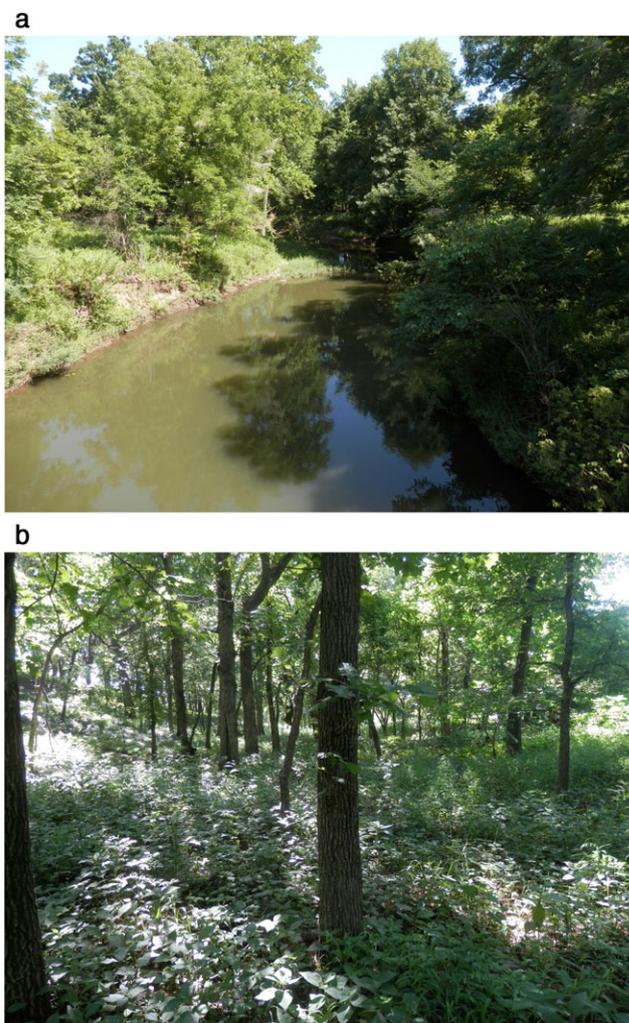


FIGURE 2 Sample views of a tallgrass prairie channel, Sand Creek in the Tallgrass Prairie Preserve of Oklahoma. (a) Active channel is approximately 15 m wide, perennial, and incised 1–2 m below the floodplain. (b) Floodplain has riparian forest and herbaceous species that provide prime habitat for ticks and chiggers. Floodplain is approximately 150 m wide [Colour figure can be viewed at wileyonlinelibrary.com]

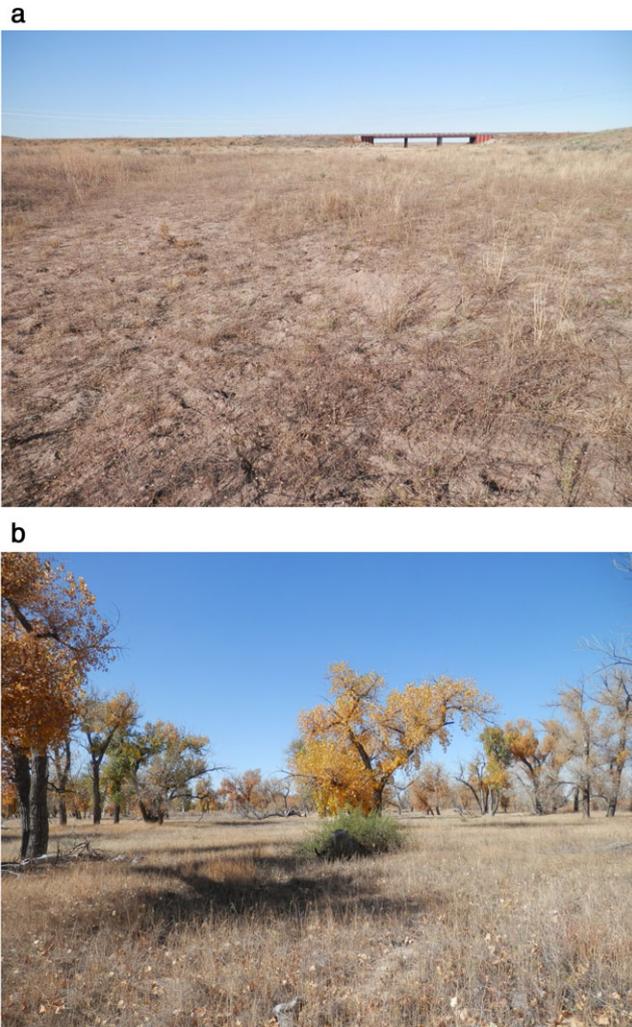


FIGURE 3 Sample views of shortgrass prairie channels in eastern Colorado. (a) Downstream view of South Fork Republican River, with bridge on an unpaved road at rear of view. Active channel in foreground is approximately 10 m wide; floodplain is approximately 100 m wide. (b) Downstream view of the floodplain along Big Sandy Creek, showing the open cottonwood woodland characteristic of larger channels in the region. Active channel (not visible) is towards the left in this view and was dry at the time the photo was taken. Floodplain is approximately 350 m wide [Colour figure can be viewed at wileyonlinelibrary.com]

forest (Figure 3). Mixed grass prairie is transitional between tallgrass and shortgrass prairies and contains grass species characteristic of the other prairie types.

Field sites were chosen to represent minimal human alteration, rather than on the basis of channel geometry characteristics such as sinuosity or gradient. This precluded inclusion of the largest rivers flowing through the prairies of the United States. Grassland ecosystems within the United States have been targeted for crops and grazing since settlement of the continental interior by people of European descent during the 19th century. Prairies once covered 40% of the conterminous United States but are now among the most endangered ecosystems in the nation (Samson & Knopf, 1994). Tallgrass prairie once covered 575,000 km² of North America, but only an estimated 2% now remains in a natural state. Of the 830,000 km²

of shortgrass prairie, between 20% and 40% now remains in a relatively natural state. Between 20% and 50% of mixed grass prairie remains. Major prairie river corridors such as the Illinois and the Missouri River and western, prairie tributaries of the Mississippi River (e.g., Platte, Arkansas, and Republican) have been highly modified by channelization, levees, and flow regulation, all of which have limited or effectively severed channel-floodplain connectivity and thus altered organic carbon dynamics within river corridors (Wohl, 2013c). The net effect of these alterations is likely to be substantial reductions in carbon stocks within river corridors, as demonstrated for the lower Mississippi River alluvial valley (Hanberry, Kabrick, & He, 2015). Consequently, we did not attempt to field-sample organic carbon storage within the corridors of larger prairie rivers, but we did use NRCS SSURGO online soils database, n.d. database values of bulk density and percent organic matter in alluvial soils along these rivers to estimate average soil organic carbon content. We refer to these sites as remotely sampled sites.

4 | METHODS

Intact soil cores were obtained in 19-cm vertical increments to depths of ≤ 1.0 m at transects across river corridors using a hand-held soil corer (Figure 4). Transects were spaced at intervals of 5X average width of the active channel and three transects were included in each study site. Each transect included at least 10 sample points at which multiple vertical increments were sampled. Sample points along each transect were spaced at equal intervals where there was no change in surface topography of the floodplain. Where the swale of a secondary or abandoned channel or a beaver pond was present, sample points were spaced more closely to include the variability associated with these features. At some sites, the presence of coarse sediment at depth limited sampling to < 1.0 m total depth. Each vertical increment of sample was bagged separately and kept frozen until submitted to the Colorado State University Soil and Water Testing Laboratory for analysis. In the lab, samples are dried and sieved to < 2 mm before subsamples are analysed for total carbon (TC) and CaCO₃ content. Organic carbon by weight is TC minus CO₃-C (Nelson & Sommers, 1982; Sherrod, Dunn, Peterson, & Kolberg, 2002). Samples were analysed for grain-size distribution using $\frac{1}{2}$ phi interval sieving for the range of -2 to > 3 phi units (0.0625 to 4 mm). We used soil bulk density values from the SSURGO database for field-sampled and remotely assessed sites, with bulk density averaged over the upper 100 cm of soil.

Because it was impractical to physically ascertain the actual thickness of fluvial sediments related to the contemporary channel, we calculated the volume of fluvial sediment for estimates of floodplain soil organic carbon stock using an arbitrary maximum thickness of 1.0 m for fluvial sediments under the longitudinal valley axis. We assumed a trapezoidal subsurface geometry with 3:1 side slopes based on measured valley side slopes exposed above the contemporary channel at multiple field sites. We measured the width of the river corridor at sample sites using a TruPulse 360B laser rangefinder. We defined the outer limits of the river corridor based on changes in topography and vegetation (Figure 4).

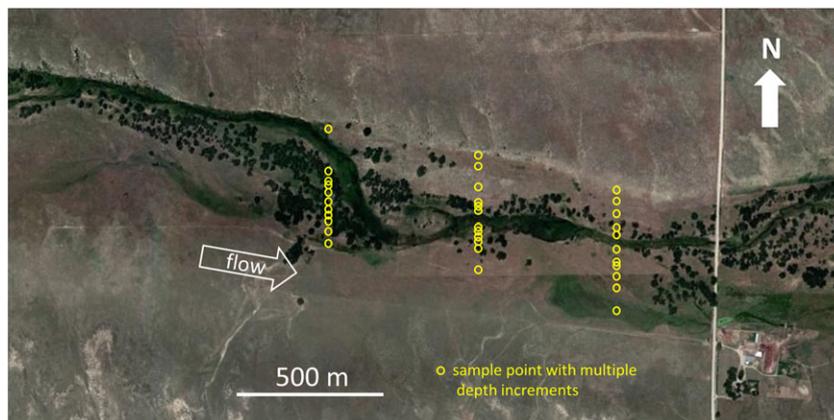


FIGURE 4 Aerial view of the sampling locations along the Arikaree River corridor in eastern Colorado. Yellow circles indicate horizontal position of sample points along each of three transects and spread of sample points in each transect indicates lateral extent of river corridor. White arrow indicates flow direction. Base imagery from Google Earth [Colour figure can be viewed at wileyonlinelibrary.com]

We expanded the range of sites analysed by using NRCS SSURGO soil maps to identify soil units within the floodplain at remotely sampled sites. We identified the spatial extent of the floodplain at these sites using Google Earth imagery and topographic and geologic maps. Where more than one soil unit was mapped within the floodplain, we used a simple average value of bulk density and percent organic matter in calculating organic carbon stocks. Percent organic matter was halved to estimate percent organic carbon within floodplain sediment (Pribyl, 2010).

To test *H1*, the spatial variability of soil organic carbon (%OC) at a subset of field-sampled sites was assessed by calculating Moran's *I* with an inverse distance weighting method in the *ape* package in R (Paradis, Claude, & Strimmer, 2004). The null hypothesis for this analysis is that no spatial autocorrelation exists (i.e., random distribution of %OC through the cross section). The alternative is that spatial autocorrelation exists (i.e., high %OC values near other high %OC values or high and low %OC values systematically occurring next to one another). The spatial variability of %OC was assessed within a planar, valley-fill cross section for three tallgrass and three shortgrass prairie river corridor transects and three mountain river corridor transects from the Southern Rocky Mountains in order to compare spatial variability at laterally mobile prairie channels with variability in a laterally confined mountain channel. The sites used in these analyses were those with the greatest number of possible vertical increments (i.e., sites where coarse-grained subsurface layers did not limit sample depths). Each transect was from a different river in each region (Arikaree, South Fork Republican, and Kiowa for shortgrass; Sand, Fleck, Schoolhouse for tallgrass; Little Beaver, Fish, Bennett for mountain).

To test *H2*, the values of %OC from all samples at each field site were grouped into tallgrass and shortgrass prairie populations. To test *H3*, we evaluated OC stock (Mg C/ha) values for three populations: tallgrass, shortgrass, and forested river floodplains of similar drainage area from the Southern Rocky Mountains of Colorado. Because a Shapiro–Wilk test indicates that the data are non-normal, a Wilcoxon rank sum test was used to evaluate differences between the tallgrass and shortgrass populations and Kruskal–Wallis and Dunn's tests were used to compare differences in medians among tallgrass, shortgrass, and forested sites. A Wilcoxon rank sum test was also used to evaluate differences between swale and other sites (overbank, levee, channel lag deposits) within a study reach.

The floodplain soil organic carbon stock values reported here represent first-order approximations because of the large uncertainties in volume of floodplain sediment; the use of a single average value of soil bulk density; and the spatial variability in organic carbon concentrations within the floodplain and use of a single median value for calculations. In addition, we only measure soil organic carbon and do not include living plant roots visible to the naked eye or belowground biomass, which can be substantial in prairies and can contribute significantly to soil organic matter (Seastedt, Parton, & Ojima, 1992). Floodplain soil organic carbon is typically the largest component of carbon within a river corridor (Sutfin et al., 2016), but including only this component means that our estimates of organic carbon in river corridors represent minimum values.

5 | RESULTS

A total of 370 sediment samples (each sample is a vertical increment core) were taken at six study reaches in the tallgrass prairie and six reaches in the shortgrass prairie. Table 1 summarizes characteristics of the field sites and the remotely sampled sites. The much smaller drainage areas of the field-sampled tallgrass prairie sites reflect the lack of unaltered larger river corridors in the tallgrass prairies. Of the shortgrass prairie sites, all but the Arikaree River are ephemeral. The Arikaree is intermittent at the sample site but includes a small beaver dam and pond.

The tallgrass prairie sites generally have finer-grained sediment (D_{50} averages 0.15 mm) within the floodplain than the shortgrass prairie sites (D_{50} averages 0.4 mm; Figure 5), as expected based on the more intense rock-weathering and soil-formation conditions of the wetter climate in regions of tallgrass prairie. The median values of %OC using NRCS data (1.5 and 0.4 for tallgrass and shortgrass, respectively) are very similar to those from the field samples (1.8 and 0.5 for tallgrass and shortgrass, respectively), although the tallgrass field sites have a larger discrepancy between median values of the NRCS (0.8%) and field data (1.8%) than the shortgrass sites (NRCS 0.4%, field 0.51%).

The Arikaree River sample area exemplifies a pattern consistently seen at tallgrass and shortgrass field sites. Where surface topography is sufficiently intact to preserve natural levees and abandoned channels in the form of swales, the swale sites (and the wetted active

TABLE 1 Characteristics of the study sites

Site	Drainage area (km ²)	Rcw (m); Rcv (m ³)	Bulk density ^a (g/cm ³)	% OC by weight ^b	OC stock ^c (Mg C/ha)
Tallgrass prairie					
Sand Cr, OK	32	190; 19,300	1.51	1.08 (1.5)	166(230)
Palmer Cr, KS	12	290; 29,300	1.33	3.05 (1.1)	410 (148)
Schoolhouse Cr, KS	3.8	50; 5300	1.33	3.89 (1.1)	517 (155)
Fleck Cr, MO	11	230; 23,300	1.48	2.24 (0.5)	332 (75)
E Drywood Cr, MO	9.2	35; 3800	1.48	2.19 (0.5)	324 (80)
Unnamed creek, MO	0.7	20; 2300	1.48	4.12 (0.5)	610 (85)
Median	10.1		1.48	1.80 (0.8)	371 (116)
Shortgrass prairie					
Illinois R at Hennepin, IL ^d	30,400	3430; 343,300	1.39	(1.5)	209
Fox R at Dayton, IL	7340	790; 79,300	1.40	(2.2)	309
Kyte R at Flagg Center, IL	3776	270; 27,300	1.32	(3)	400
Panther Cr near El Paso, IL	258	100; 10,300	1.32	(2.2)	299
E Branch Panther at El Paso	85	30; 3300	1.30	(2)	286
Illinois R at mouth	72,700	4550; 455,300	1.38	(4.2)	580
Median			1.35	(2.2)	304
Shortgrass prairie					
ECO 1 (SF Republican R, CO)	1636	60; 6300	1.46	0.03 (0.3)	4 (46)
ECO 2 (Spring Cr, CO)	856	40; 4300	1.43	0.10 (0.8)	14 (123)
ECO 3 (Big Sandy Cr, CO)	861	340; 34,300	1.70	0.78 (0.2)	133 (34)
ECO 4 (E Bijou Cr, CO)	792	410; 41,300	1.70	1.92 (0.6)	326 (103)
ECO 5 (Kiowa Cr, CO)	692	440; 44,300	1.53	1.46 (0.1)	223 (15)
Arikaree R, CO	3080	430; 43,300	1.68	0.77 (0.4)	129 (68)
Median	1190		1.61	0.51 (0.4)	131 (57)
Unnamed Arikaree trib, CO	2.6	50; 5300	1.44	(0.6)	92
Missouri R at Pierre, SD	676,390	2840; 284,300	1.42	(0.4)	57
S Platte near Crook, CO	52,794	3960 396,300	1.58	(0.4)	63
S Platte near Kersey, CO	26,830	1160; 116,300	1.62	(0.3)	49
Poudre R at Greeley, CO	5228	810; 81,300	1.45	(1.2)	175
Median			1.45	(0.4)	63

Note. Rcw = river corridor width; average values based on field data (at field-sampled sites) and Google Earth measurements at remote sites; these represent historical widths where valley is confined by artificial levees; total volume of fluvial sediments used in carbon stock estimate based on 100 cm maximum depth and 100 m length of valley bottom with 3:1 valley side slopes: Rcv is fluvial sediment volume used in calculating organic carbon stock.

^aBulk density from SSURGO database; average value for upper 100 cm of soil.

^bParenthetical values are using % by weight organic matter for the upper 100 cm of the soil, from the NRCS SSURGO database, divided by half; mean values used.

^cParenthetical values use SSURGO value of % organic carbon for calculation of organic carbon stock.

^dGrey-shaded cells are remotely sampled sites.

channel, in the case of the Arikaree) have higher percentages of organic carbon in the floodplain sediment than other sites such as overbank, levee, or channel lag deposits (Figure 6). The difference in these two populations at the Arikaree site is significant ($p = 0.04$).

The two-dimensional spatial patterns of organic carbon content with depth from the surface and distance across the floodplain at all field sites indicate substantial heterogeneity (Figure 7) and organic carbon concentration does not necessarily follow the expected decrease at greater depths that has been described for many upland soils (Jobbágy & Jackson, 2000). However, Moran's I results indicate that none of the nine transects analysed displays patterns of spatial autocorrelation with respect to %OC at $\alpha = 0.05$ (Table 2). A non-parametric Kruskal–Wallis test indicates no significant difference between the groups. In other words, there is no evidence to suggest

a non-random distribution of organic carbon in the measured channel cross-sections and results do not support $H1$.

Table 1 lists the median values of organic carbon concentration for all samples at each field site and each remotely sampled site, as well as median values across all samples within each of four populations (field-sampled tallgrass, remotely sampled tallgrass, field-sampled shortgrass, and remotely sampled shortgrass). The Wilcoxon rank sum test indicates that median values of organic carbon concentration at both field-sampled and remote sites in the tallgrass prairie are significantly higher (p value < 0.001) than those of the shortgrass prairie (Figure 8). Consequently, the results support $H2$.

Median values of organic carbon stock at field-sampled sites are largest at tallgrass prairie sites relative to forested and shortgrass prairie sites (Table 1) and values of forested sites tend to be intermediate

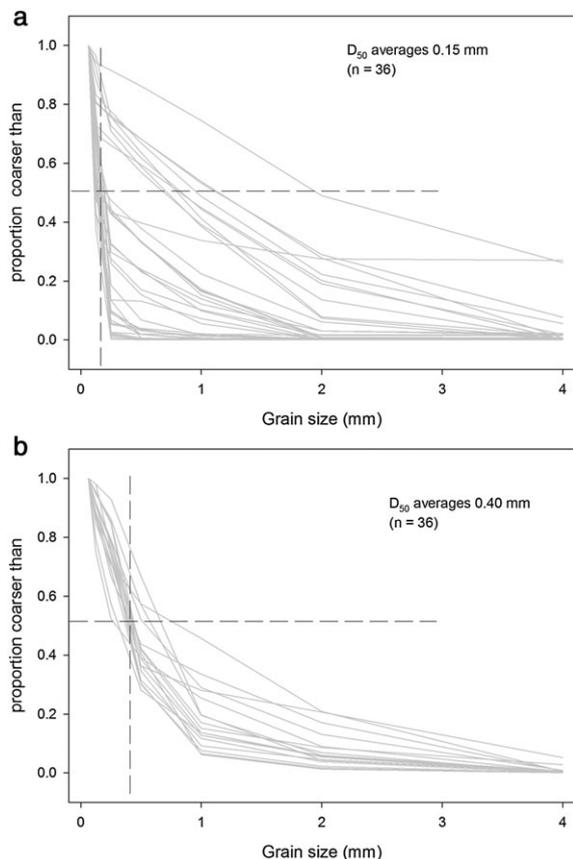


FIGURE 5 Cumulative grain-size distribution curves for (a) tallgrass and (b) shortgrass prairie sites sampled in the field. Dashed horizontal and vertical lines indicate the position of the median grain size for all samples, which is also listed in the legend, along with the sample size

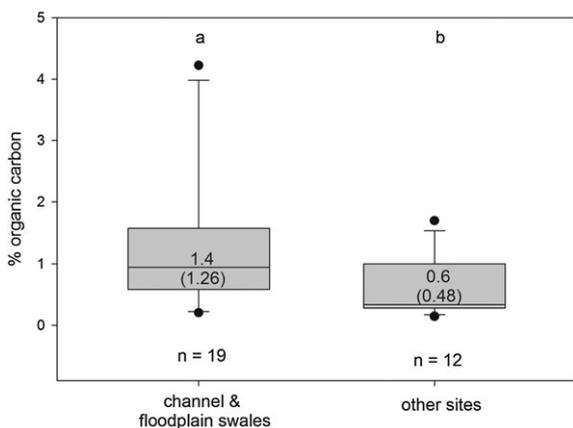


FIGURE 6 Percentages of organic carbon content in floodplain soils at different locations within the Arikaree River corridor in the shortgrass prairie of Colorado. Median value in box, with standard deviation in parentheses and sample size listed below box. The line within each box indicates the median value, box ends are the upper and lower quartile, whiskers are the 10th and 90th percentiles, and solid dots are outliers. Letters above each box indicate statistical differences ($p = 0.04$)

(Table 3). Using the organic carbon stock values in Table 3, no difference exists between forest and shortgrass ($p = .27$) or between forest and tallgrass ($p = .12$) sites. A significant difference ($p = .007$) exists

between tallgrass and shortgrass sites (Figure 9). The results thus do not support *H3* because river corridors at forested sites do not have significantly greater values of OC stock than prairie river corridors.

6 | DISCUSSION

As described in the previous section, statistical analyses do not indicate significant spatial heterogeneity in the distribution of floodplain soil organic carbon. However, we regard our analyses as a preliminary, rather than a definitive, test. Because of the way in which samples were collected, with substantial longitudinal distances between successive transects, we could not analyse spatial heterogeneity in three dimensions. Each analysis using Moran's *I* could only test spatial heterogeneity among the samples of a single river-corridor transect in which the total number of samples was limited to ~40, which limits the power of the analysis. Figure 7 clearly indicates the presence of spatial heterogeneity in soil carbon and this heterogeneity reflects differences in depositional environment and grain size (Figure 6).

The finding that spatial heterogeneity in floodplain soil organic carbon concentrations results from different depositional environments and associated differences in grain size and soil moisture accords with previous research on floodplain soil organic carbon. The distribution of sediment-associated carbon in floodplains of south-eastern Australia's Barwon–Darling River relates primarily to textural differences among floodplain depositional environments (Southwell & Thoms, 2011). The Australian study sites are located in drylands that are similar to the shortgrass prairie sites in this study. A spatially detailed study of particulate organic matter and dissolved organic carbon along the anabranching Macintyre River in a semi-arid portion of Australia found that secondary channels (anabranches) accumulate organic matter and carbon during periods of hydrological disconnection from the main channel. The fate of this organic matter and carbon (transport into the main channel vs burial in sediment) during periods of hydrological connection depends on the characteristics of individual flow pulses and location within the secondary channel (McGinness, Thoms, & Southwell, 2002), but secondary channels are hot spots of carbon accumulation.

Prairie river corridors, such as upland prairie areas, have experienced encroachment of woody vegetation during the past 150 years (Briggs et al., 2005; Riley & Dodds, 2012). Replacement of grasslands by woody plants results in a rapid increase in spatial heterogeneity of soil resources such as soil moisture and available nitrogen (Kleb & Wilson, 1997; Pärtel & Wilson, 2002), which affect soil organic carbon, and significant carbon accrual in both plant biomass and soils (McKinley & Blair, 2008). Woody plant invasion can decrease above-ground net primary production in xeric sites but increase production in mesic sites (Knapp et al., 2008). Expansion of woody vegetation into prairie river corridors thus has the potential to significantly alter floodplain soil carbon stocks. This may be a more significant effect in the future; however, because where detailed historical analyses have been undertaken (e.g., Konza Prairie of Kansas), only an estimated 10–15% of river corridors were forested as of circa 2000 (Briggs et al., 2005). The shortgrass prairie sites sampled for this study had open floodplain woodlands of mature cottonwood (*Populus* spp.) trees along the larger

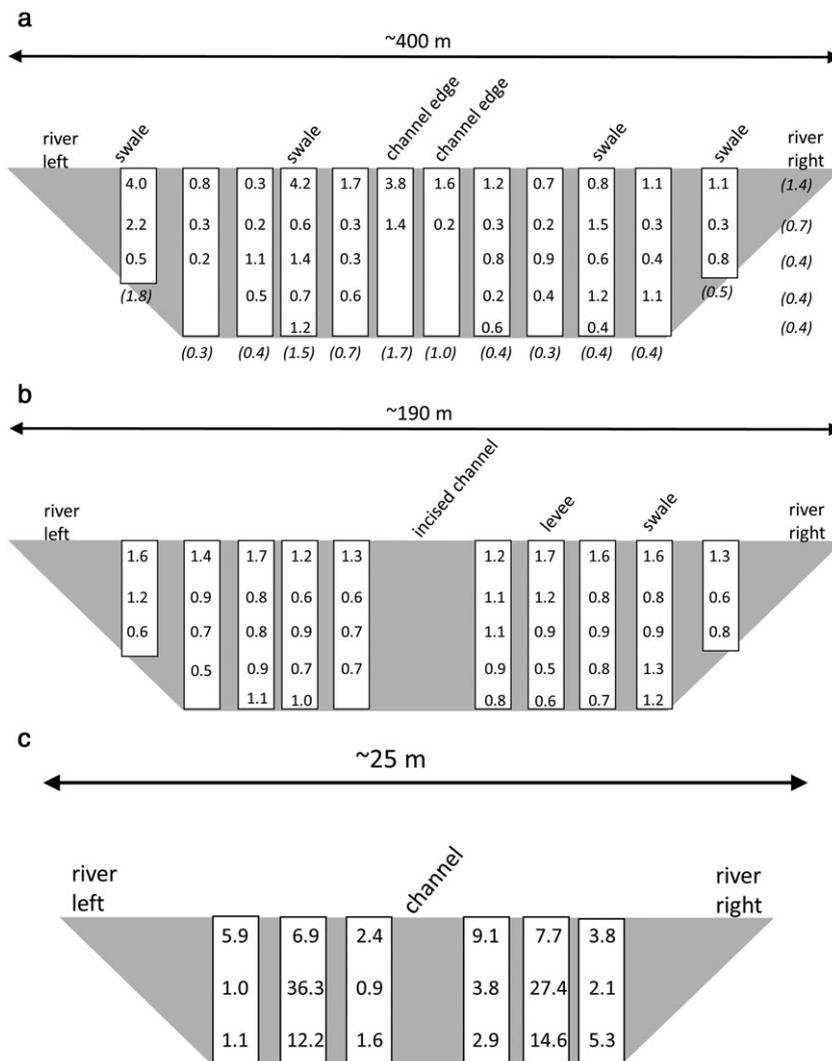


FIGURE 7 Schematic illustration of spatial variation in percentages of soil organic carbon among samples at (a) the Arikaree River, Colorado (shortgrass prairie), (b) Sand Creek, Oklahoma (tallgrass prairie), and (c) Little Beaver Creek, Colorado (forested mountain) field sites. Relative depth and lateral position of percent organic carbon values are correct, but lateral distances and depths are not to scale. View is downstream, as indicated by river left and right labels. Samples at the edge of the active channel, which contained water at the time of sampling, are shallow. Surface location of swales indicated by text at top of idealized channel cross section; abandoned channel deposits do not necessarily extend to the bottom of the sampled column because of lateral channel mobility through time. Features others than swales, channel edge, and levees are not identified. Valley bottom width indicated by arrows at top of each figure. Values of standard deviation among vertical samples below each column in parentheses and italics. Values of standard deviation at a depth across the valley at right in parentheses and italics

TABLE 2 Moran's *I* and significance tests for %OC at the shortgrass, tallgrass, and mountain floodplain sites

Sites	Moran's <i>I</i>	<i>p</i> value
Shortgrass		
Arikaree	0.13	.19
SF Republican	0.29	.21
Kiowa	0.18	.34
Tallgrass		
Sand	-0.07	.68
Fleck	0.16	.47
Schoolhouse	0.37	.39
Mountain		
Little Beaver	0.25	.07
Fish	0.18	.11
Bennett	0.26	.29

ivers (Figure 3). Analyses of changes in channel planform and riparian vegetation over multiple decades indicate that shortgrass prairie rivers can repeatedly alternate between a braided planform with minimal to no woody vegetation immediately following a large flood and a sinuous planform with cottonwood gallery forests if several decades have passed since the last major flood (e.g., Friedman & Lee, 2002). The

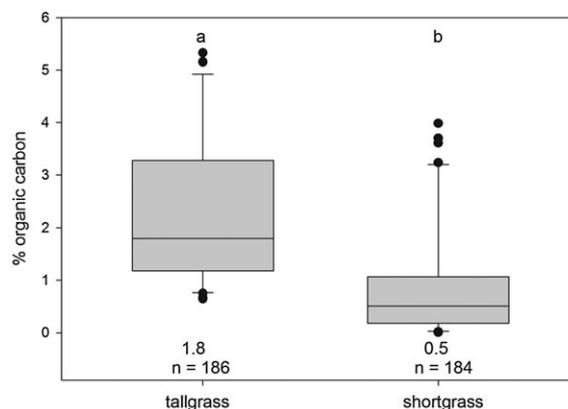
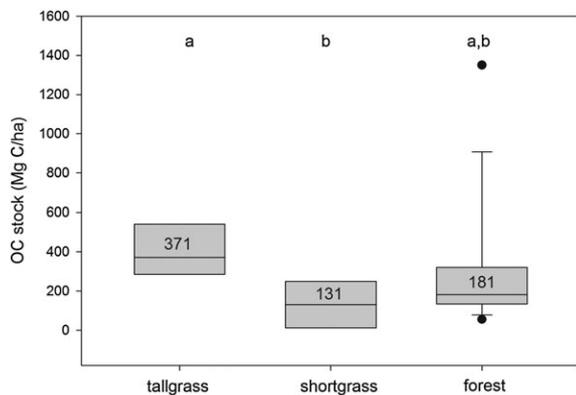


FIGURE 8 Percentages of organic carbon content in floodplain soils at different locations within the tallgrass and shortgrass river corridors sampled in the field. Median value and sample size listed below box. The line within each box indicates the median value, box ends are the upper and lower quartile, whiskers are the 10th and 90th percentiles, and solid dots are outliers. Letters at the top of the plot indicate significantly different median values

shortgrass prairie sites in eastern Colorado have widely spaced mature cottonwoods that likely date from major regional flooding episodes in 1935 and 1965 (Friedman & Lee, 2002). The tallgrass prairie sites had

TABLE 3 Organic carbon stocks from floodplain soils in temperate-latitude forested sites in the US; italics indicate similar latitude to the prairie sites (NC, TN, VA, KT, CO, n NM)

Site	Drainage area (km ²)	OC stock (Mg C/ha)	Reference
Forested watersheds			
Rhode Island	1.8	185	Ricker, Stolt, and Zavada (2014)
	1	287	
	3	417	
	0.8	130	
	3	213	
Congaree, SC	21,000	177	Ricker and Lockaby (2015)
MF Flathead, MT	2300	54	Appling, Bernhardt and Stanford (2014)
Mid-Atlantic Piedmont, US	11–1230	135–1350	Walter and Merritts (2008)
Front Range, CO	20–100	276	Sutfin (2016)
	10–15	170	
	10–15	464	
	10–100	158	
	10–20	102	
Median		181	
Grassland watersheds			
Tallgrass sites	32	166	This study
	12	410	
	3.8	517	
	11	332	
	9.2	324	
	0.7	610	
Median		371	
Shortgrass sites	1636	4	This study
	856	14	
	861	133	
	792	326	
	692	223	
	3,080	129	
Median		131	

**FIGURE 9** Organic carbon stocks for three types of river corridors. The line within each box indicates the median value, box ends are the upper and lower quartile, whiskers are the 10th and 90th percentiles, and solid dots are outliers. Letters at the top of the plot indicate significantly similar and different median values

slightly more dense floodplain forest than the Colorado sites (Figure 2) but information on potential woody vegetation encroachment through time is not available.

An important implication of the results described here is that river corridors in prairie regions, especially in tallgrass prairie, can contain substantial stocks of organic carbon in floodplain soils. Some process apparently concentrates organic carbon in floodplain soils of tallgrass

prairie sites sufficiently to create higher median values than found in forested floodplain soils, despite lower NPP in prairies than in forested environments. Although the extensive belowground biomass in tallgrass prairies can make important contributions to soil organic matter (Seastedt et al., 1992), we speculate that the primary process acting here is the presence of wetlands in prairie river corridors. Although such floodplain wetlands are now rare after more than a century of beaver trapping, flow regulation, levee construction, removal of instream wood, and land drainage, historical records from tallgrass prairie regions indicate the ubiquity and long duration of bottomland flooding in these regions (Wohl, 2013c). Floodplain wetlands are present in some of the relatively unaltered river corridors at which we conducted field sampling. The Arikaree River, CO and Sand Creek, OK have beaver dams and ponds, for example, and instream wood and floodplain ponds are present along Fleck Creek, MO and Schoolhouse Creek, KS. Organic carbon storage within river corridors of the tallgrass (and shortgrass) prairie has almost certainly been reduced through diverse forms land use and river engineering during the past century (Hanberry et al., 2015; Wohl et al., 2017) but may still remain unexpectedly high because of the past occurrence of wetlands.

Another implication of the results described here is that the similar values of median %OC and soil bulk density derived from field sampling and from the SSURGO database suggest that values derived from the database can be used for regional-scale estimates of OC stock in floodplain soils. Given the labour-intensive nature of field-

based soil organic carbon assessments, and the growing interest in quantitatively estimating organic carbon storage within river corridors (Cole et al., 2007; Sutfin et al., 2016; Wohl et al., 2017), the ability to use existing remote data is encouraging.

7 | CONCLUSIONS

Estimates of floodplain soil organic carbon stock in river corridors of the tallgrass and shortgrass prairies derived from field samples and from the NRCS SSURGO database indicate that river corridors in the tallgrass prairie are particularly enriched in soil organic carbon. This may partly reflect the greater historical presence of floodplain wetlands prior to intensive land use and river engineering since the 19th century. Although many efforts to increase organic carbon storage focus on afforestation or forest preservation in upland environments, greater attention to river corridors and floodplain wetlands can also form an important component of enhanced carbon sequestration.

ACKNOWLEDGEMENTS

We thank the National Geographic Society and the Colorado State University Water Center for financial support for this research. We also thank Missouri State Parks, the National Park Service, and The Nature Conservancy for permission to collect samples at field sites. The manuscript benefited from comments by two anonymous reviewers and Martin Thoms.

ORCID

E. Wohl  <http://orcid.org/0000-0001-7435-5013>

REFERENCES

- Appling, A. P., Bernhardt, E. S., & Stanford, J. A. (2014). Floodplain biogeochemical mosaics: A multidimensional view of alluvial soils. *Journal of Geophysical Research: Biogeosciences*, 119, 1538–1553.
- Beckman, N. D., & Wohl, E. (2014). Carbon storage in mountainous headwater streams: The role of old-growth forest and logjams. *Water Resources Research*, 50, 2376–2393.
- Bernal, B., & Mitsch, W. J. (2012). Comparing carbon sequestration in temperate freshwater wetland communities. *Global Change Biology*, 18, 1636–1647.
- Bridgman, S. D., Megonigal, J. P., Keller, J. K., Bliss, N. B., & Trettin, C. (2006). The carbon balance of North American wetlands. *Wetlands*, 26, 889–916.
- Briggs, J. M., Knapp, A. K., Blair, J. M., Heisler, J. L., Hoch, G. A., Lett, M. S., & McCarron, J. K. (2005). An ecosystem in transition: Causes and consequences of the conversion of mesic grassland to shrubland. *BioScience*, 55, 243–254.
- Buell, G. R., & Markewich, H. W. (2004). Data compilation, synthesis, and calculations used for organic-carbon storage and inventory estimates for mineral soils of the Mississippi River basin. US geological survey professional paper 1686-a, Reston, VA, 46 p.
- Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., ... Melack, J. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems*, 10, 172–185.
- Collins, B. D., Montgomery, D. R., Fetherston, K. L., & Abbe, T. B. (2012). The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology*, 139–140, 460–470.
- Ehrman, T. P., & Lamberti, G. A. (1992). Hydraulic and particulate matter retention in a 3rd-order Indiana stream. *Freshwater Science*, 11, 341–349.
- Friedman, J. M., & Lee, V. J. (2002). Extreme floods, channel change, and riparian forests along ephemeral streams. *Ecological Monographs*, 72, 409–425.
- Gibson, D. J., & Hulbert, L. C. (1987). Effects of fire, topography, and year-to-year climatic variation on species composition in tallgrass prairie. *Vegetatio*, 72, 175–185.
- Hanberry, B. B., Kabrick, J. M., & He, H. S. (2015). Potential tree and soil carbon storage in a major historical floodplain forest with disrupted ecological function. *Perspectives in Plant Ecology, Evolution and Systematics*, 17, 17–23.
- Harvey, J., & Gooseff, M. (2015). River corridor science: Hydrologic exchange and ecological consequences from bedforms to basins. *Water Resources Research*, 51, 6893–6922.
- Hill, B. H., & Gardner, T. J. (1987). Benthic metabolism in a perennial and an intermittent Texas prairie stream. *The Southwestern Naturalist*, 32, 305–311.
- Hilton, R. G., Galy, A., Hovius, N., Hornig, M.-J., & Chen, H. (2011). Efficient transport of fossil organic carbon to the ocean by steep mountain rivers: An orogenic carbon sequestration mechanism. *Geology*, 39, 71–74.
- Hilton, R. G., Meunier, P., Hovius, N., Bellingham, P. J., & Galy, A. (2011). Landslide impact on organic carbon cycling in a temperate montane forest. *Earth Surface Processes and Landforms*, 36, 1670–1679.
- Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, 10, 423–436.
- Johnson, M. S., Lehmann, J., Riha, S. J., Krusche, A. V., Richey, J. E., Ometto, J. P. H. B., & Couto, E. G. (2008). CO₂ efflux from Amazonian headwater streams represents a significant fate for deep soil respiration. *Geophysical Research Letters*, 35, L17401.
- Johnston, C. A. (2014). Beaver pond effects on carbon storage in soils. *Geoderma*, 213, 371–378.
- Kayranli, B., Scholz, M., Mustafa, A., & Hedmark, A. (2010). Carbon storage and fluxes within freshwater wetlands: A critical review. *Wetlands*, 30, 111–124.
- Kirschbaum, M. U. F. (2000). Will changes in soil organic carbon act as a positive or negative feedback on global warming? *Biogeochemistry*, 48, 21–51.
- Kleb, H. R., & Wilson, S. D. (1997). Vegetation effects on soil resource heterogeneity in prairie and forest. *The American Naturalist*, 150, 283–298.
- Knapp, A. K., Briggs, J. M., Collins, S. L., Archer, S. R., Bret-Harte, M. S., Ewers, B. E., ... Cleary, M. B. (2008). Shrub encroachment in North American grasslands: Shifts in growth form dominance rapidly alters control of ecosystem carbon inputs. *Global Change Biology*, 14, 615–623.
- Knapp, A. K., & Seastedt, T. R. (1986). Detritus accumulation limits productivity of tallgrass prairie. *BioScience*, 36, 662–668.
- Mann, P. J., Eglinton, T. I., McIntyre, C. P., Zimov, N., Davydova, A., Vonk, J. E., ... Spencer, R. G. M. (2015). Utilization of ancient permafrost carbon in headwaters of Arctic fluvial networks. *Nature Communications*, 6, 7856. <https://doi.org/10.1038/ncomms8856>
- McGinness, H. M., Thoms, M. C., & Southwell, M. R. (2002). Connectivity and fragmentation of flood plain-river exchanges in a semiarid, anabranching river system. In F. J. Dyer, M. C. Thoms, & J. M. Olley (Eds.), *The structure, function, and management implications of fluvial sedimentary systems* (pp. 19–26). IAHS Pub. No. 276: Oxfordshire.
- McGuire, A. D., Melillo, J. M., Joyce, L. A., Kicklighter, D. W., Grace, A. L., Moore, B., & Vorosmarty, C. J. (1992). Interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America. *Global Biogeochemical Cycles*, 6, 101–124.

- McKinley, D. C., & Blair, J. M. (2008). Woody plant encroachment by *Juniperus virginiana* in a mesic native grassland promotes rapid carbon and nitrogen accrual. *Ecosystems*, *11*, 454–468.
- Mitra, S., Wassmann, R., & Vloek, P. L. G. (2005). An appraisal of global wetland area and its organic carbon stock. *Current Science*, *88*, 25–35.
- Mitsch, W. J., Bernal, B., Nahlik, A. M., Mander, U., Zhang, L., Anderson, C. J., ... Brix, H. (2013). Wetlands, carbon, and climate change. *Landscape Ecology*, *28*, 583–597.
- Nelson, D. W., & Sommers, L. E. (1982). Total carbon, organic carbon, and organic matter methods of soil analysis. Part 2, Chemical and microbiological properties, 539–579.
- NRCS SSURGO online soils database. (n.d.). Accessed February 2017. <https://websoilsurvey.sc.egov.usda.gov/app/HomePage.htm>
- Paradis, E., Claude, J., & Strimmer, K. (2004). APE: Analyses of phylogenetics and evolution in R language. *Bioinformatics*, *20*, 289–290.
- Pärtel, M., & Wilson, S. D. (2002). Root dynamics and spatial patterns in prairie and forest. *Ecology*, *83*, 1199–1203.
- Post, W. M., Emanuel, W. R., Zinke, P. J., & Stangenberger, A. G. (1982). Soil carbon pools and world life zones. *Nature*, *298*, 156–159.
- Pribyl, D. W. (2010). A critical review of the conventional SOC to SOM conversion factor. *Geoderma*, *156*, 75–83.
- Ricker, M. C., & Lockaby, B. G. (2015). Soil organic carbon stocks in a large eutrophic floodplain forest of the southeastern Atlantic Coastal Plain, USA. *Wetlands*, *35*, 291–301.
- Ricker, M. C., Stolt, M. H., & Zavada, M. S. (2014). Comparison of soil organic carbon dynamics in forested riparian wetlands and adjacent uplands. *Soil Science Society of America Journal*, *78*, 1817–1827.
- Riley, A. J., & Dodds, W. K. (2012). The expansion of woody riparian vegetation, and subsequent stream restoration, influences the metabolism of prairie streams. *Freshwater Biology*, *57*, 1138–1150.
- Robertson, A. I., Bunn, S. E., Boon, P. I., & Walker, K. F. (1999). Sources, sinks and transformations of organic carbon in Australian floodplain rivers. *Marine and Freshwater Research*, *50*, 813–829.
- Ruesch, A., & Gibbs, H. K. (2008). New IPCC Tier-1 global biomass carbon map for the year 2000. Available online from the Carbon Dioxide Information Analysis Center [<http://cdiac.ornl.gov>], Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Samson, F., & Knopf, F. (1994). Prairie conservation in North America. *BioScience*, *44*, 418–421.
- Sanders, L. M., Taffs, K. H., Stokes, D. J., Sanders, C. J., Smoak, J. M., Enrich-Prast, A., ... Marotta, H. (2017). Carbon accumulation in Amazonian floodplain lakes: A significant component of Amazon budgets? *Limnology and Oceanography*, *2*, 29–35.
- Schlesinger, W. H., & Melack, J. M. (1981). Transport of organic carbon in the world's rivers. *Tellus*, *33*, 172–187.
- Scott, D. N., & Wohl, E. E. (2017). Evaluating carbon storage on subalpine lake deltas. *Earth Surface Processes and Landforms*, *42*, 1472–1481.
- Seastedt, T. R., Parton, W. J., & Ojima, D. S. (1992). Mass loss and nitrogen dynamics of decaying litter of grasslands: The apparent low nitrogen immobilization potential of root detritus. *Canadian Journal of Botany*, *70*, 384–391.
- Sherrod, L. A., Dunn, G., Peterson, G. A., & Kolberg, R. L. (2002). Inorganic carbon analysis by modified pressure-calciometer method. *Soil Science Society of America Journal*, *66*, 299–305.
- Sims, P. L., & Singh, J. S. (1978). The structure and function of ten western North American grasslands: III. Net primary production, turnover and efficiencies of energy capture and water use. *Journal of Ecology*, *66*, 573–597.
- Smith, J. C., Galy, A., Hovius, N., Tye, A. M., Turowski, J. M., & Schleppei, P. (2013). Runoff-driven export of particulate organic carbon from soil in temperate forested uplands. *Earth and Planetary Science Letters*, *365*, 198–208.
- Southwell, M., & Thoms, M. (2006). A gradient or mosaic of patches? The textural character of inset-flood plain surfaces along a dryland river system. In J. S. Rowan, R. W. Duck, & A. Werritty (Eds.), *Sediment dynamics and the hydromorphology of fluvial systems* (pp. 487–495). Wallingford, UK: IAHS Publ. 306.
- Southwell, M., & Thoms, M. (2011). Patterns of nutrient concentrations across multiple floodplain surfaces in a large dryland river system. *Geographical Research*, *49*, 431–443.
- Sutfin, N. A. (2016). Spatiotemporal variability of floodplain sediment and organic carbon retention in mountain streams of the Colorado Front Range. *Dissertation*. Fort Collins, Colorado, USA: Colorado State University.
- Sutfin, N. A., Wohl, E. E., & Dwire, K. A. (2016). Banking carbon: A review of organic carbon storage and physical factors influencing retention in floodplains and riparian ecosystems. *Earth Surface Processes and Landforms*, *41*, 38–60.
- Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., & Zimov, S. (2009). Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, *23*, GB2023.
- Thoms, M. C. (2003). Floodplain-river ecosystems: Lateral connections and the implications of human interference. *Geomorphology*, *56*, 335–349.
- Walter, R. C., & Merritts, D. J. (2008). Natural streams and the legacy of water-powered mills. *Science*, *319*, 299–304.
- Wohl, E. (2013a). Floodplains and wood. *Earth-Science Reviews*, *123*, 194–212.
- Wohl, E. (2013b). Landscape-scale carbon storage associated with beaver dams. *Geophysical Research Letters*, *40*, 1–6.
- Wohl, E. (2013c). *Wide rivers crossed: The South Platte and the Illinois of the American prairie*. Boulder, CO: University Press of Colorado.
- Wohl, E., Hall, R. O., Llninger, K. B., Sutfin, N. A., & Walters, D. (2017). Carbon dynamics of river corridors and the effects of human alterations. *Ecological Monographs*, *87*, 379–409.

How to cite this article: Wohl E, Pfeiffer A. Organic carbon storage in floodplain soils of the U.S. prairies. *River Res Applic.* 2018;34:406–416. <https://doi.org/10.1002/rra.3269>