# Carbon sequestration potential of process-based river restoration

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### Abstract

Floodplain restoration can enhance capacity for carbon sequestration by facilitating higher water tables, deposition of fine sediment, and increased input and residence time of organic matter. We measured floodplain soil organic carbon stocks in nine stream restoration projects across the western United States and compared them to nearby degraded and reference condition floodplains. Degraded floodplains had the lowest soil mean carbon stocks in the majority of floodplains measured (range 161-894 Mg C/ha), and reference stocks had the highest stocks (range 391-904 Mg C/ha) of those with statistically significant differences between the three categories. Across all sites measured, stream restoration sites, referred to as treatment sites, had stocks (range 203-1028 Mg C/ha) similar to degraded condition floodplains but the largest range. When modeled under degraded conditions, four out of nine of the treatment sites had significantly higher OC stocks than predicted. Climate and geologic variables are most influential in predicting carbon stocks, and floodplains in the interior western USA have the highest carbon stocks. As the demand for carbon sequestration increases due to climate change, ecologically responsible floodplain restoration provides a significant opportunity for carbon storage. However, despite the statistically significant relationships we observed in this dataset, the variations within the data in relation to degraded/treatment/reference categories illustrate the uncertainties in quantifying the effects of restoration on floodplain carbon stocks.


## 1. Introduction

Stream restoration can potentially increase floodplain carbon stocks by enhancing deposition of organic matter and sequestration of soil organic carbon. Within the global carbon cycle, however, potential magnitudes of organic carbon stocks in the freshwater hydrosphere are not yet well constrained and the uncertainty is particularly substantial for carbon stocks in river corridors (i.e., active channels and floodplains; Battin et al., 2009; Aufdenkampe et al., 2011; Hilton and West, 2020). This uncertainty partly reflects the limited number of field-based quantifications of river corridor carbon stocks (Sutfin et al., 2016; Hinshaw and Wohl, 2021) and partly reflects the substantial spatial variability that can be present in these stocks, with limited portions of a river corridor accounting disproportionately for total carbon stock in the river network or the entire watershed (Wohl et al., 2012; Wohl and Knox, 2022). Despite these uncertainties, there is a growing need to quantitatively estimate and predict organic carbon stocks in river corridors in connection with the potential for carbon sequestration as one of the goals of stream restoration (e.g., Yan et al., 2022).

Here, we examine whether there are detectable differences in floodplain carbon stock in categories of impacted or degraded floodplains, treatment floodplains that have recently undergone restoration, and reference floodplains that display relatively greater floodplain function and connectivity. This study design conceptually models carbon storage potential as a result of restoration at short and longer timescales, where treated floodplains represent short timescales and reference floodplains represent longer timescales. Before-after restoration studies are necessary to directly attribute changes in carbon stocks to restoration activities. We recommend this strategy in future as more restoration projects emphasize hydrologically reconnecting the channel and floodplain, but these studies will be most effective when they include a timespan of a decade or more from before to after treatment. We were not able to access the restoration sites in this study before treatment.

We first review existing knowledge of organic carbon stocks in river corridors and how human activities have altered these stocks. We then discuss how stream restoration might enhance carbon stocks and describe the design of this study, in which our objective is to determine whether there are differences in carbon stocks in the three categories of floodplains at diverse sites in the western United States.

**Organic carbon stocks in river corridors**

Carbon stock refers to the mass of carbon stored in a carbon pool such as soil or living vegetation. Carbon sequestration refers to the ability to capture and store carbon; sequestration can maintain or increase carbon stocks. Within river corridors, floodplains typically contain much greater carbon stock than active channels. Within floodplains, carbon stocks occur as living biomass (i.e., vegetation and aquatic organisms), dissolved carbon in surface and ground water, dead biomass including large wood in the floodplain, and soil organic carbon (Sutfin et al., 2016; Wohl et al., 2017). Floodplain soil organic carbon (SOC) typically forms the largest stock within a river corridor unless the river corridor lacks a floodplain (Scott and Wohl, 2018b). Published values for floodplain SOC range from 1.4 Mg C/ha at a site in South Carolina, USA to 7735 Mg C/ha on a floodplain in northwestern Montana, USA (Sutfin et al., 2016). We seek to quantitatively estimate existing and potential floodplain SOC stocks in connection with floodplain restoration. Although riparian vegetation growth increases organic carbon stocks within aboveground biomass (e.g., Hanberry et al., 2015), we do not account for living biomass (plants and vegetation) in this study. Rather, we focus on SOC as an integrative representation of above- and below-ground carbon stocks at longer timescales.

Although typically the largest carbon stock in floodplains, SOC is highly spatially variable (Samaritani et al., 2011; Sutfin et al., 2016; Wohl et al., 2017). In this context, we use soil to refer to all mineral sediment and particulate organic matter in floodplain alluvium. Floodplain SOC stocks reflect complex interactions among climate; geology; soil moisture, texture, and residence time; biomass; and organic matter supply (Hinshaw and Wohl 2021). Optimal conditions for large floodplain SOC stocks are wide, wet, relatively stable valley bottoms with long sediment residence times, cooler climates, and high organic matter inputs (Sutfin et al., 2016; Hinshaw and Wohl 2021; Sutfin et al., 2021). Residence times of floodplain sediment and associated SOC depend on fluvial erosion rates and vary from years to decades in small floodplains or locations close to the active channel(s) to thousands of years in larger floodplains and at locations farther from the channel (Wohl, 2015; Sutfin and Wohl, 2019). Residence time of floodplain SOC also reflects rates of mineralization through microbial processing that releases $CO_2$ to the atmosphere and dissolved organic carbon to downstream transport and to groundwater (Bouillon et al., 2009; Handique, 2015).

Spatial and temporal variations in soil moisture, organic matter inputs, and soil residence time can create significant lateral and longitudinal variations in floodplain SOC in large floodplains (Lininger et al., 2018) and longitudinal variations in smaller mountain streams (Scott and Wohl, 2018a; Sutfin and Wohl, 2019). Consequently, quantitative estimates of floodplain SOC stock may be most accurate and appropriately applied at the reach scale, where a reach is a length of river corridor with consistent channel and valley geometry that is at least several times as long as average channel width. Spatial variations in floodplain SOC also complicate attempts to use space-for-time substitutions in which sites from different rivers or different portions of a river are used to understand potential temporal changes following restoration, for example. This is the approach we use in this study, but we acknowledge the limitations and uncertainties inherent in this approach.

**Human alterations and restoration of floodplain carbon stocks**

Human alterations of river corridors can reduce organic carbon stocks in floodplain vegetation, downed wood, and soil (Hanberry et al., 2015; Wohl et al., 2017). Alterations include floodplain drainage that reduces primary productivity and soil moisture; deforestation that reduces primary productivity; and removal of large, downed wood from the channel and floodplain that reduces sediment trapping and eventual soil development. In addition, flow regulation, artificial levee construction, and channelization decrease channel-floodplain connectivity, in turn reducing associated floodplain inundation and deposition of sediment and organic matter.

Stream restoration can potentially enhance carbon stocks by restoring processes that facilitate higher floodplain water tables and associated reducing conditions in the soil, as well as greater floodplain primary productivity and increased deposition of sediment and organic matter. Access to soil moisture from raised water tables facilitates new riparian vegetation growth that provides higher supply of organic matter via leaf litter. The conditions optimal for promoting large floodplain carbon stocks correspond to Stage 0 anastomosing wet woodland or anastomosing grassed wetland in the Cluer and Thorne (2014) stream evolution model. Reconfiguration and reconnection of river corridors to achieve Stage 0 conditions has been increasingly applied in the United States as part of stream restoration efforts within the past decade (Booth et al., 2009; Powers et al., 2019; Mattern et al., 2020; Flitcroft et al., 2022).

The process of stream restoration implementation has a non-zero carbon footprint, estimated by Chiu et al. (2022) as 9-14 kg $CO_2$ per meter of stream restored. However, ecological restoration can transform the relative proportions of landscapes considered as carbon sources versus sinks and provide significant capacity to more efficiently sequester, rather than emit, carbon over decadal timescales (Zhou et al., 2020).

Commonly, only a small portion of the project budget for most stream restoration projects is allocated to monitoring, and practically no budget is allocated to measure carbon stocks. However, incentives exist for practitioners to start measuring carbon. Other than the informational value of quantification of carbon sequestered from the atmosphere, carbon credits in the units of tons of carbon can be sold on the carbon market (Wara, 2007; Schneider et al., 2019). This practice is widely applied within industries of agriculture and forestry (Ribaurdo et al., 2010; Paul et al., 2013), and floodplain restoration could also qualify for carbon offsets (e.g., Matzek et al., 2015; Sapkota and White, 2020).

To our knowledge, only one study thus far has directly examined the effects of restoration on carbon stock in river corridors. Samaritani et al. (2011) compared soil carbon stocks and fluxes in channelized and restored portions of the Thur River in Switzerland in the context of spatial heterogeneity and temporal variability but did not explicitly compare total carbon stock between restored and degraded areas. The restored floodplain had a larger range and higher heterogeneity of organic carbon stocks and fluxes. Related studies indicate the effects of human alterations on river corridor carbon stock by comparing altered and natural river corridors in the same region. Cabezas and Comin (2010) found that floodplain soils with natural land cover have higher organic carbon stocks than agricultural portions of the floodplain along Spain's Middle Ebro River, a pattern similar to that from Lininger and Polvi (2020), who showed decreasing floodplain SOC stocks with increasing human alteration in Swedish river corridors.

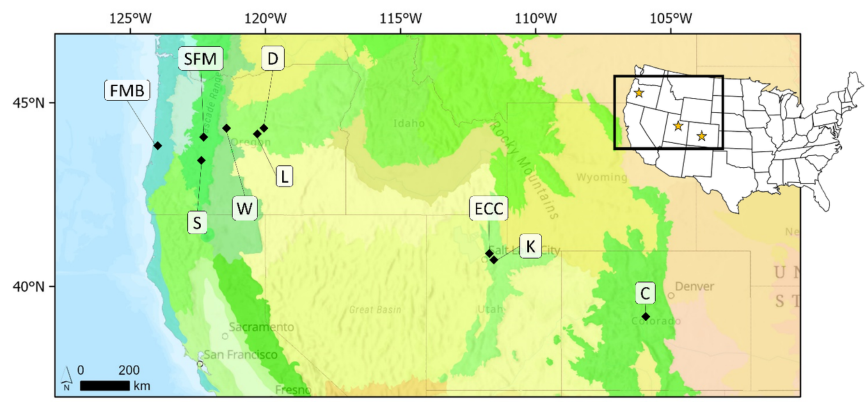
To enhance our understanding of carbon sequestration potential in stream restoration, we must address at least two questions: (1) Can measurable quantities of carbon be added to floodplain soil through restoration, and over what timescales?, and (2) What framework best facilitates understanding and measuring carbon stocks in stream restoration? Ideally, measurement of carbon in stream restoration would occur before and after restoration takes place. As a surrogate for pre and post restoration conditions, we use three alternative floodplain states to evaluate floodplain SOC stocks: degraded, treatment, and reference. Alternative states are self-reinforcing states of equilibrium that can exist simultaneously under the same environmental conditions (Holling, 1973; May, 1977). We consider our categories of floodplain to approximate alternative states of semi-equilibrium that have been affected by different levels of human intervention. We use the terminology of degraded, treatment, and reference to designate potential near-endmembers and an intermediate position on a spectrum of restoration, but recognize that 1) degraded and reference sites are not exact endmember positions, 2) the treatment, or stream restoration project category, is likely not in equilibrium and may fall anywhere along the spectrum, and 3) reference conditions do not always provide ideal comparisons because we may not be able to restore streams to a selected reference state (Dufour and Piegay 2009), and it may not be possible to find exact matches between reference, treatment, and degraded sites with respect to the many environmental variables that can influence river corridors and carbon stock.

We use the term treatment instead of restored because stream restoration sites are not "restored" as soon as construction takes place. The term degraded can encompass a range of impaired or impacted floodplain conditions. Degraded sites represent intensive land uses that have degraded natural floodplain processes over time, and commonly include histories of levee construction, channel straightening, grazing, agriculture, timber harvest, or other activities that disconnect channels from their floodplains. We use degraded as a descriptive term and recognize that degraded floodplains can fall within a spectrum of conditions that may not be directly caused by one single type of floodplain alteration. Rather, floodplains chosen for the degraded category can represent the culmination of land or resource uses that may have limited floodplain function over the past few centuries.

The primary objective of this study is to quantitatively compare floodplain organic carbon stocks in degraded, treatment, and reference stream corridors. Given the assumptions outlined above, we hypothesize that degraded sites contain the least carbon, treatment sites contain an intermediate amount of carbon, and reference sites contain the most carbon. Our secondary objective is to use the data to examine factors that influence floodplain SOC stock at sites across the regional scale of the western United States.

## 2. Study Areas

We include data from 9 sites in the western United States (6 in Oregon, 2 in Utah, 1 in Colorado; Figure 1, Table 1). Each site includes all three categories of degraded, treatment, and reference floodplain sampling areas, with multiples of each category of reach where possible. We combined data for multiple treated reaches along the same stream where applicable, particularly in Fivemile Bell and Whychus Creek in Oregon and East Canyon Creek in Utah. In all sites except Colorado, floodplain categories are as physically close to each other as possible, typically along the same streams, to reduce variability due to climate and geology. In Colorado, the first iteration of samples was lost in transit; thus, we provide all three categories from different locations within the South Park region of Colorado but acknowledge the limitations of direct comparison between categories.




Associated with each treatment site is at least one reference site and at least one degraded site. In two cases, two sites within the same ecoregion share a reference site. This occurs in Deep Creek and Lost Creek in Oregon and Kimball Creek and East Canyon Creek in Utah. These two sets of sites are within reasonable proximity to share the same reference site of Gray's Creek (Oregon) and McLeod Creek (Utah), respectively. Some but not all degraded sites in our dataset are candidate sites for future restoration projects and can thus benefit from baseline data before restoration takes place. We chose each floodplain and assigned it to a category based on personal communications with local stakeholders and project designers, particularly scientists at the USDA Forest Service, Utah State University Swaner Preserve and EcoCenter, and the stream restoration company EcoMetrics in Colorado. Individual site characteristics are listed in Table 1.

**Table 1. Site characteristics of stream restoration projects considered in the study.**

| Restoration Project Stream Name |
|---|

Fivemile Bell, OR
Staley Creek, OR
South Fork McKenzie River, OR
Whychus Creek, OR
Deep Creek, OR
Lost Creek, OR
East Canyon Creek, UT
Kimball Creek, UT
Salt Creek, CO
[a]Sample sizes refer to number of floodplain soil samples collected and include shared reference samples for sites where refere

Restoration techniques used at each treatment site varied, but the basic objective was to hydrologically reconnect the channel and floodplain. The primary techniques involved (i) introducing large wood or beaver dam analogues to the channel to create obstructions that would enhance in-channel sedimentation and overbank flow and/or (ii) re-grading the valley floor by removing or adding floodplain sediment and decreasing the flow stage needed to create overbank flow (Powers et al., 2019). Most of the river restoration projects employing these techniques have been undertaken only within the past decade, limiting the ability to evaluate longer-term patterns of river response, including carbon sequestration.

## 3. Methods

### *3.1 Field Methods*

We followed the field methods described in Hinshaw and Wohl (2021) and collected 11 soil samples per moisture class (wet or dry), where possible, in each category (degraded, treatment, reference) of floodplain using a 3-cm-diameter 30-cm-length spoon sampling soil corer. The sample size of 11 per category is drawn from supplemental information in Sutfin and Wohl (2017), where bias and variance are shown to stabilize after 11 samples per geomorphic unit. Moisture categories were determined based on vegetation (riparian vs upland species), microtopography, and soil moisture conditions at the time of sampling. Moist soil with wetland vegetation (e.g., sedges, rushes) was categorized as wet; all other sites were categorized as dry. All sampling was conducted during relatively dry summer conditions. Dividing samples into separate moisture categories is intended to account for differences in carbon content of saturated vs dry soil found in previous literature (e.g., Moyano et al., 2012; Manning et al., 2015) and we used simple t-tests to test for differences between wet and dry samples. At each sampling location, we noted vegetation present and sample depth.

Samples were obtained at 30-cm vertical intervals at multiple depths to 90 cm from the same sampling hole where the floodplain sediment was sufficiently deep. Soil texture by hydrometer and total and organic carbon analyses were done by a commercial laboratory. Bulk density estimates were assigned based on soil type using the median estimate from a collection of approximations using pedotransfer functions from Leonaviciute (2000) and Ruehlmann and Korschens (2009); regression analyses of data from Chaudhari et al. (2013); and a table of common bulk density values from StructX (Structx 2023). In total, 653 samples collected over the summers of 2020-2022 were used in the analyses for this study. The bulk density values were used in the following equation to convert from organic carbon content to organic carbon stock (Eq. 1):

$$\text{Organic Carbon Stock } \left(\frac{\text{Mg}}{\text{ha}}\right) = Organic\ Carbon\ \%\ * 1\ m\ depth * \text{bulk density } \left(\frac{\text{Mg}}{m^3}\right) * 10,\ 000\frac{m^2}{\text{ha}} [1]$$

### *3.2 Data Analysis*

#### *3.2.1 Within-site comparisons*

Without considering stream restoration intervention, the long-term carbon sequestration potential at a particular degraded site could be conceptually considered as the difference in carbon stocks between reference and degraded categories. Accordingly, the short-term carbon storage since restoration, if any, could be represented conceptually by the difference between degraded and treatment categories. We examined relationships of carbon stock via within-site comparisons, where we compared carbon stocks between degraded, treatment, and reference categories within one site using ANOVA tests and pairwise comparisons between treatments using the emmeans package in R version 4.2.2 (Lenth 2023, R Core Team 2022).

*3.2.2 Predicting treatment stocks under degraded conditions*

With the intent to conceptually estimate carbon sequestered since restoration treatment, we predicted treatment floodplain carbon stocks with models created for degraded floodplains. Hypothetically, model-predicted treatment stocks represent pre-treatment conditions at the treatment category floodplain, i.e., if it were still degraded. We utilize this method as a thought exercise and recognize the large assumption that pre-restoration conditions are similar to the degraded floodplains associated with each restoration project. We acknowledge the centrality of the assumption and suggest that direct, repeat pre and post measurements would better represent the estimate of carbon sequestered since restoration. After predicting treatment stocks using the degraded-derived models, we calculated the differences between measured and predicted treatment stocks as a first-order approximation of how much carbon could be sequestered if environmental conditions are sufficiently similar between degraded, treatment, and reference sites.

3.2.3 *Across-site comparisons*

We tested for differences between degraded, treatment, and reference carbon stocks (Mg/ha) for sites combined by Level III ecoregion (Omernik and Griffith, 2014). We categorized Type III ecoregions by where the treatment floodplain was located for a set of degraded, treatment, and reference floodplains within a site.

Along with testing categories and regions for all data, we also explored models that best explain carbon stock for the entire dataset. We used ANOVA tests for both the ecoregion comparisons and the entire dataset categorical comparisons and compared estimated marginal means with the emmeans package in R (Lenth 2023). Then, using the complete dataset, we investigated correlations between carbon stock and potential numeric predictor variables related to soil texture and climate. Using variables with significant correlations and additional categorical predictor variables of research interest, we used three types of models to estimate carbon content (%). We used carbon content rather than stocks to avoid uncertainty introduced by the assigned bulk density values that were used to calculate stocks, i.e., we used direct laboratory results with no modification. We split the dataset using 80% of sample points for model building and the remaining 20% for model evaluation.

We compared three modeling approaches to carbon estimation using a variety of predictors including treatment category within a site. In all models discussed, we excluded data from Colorado due to the non-associated nature of the degraded-treatment-reference datasets in this region. In the Colorado dataset, degraded, treatment, and reference sites are far (>10 km) apart and not along the same stream. Using data from Oregon and Utah only, we began with a linear mixed model. To account for the lack of independence of samples from the same floodplains, lack of independence of samples from different depths from the same hole, and the availability-based nature of the stream restoration projects we chose to sample, we modeled carbon content as a mixed model with random and fixed effects in a nested block study design using the lmer function from the lme4 package in R version 4.1.3 (R Core Team, 2022). Due to the large number of complexities to be considered in the mixed generalized linear model, we also modeled carbon using a gradient boosted regression tree model that utilizes elements of decision trees and machine learning to account for characteristics of the dataset without the need to account for the same linear model sensitivities. The gradient boosting model was built with the dismo package in R (Hijmans et al., 2021). Parameters for this model were those suggested by Elith et al. (2008). In addition, we modeled the data with a random forest model using regression decision trees with the randomForest package in R (Liaw and Wiener 2002). We compared results from the three models with the root mean square error (RMSE) and the coefficient of determination ($R^2$) between 20% of the data reserved for model evaluation and the model predictions.

## 4. Results

*4.1 Within-site comparisons*

In all sites except those in Colorado, either treatment or reference stocks are highest, and either treatment or degraded are the lowest of the three categories (Figure 2, Tables 2 & 3). Reference stocks are generally estimated to be higher than degraded stocks (seven of nine sites) although the result is only significant at the 95% confidence level for three sites. Colorado sites excluded, the only sites with statistically highest stocks are reference sites (Fivemile Bell, Whychus Creek, and East Canyon Creek). Colorado sites have the highest stocks in degraded floodplains, lowest in treatment floodplains, and intermediate stocks in reference floodplains. Although we expected carbon stocks to vary with moisture, only three floodplains of the 38 measured (East Canyon Creek Degraded Reach 1, Staley Creek Degraded Reach 2, and South Fork McKenzie Reference Reach) have significant differences between carbon stocks for wet versus dry samples. Therefore, for simplicity, we did not account for moisture when conducting tests for significant differences between categories.

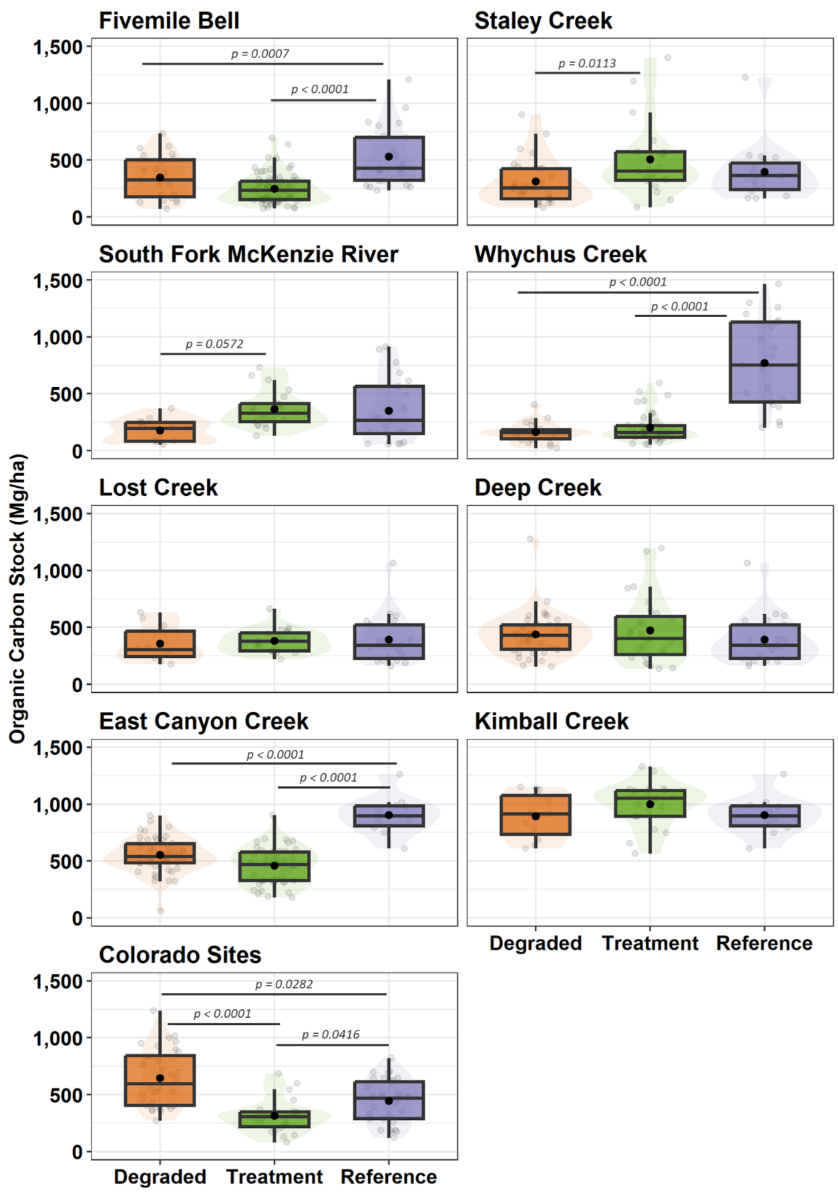


**Table 2.** Carbon stocks at each site. Every site consists of three sampling categories: degraded, treatment, and reference. In several sites, multiple reaches were measured within a category at each site.

| Site | Value[a] | Degraded Stocks (Mg/ha) Reach 1 | Degraded Stocks (Mg/ha) Reach 2 | Degraded Stocks (Mg/ha) Reach 3 | Treatment Stocks (Mg/ha) Reach 1 | Treatment Stocks (Mg/ha) Reach 2 | Treatment Stocks (Mg/ha) Reach 3 | Reference Stocks (Mg/ha) Reach 1 | Re St (M Re 2 |
|---|---|---|---|---|---|---|---|---|---|
| **Fivemile Bell** | Mean C stocks | 397 ± 115 | 293 ± 127 | | 247 ± 47 | 283 ± 48 | 228 ± 63 | 593 ± 166 | |
| *Oregon Coast Range* | No. samples | 12 | 11 | | 31 | 17 | 24 | 25 | |
| | Combined mean | **347 ± 81** | **347 ± 81** | **347 ± 81** | **249 ± 30** | **249 ± 30** | **249 ± 30** | **593 ± 166*** | **59 16** |
| **South Fork McKenzie River** *Willamette National Forest, Oregon* | Mean C stocks | 177 ± 71 | | | 364 ± 73 | | | 348 ± 130 | |
| | No. samples | 11 | 0 | 0 | 21 | 0 | 0 | 21 | 0 |
| | Combined mean | **177 ± 71** | **177 ± 71** | **177 ± 71** | **364 ± 73** | **364 ± 73** | **364 ± 73** | **348 ± 130** | **34 13** |
| **Staley Creek** *Willamette National Forest, Oregon* | Mean C stocks | 279 ± 132 | 338 ± 119 | | 659 ± 273 | | | 396 ± 146 | |
| | No. samples | 11 | 15 | | 21 | | | 15 | |
| | Combined mean | **313 ± 83** | **313 ± 83** | **313 ± 83** | **659 ± 273** | **659 ± 273** | **659 ± 273** | **396 ± 146** | **39 14** |
| **Whychus Creek** *near Sisters, Oregon* | Mean C stocks | 154 ± 41 | 170 ± 81 | | 176 ± 43 | 249 ± 99 | | 811 ± 191 | |
| | No. samples | 12 | 10 | | 24 | 14 | | 22 | |
| | Combined mean | **161 ± 39** | **161 ± 39** | **161 ± 39** | **203 ± 44** | **203 ± 44** | **203 ± 44** | **811 ± 191*** | **81 19** |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Lost Creek**[b] *near Ochoco National Forest, Oregon* | Mean C stocks | 355 ± 116 | | | 380 ± 51 | | | 391 ± 96 | |
| | No. samples | 10 | | | 19 | | | 21 | |
| | Combined mean | **355 ± 116** | **355 ± 116** | **355 ± 116** | **380 ± 51** | **380 ± 51** | **380 ± 51** | **391 ± 96** | **39 96** |
| **Deep Creek**[b] *Ochoco National Forest, Oregon* | Mean C stocks | 421 ± 143 | 452 ± 58 | | 515 ± 141 | | | 391 ± 96 | |
| | No. samples | 16 | 22 | | 28 | | | 21 | |
| | Combined mean | **439 ± 65** | **439 ± 65** | **439 ± 65** | **515 ± 141** | **515 ± 141** | **515 ± 141** | **391 ± 96** | **39 96** |
| **East Canyon Creek**[c] *near Park City, Utah* | Mean C stocks | 538 ± 103 | 564 ± 66 | 551 ± 89 | 430 ± 75 | 488 ± 72 | | 904 ± 127 | |
| | No. samples | 16 | 20 | 11 | 22 | 21 | | 10 | |
| | Combined mean | **552 ± 46** | **552 ± 46** | **552 ± 46** | **458 ± 51** | **458 ± 51** | **458 ± 51** | **904 ± 127*** | **90 12** |
| **Kimball Creek**[c] | Mean C stocks | 894 ± 135 | | | 1028 ± 102 | | | 904 ± 127 | |
| *near Park City, Utah* | No. samples | 11 | | | 22 | | | 10 | |
| | Combined mean | **894 ± 135** | **894 ± 135** | **894 ± 135** | **1028 ± 102** | **1028 ± 102** | **1028 ± 102** | **904 ± 127** | **90 12** |
| **Colorado Sites** | Mean C stocks | 768 ± 116 | 763 ± 303 | 419 ± 58 | 313 ± 67 | | | 403 ± 92 | 64 26 |
| *South Park, Colorado*[d] | No. samples | 15 | 6 | 11 | 22 | | | 22 | 11 |
| | Combined mean | **647 ± 91*** | **647 ± 91*** | **647 ± 91*** | **313 ± 67** | **313 ± 67** | **313 ± 67** | **484 ± 106** | **48 10** |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **All sites combined** | Combined mean | **447 ± 34** | **447 ± 34** | **447 ± 34** | **413 ± 38** | **413 ± 38** | **413 ± 38** | **538 ± 59** | **53 59** |

[a] Error values are margin of error for a 95% confidence interval
[b] Lost Creek and Deep Creek use the same reference reach data from Gray's Creek.
[c] East Canyon Creek and Kimball Creek use the same reference reach data from McLeod Creek.
[d] Sites in Colorado were collected on different streams farther away from each other than typical datasets.
Degraded Reach

[a] Error values are margin of error for a 95% confidence interval
[b] Lost Creek and Deep Creek use the same reference reach data from Gray's Creek.
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[d] Sites in Colorado were collected on different streams farther away from each other than typical datasets.
Degraded Reach

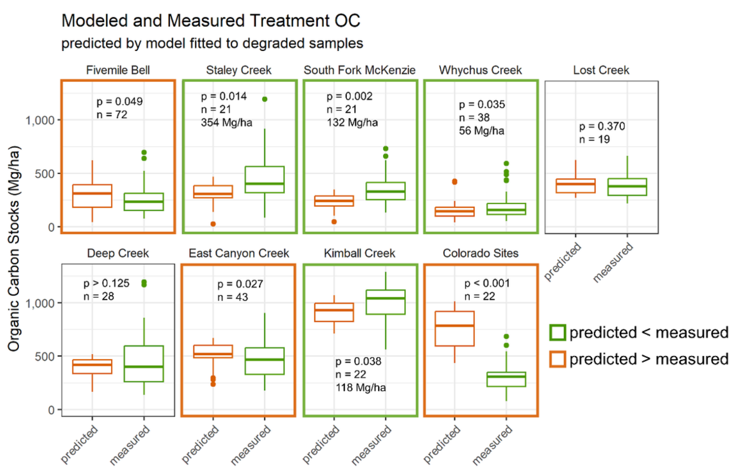
**Table 3.** Ranked categories of floodplains **Table 3.** Ranked categories of floodplains

| Site | Degraded Stocks | Treatment Stocks |
|---|---|---|
| Fivemile Bell | intermediate | lowest |
| Staley Creek | lowest | highest |
| South Fork McKenzie River | lowest | highest |
| Whychus Creek | lowest | intermediate |
| Lost Creek | lowest | intermediate |
| Deep Creek | intermediate | highest |
| East Canyon Creek | intermediate | lowest |
| Kimball Creek | lowest | highest |
| Colorado Sites | highest* | lowest |
| indicates significance at the 95% confidence level | * indicates significance at the 95% confidence level | * indicates significa |

*4.2 Modeled treatment stocks*

When treatment stocks were estimated with a degraded model fitted to each site, the four sites of Staley Creek, South Fork McKenzie River, Whychus Creek, and Kimball Creek showed higher measured than predicted treatment stocks at the 95% confidence level (Figure 2). Three sites had lower than predicted stocks, and two did not show significant differences. The estimated differences between measured and predicted treatment stocks for sites where measured stocks exceeded predicted stocks are 354 Mg/ha, 132 Mg/ha, 56 Mg/ha, and 118 Mg/ha for Staley Creek, South Fork McKenzie River, Whychus Creek, and Kimball Creek, respectively (Figure 2).

*4.3 Across-site comparisons*



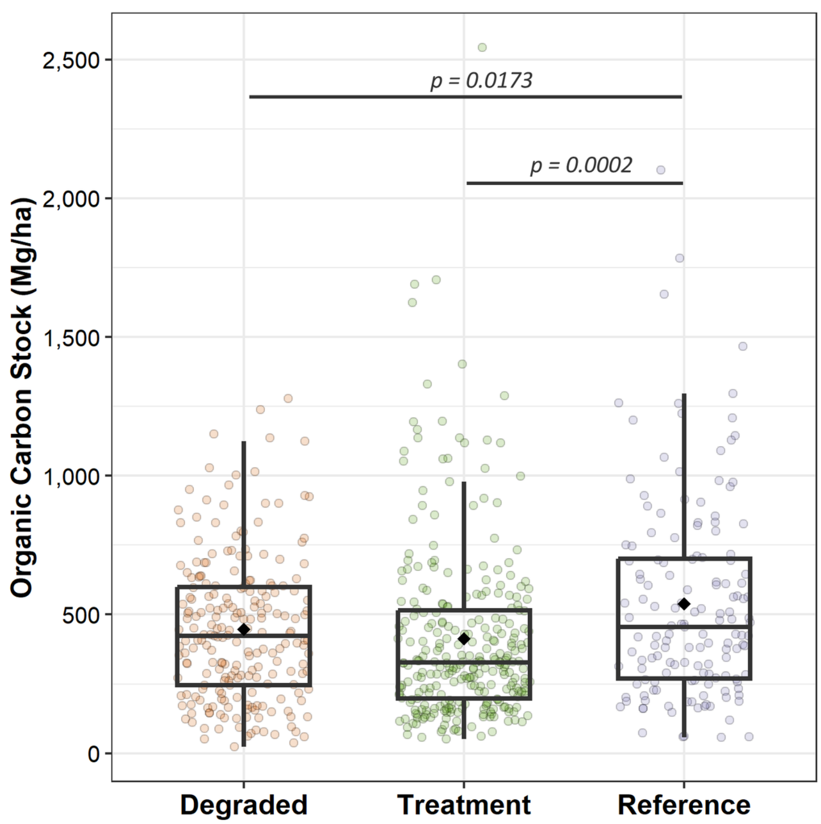

When analyzing all sites together, we found the largest magnitude correlations between carbon stocks and grain size, particularly between percent silt content (ρ= 0.531, p = 9E-49) and sand content (ρ= -0.524, p = 2E-47) with positive and negative correlations, respectively (Table 4). Correlations between organic carbon stocks and location data, climate data, and elevation are weak (<0.3) but significant and suggest that carbon stocks are somewhat higher in the high elevation mountain ranges in the interior of the continent that have cooler climates.

Table 4. Correlations between organic carbon stock and numeric variables. All correlations are significant at the 95% confidence level.

| Variable | Pearson Correlation with Carbon Stock | p-value |
|---|---|---|
| % Silt | 0.531 | 9.2E-49 |
| % Sand | -0.524 | 2.4E-47 |
| % Clay | 0.298 | 7.0E-15 |
| Depth | -0.292 | 2.6E-14 |
| x (longitude) | 0.284 | 1.4E-13 |
| elevation | 0.279 | 3.8E-13 |
| y (latitude) | -0.275 | 7.9E-13 |
| Mean annual temperature | -0.244 | 2.8E-10 |
| Drainage area | -0.217 | 2.1E-08 |
| Mean annual precipitation | -0.204 | 1.4E-07 |
| NDVI | 0.124 | 1.5E-03 |

The Wasatch and Uinta Ecoregion, represented by samples collected in Utah, had significantly higher carbon stocks than all other ecoregions (p [?] 0.0016 for all pairwise comparisons). Within ecoregions, reference stocks are highest in the Coast Range, Blue Mountains and Wasatch and Uinta regions.

Combining all samples from all sites revealed significantly higher reference carbon stocks than degraded and treatment, and no significant difference between degraded and treatment (Figure 4). This result was the same for a simple comparison of the three treatment categories and a model comparison that accounted for moisture, site, sample location, and depth.

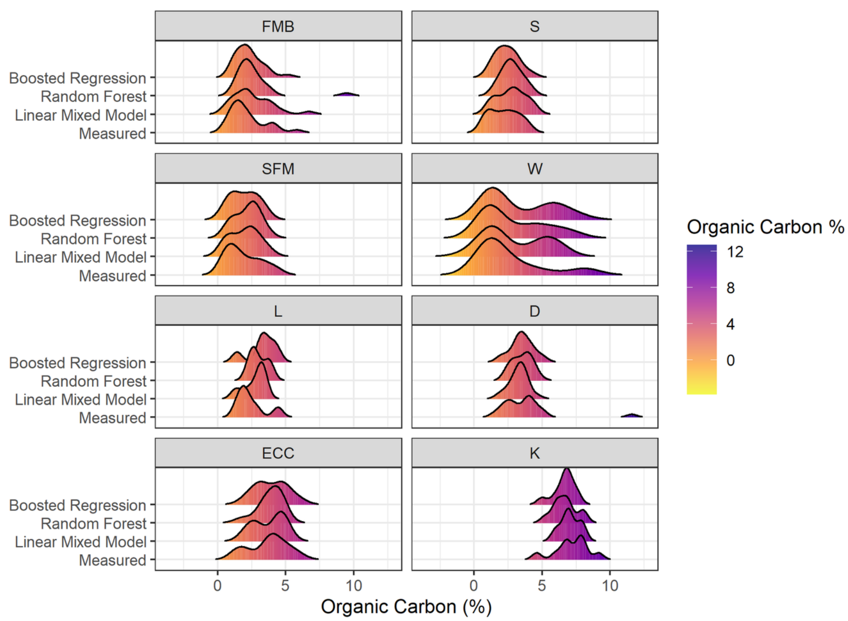


*4.4 Regional modeling*

We modeled data from all locations combined using a linear mixed model, a random forest model, and a gradient boosted regression model (Figure 5). Because Colorado site categories (degraded, treatment, reference) are not along similar streams like the other site datasets, we excluded Colorado from the model comparison. With the remaining data, we included 80% of the dataset in all three models and reserved 20% of the dataset for model evaluation. We compared the models with the root mean square error and coefficient of determination ($R^2$) between the measured and predicted data. The random forest model had the lowest root mean square error (RMSE) of the 3 models at 1.26 % OC and the highest $R^2$ of 0.68. All models tended to overestimate degraded and reference carbon content of the dataset. Model descriptions and results are shown in Table 5.

Table 5. Model predictors, results, and errors from linear mixed, random forest, and boosted regression models built to predict % organic carbon in randomly selected 20% proportion of the total data.

| Model | Predictor Variables |
|---|---|
| Measured Data | NA |
| Linear Mixed Model | Site, reach sample hole, depth, mean annual temperature, NDVI, silt+clay, soil type |
| Random Forest Model | treatment, depth, texture, elevation, NDVI, mean annual temperature, drainage area, land cov |
| Boosted Regression Model | treatment, depth, texture, elevation, NDVI, mean annual temperature, drainage area, land cov |




In summary, the results presented here provide partial support for the original hypothesis in that reference sites generally have the highest values of floodplain soil organic carbon stock. The strongest predictors of floodplain soil carbon stock are percent silt content and climate, with the greatest stock in relatively cool, wet climates.

## 5. Discussion

The sites selected for soil sampling represent a geographic range of elevation, climate, and lithology for the western United States. The values of floodplain SOC at these degraded, treatment, and reference sites fall within the most common range (100-1000 Mg C/ha; Sutfin et al., 2016) of published values for floodplain SOC in temperate-latitude rivers. Our primary objective was to determine whether there are detectable differences in floodplain carbon stock between the categorized floodplain states of degraded, treatment, and reference, and to assess the carbon sequestration potential of stream restoration within the context of these simple categories. A secondary objective was to examine factors that influence floodplain SOC stock at a larger, regional scale across the western United States.

*5.1 Within-site comparisons*

Degraded floodplains have the lowest carbon stocks in the majority of sites, which supports the hypothesis although the results are not statistically significant. Among sites with complete datasets, treatment and reference were tied for having the highest carbon stocks, but the reference category has more statistically significantly higher stocks than the treatment category.

Deep Creek is the only site where reference soil carbon stocks are lower than both treatment and degraded stocks. The reference site chosen for Deep Creek was Gray's Creek, a beaver meadow about 15 km away from Deep Creek. Gray's Creek and Deep Creek are within the North Fork Crooked River watershed, but the two sites are underlain by different geology. Gray's Creek lies within Eocene- to Oligocene-aged volcaniclastic tuff in the John Day Formation, while Deep Creek overlies the Columbia River Basalt formation of Miocene age. Basalt weathers to clay minerals, while tuff contains higher silica content and is more resistant to weathering than basalt. In our dataset, floodplain soils underlain by basalt bedrock geology contained a higher proportion of silt and clay. The results from correlation of numerical predictor variables show that grain size has the largest magnitude of negative correlation to carbon stock, indicating that silt and clay content are significant contributors to carbon stock, as demonstrated in previous work (e.g., Cai et al., 2016). Gray's Creek also has a smaller drainage area than Deep Creek, with 42 $km^2$ and 224 $km^2$, respectively. Deep Creek hosts large ponderosa pine (*Pinus ponderosa)* trees and is classified as evergreen forest in the National Land Cover Dataset (Homer et al., 2012), while Gray's Creek is classified as emergent vegetation and contains no large trees other than willows. Gray's Creek is also the reference site chosen for Lost Creek. Lost Creek is within the same geological formation as Gray's Creek and trends from least to greatest mean carbon stocks in degraded, treatment, and reference sites. In hindsight, a different reference condition should have been chosen for Deep Creek but this oversight indicates the importance of considering the underlying geology when associating categories of floodplain.

High variance of soil carbon stocks from our samples reflects relatively low sample sizes per floodplain category at each site, but also aligns with the variable nature of soil organic carbon accumulation over time. Floodplains are highly dynamic ecosystems that undergo frequent disturbance and include multiple stages of vegetative succession and soil development. Floodplain heterogeneity enhances diversity of habitats for aquatic and terrestrial species, and in turn supports more biodiverse and resilient floodplains (Wohl, 2016). Increased heterogeneity and river mobility within the floodplain are desirable goals for many restoration projects, but multiple sequences of disturbance and succession induced by frequent lateral channel migration can also lead to a variety of patches with different soil carbon concentrations and stocks (Lininger et al., 2018; Sutfin et al., 2021).

*5.2 Modeled treatment stocks*

Predicted treatment stocks were lower than measured treatment stocks in four sites when models using degraded category data were used to estimate SOC stocks in treatment floodplains. Models made separately for each site are intended to minimize variability in climate, geology, and soil formation processes. The input of degraded data to make these models utilizes the assumption that treatment sites were similar to degraded sites before restoration took place. To truly test this concept, a before-after-control-impact study design is appropriate. In our data, magnitudes of differences in carbon stocks in treated versus degraded, divided by the number of years since restoration, suggest carbon sequestration rates that seem unrealistically high. If the difference between measured and predicted carbon stocks serves as an estimate of carbon sequestered since treatment, under the assumption that pre-restoration conditions are well represented by degraded sites, the magnitude of carbon stored since restoration in Staley Creek, South Fork McKenzie River, Whychus Creek, and Kimball Creek is 354 Mg ha$^{-1}$, 132 Mg ha$^{-1}$, 56 Mg ha$^{-1}$, and 118 Mg ha$^{-1}$, respectively. These four sites also contained higher treatment stocks than degraded stocks. Divided by the number of years since restoration, the per-year carbon sequestration approximations for the four sites are 118 Mg ha$^{-1}$ year$^{-1}$ for Staley Creek, 66 Mg ha$^{-1}$ year$^{-1}$ for South Fork McKenzie, 14 Mg ha$^{-1}$ year$^{-1}$ for Whychus Creek, and 59 Mg ha$^{-1}$ year$^{-1}$ for Kimball Creek. Table 3 in Sutfin et al. (2016) lists accumulation rates ranging from 0.03-8 Mg C ha$^{-1}$ year $^{-1}$, which is an order of magnitude lower than the estimated differences from this study. We cannot accurately estimate carbon accumulation rates in the sites for this study because there are no measurements of antecedent conditions, but the substantial difference between our inferred rates and the range of published rates for diverse environments around the world suggests that our inferred rates are too high. Thus, we infer that the sites with measured treatment stocks that were higher than degraded stocks, or higher than modeled treatment stocks, likely contained more carbon than degraded floodplains before treatment, facilitated by historic conditions prior to degradation that likely factored into the choice to select the area for stream restoration. Laurel and Wohl (2019), for example, demonstrated that relatively high soil organic carbon stocks can persist in beaver-modified floodplains even after beavers abandon a site and the floodplain becomes drier.

In future studies, it would be beneficial to consider time since degradation, specific manner of degradation, and further information about historic conditions prior to degradation when comparing the categories of degraded, treatment, and reference. Although floodplains such as South Fork McKenzie River and Staley Creek underwent large scale regrading of the floodplain as part of restoration, it is promising that their soil carbon stocks were not destroyed by the disturbance within the organic-rich upper layer. Instead, these sites retained their existing carbon stocks and/or sequestered carbon since treatment. For purposes other than research, such as carbon offset verification, we recommend that direct comparisons to estimate magnitude of carbon stored since restoration be made on repeat pre-post data rather than assuming degraded conditions can directly reflect pre-treatment conditions.

*5.3 Across-site comparisons*

Two Colorado floodplains and all Utah sites show significant carbon stocks compared to other regions. This is likely explained by high elevation and low mean annual temperature compared to other areas. It is pertinent to consider mountain valleys of the interior western USA as zones of high potential carbon stock. Floodplain drainage, development for agriculture, and associated degradation of wide, wet valley bottoms with potential for high carbon stock (i.e., beaver meadow complexes and other wetlands) could have disproportionately high impacts on carbon sequestration (Wohl et al., 2018). Considering that US states such as Colorado likely have lower total budgets for stream restoration compared to states in the Pacific Northwest that are greatly driven by funding from fisheries conservation, carbon sequestration can serve as an additional added benefit and enhanced return on investment in stream restoration within the Intermountain West.

Both sites within the Cascades ecoregion, Staley Creek and South Fork McKenzie River, contained higher carbon stocks at treatment sites than at degraded or reference sites. Because the data in this study do not directly compare pre-and post-restoration stocks, our ability to quantify carbon sequestered directly as a result of restoration is limited. However, both projects in this region utilized similar methods of stream restoration, in which the valley bottom was regraded to fill incised channels and to lower high-elevation surfaces, and large wood was laid across the valley bottom to maintain hydraulic roughness as vegetation reestablishes. In both cases, surface water was spread across the valley bottom, and field observations of declining upland species and early succession wetland vegetation suggest water tables were raised. Whether observed increases in soil carbon stock took place at each site or persisted from former valley conditions, the manner of restoration sampled in this ecoregion facilitated the development of river corridors with processes and planforms that support carbon sequestration. In addition, carbon stocks in the form of large wood were greatly increased at both sites via the project designs.

The most influential factors contributing to carbon stock are climate and geology, as outlined in the conceptual framework for floodplain carbon stock in Hinshaw and Wohl (2021) and further illuminated by correlations between this dataset and environmental variables. Correlations between grain size, temperature, and elevation support patterns of carbon stocks described in existing literature (Wang et al., 2013; Cai et al., 2016; Qi et al., 2016). Generally, SOC stock increases with (i) elevation and associated climate trends toward cooler temperatures in all study areas and (ii) higher proportion of silt and clay. Geographically, SOC stock increases toward the center of the continent. Potential SOC stock depends primarily on intermediate to long term processes such as soil formation from weathering of underlying lithology and gradual organic matter input from vegetation, but local hydrologic and geomorphic conditions, especially those influenced by floodplain restoration, can set the stage for soil carbon emissions versus soil carbon sequestration. Elevated concentrations of SOC can persist for decades after degradation or drying (Laurel and Wohl, 2019), but rather than optimizing carbon stock potential, dry, degraded floodplains gradually decrease in SOC capacity over time (Ferre et al., 2014; Hanberry et al., 2015; Limpert et al., 2020; Lininger and Polvi, 2020).

### *5.4 Regional modeling*

Given that methods to verify carbon offsets commonly rely on models and encounter substantial uncertainty (Smith et al., 2020), the three models that we used estimated floodplain carbon stock exhibited reasonable performance. Of the three models, the Random Forest model performed the best. Although the linear mixed model results aligned well with the measured carbon and the other model results, this model relies on information about the specific sites to account for the study design and therefore would be more laborious to use in a predictive setting in contrast to the estimation setting used here to evaluate the models. In general, our goal was to create a model that uses climate and landscape variables that are easily obtainable, such as remote sensing data, to generate a first-order estimate of carbon stock. Remote indices exist that can be used to estimate carbon stock (e.g., Angelopoulou et al., 2019) but are commonly developed on barren or agricultural soils that do not contain the same level of complexity as river corridors. Future steps for the application of these models would be to test or incorporate validation data from outside of our study areas.

## 6 Conclusions

Our study design was constrained by the difficulty of finding exact environmental matches when substituting space for time in comparing reference, treatment, and degraded reaches, and by the short time since restoration was completed at the study sites. However, the results show that floodplains in reference conditions tend to contain higher carbon stocks, and therefore river restoration offers an opportunity to sequester more carbon. An important consideration is that the continuum of degraded, treatment, and reference alternative states is not linear, and does not always follow the assumed temporal order of degraded, treatment, and reference. Disturbance associated with stream restoration construction can reset floodplain SOC stock in treatment sites to lower values than carbon stock of degraded conditions, or the disturbance may not affect persistent carbon stocks with the floodplain chosen for restoration. Uncertainties regarding the potential for persistent floodplain SOC stocks that remain from conditions prior to restoration, along with the challenges of substituting space for time in a complex natural system with multiple interacting variables, strongly indicate that the effects of river restoration on floodplain SOC stocks can be most accurately assessed by (i) measuring stocks prior to restoration and repeating these measurements over a period of years following restoration and (ii) conducting analogous measurements on an adjacent portion of the river corridor not undergoing restoration or on carefully chosen degraded and reference sites.

The current estimated fluxes of carbon into and out of floodplain-wetland corridors show carbon release through methane emissions from wetlands (e.g., Saarnio et al., 2009), carbon dioxide emissions to the atmosphere (Butman and Raymond, 2011), and export of carbon out of floodplains via dissolved carbon in water (e.g., Whitworth et al., 2014) and transport of large wood (Benda and Sias, 2003). The magnitude of carbon sequestration versus carbon transport within individual river corridors or on regional to global scales remains poorly constrained (Hilton and West, 2020), but the potential for net carbon sequestration in river corridors is likely to be notable in the context of climate change.

Political and economic pressure to reduce carbon emissions and develop additional ways to measure and store carbon is likely to increase (e.g., Lindstad and Bø, 2018). Carbon offsets within the carbon market currently fall into two categories: emission reduction (e.g., Sinha and Chaturvedi, 2019) and carbon sequestration (e.g., Lal, 2007). We suggest that stream restoration can offer both. By revitalizing hydrologic conditions that limit the decomposition and extend the residence time of soil organic carbon, stream restoration involving hydrologic reconnection prevents gradual or rapid loss of carbon that is stored in soil and released during floodplain degradation. By enhancing organic matter input from regenerated riparian vegetation and creating conditions for fine sediment deposition, the potential for new carbon sequestration increases.

Despite the variations in floodplain SOC stock relative to potential restoration effects in the data analyzed here, restoration has the potential to enhance organic carbon sequestration and stocks by enhancing floodplain water tables, deposition, and wetland formation. This study shows that reference carbon stocks in anastomosing grassed wetlands and anastomosing wet woodlands are generally higher than degraded and treatment stocks within the same regions, giving the restoration community something to work toward as we strive for resilient, functioning floodplains and creative solutions to climate change.

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