Geomorphology and Climate Interact to Control Organic Carbon Stock and Age in Mountain River Valley Bottoms

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Key Points

- Mountain river valley bottoms store substantial organic carbon stocks in wood and soil
- Floodplain soil organic carbon in mountain river valley bottoms is generally young
- Glacial history, tectonics, and modern geomorphic processes regulate organic carbon storage and age in mountain river valley bottoms

Abstract

Organic carbon (OC) in valley bottom downed wood and soil represents a large, dynamic, and poorly quantified pool of carbon whose distribution and residence time affects global climate. We compare four disparate mountain river basins to show that mountain river valley bottoms store substantial OC stocks in floodplain soil and downed wood ($127.3^{+24.5}_{-37.4}$ MgC/ha, n = 178). Although soil OC is generally young (185^{+269}_{-75} yr BP, n = 121), soil burial, regulated by geomorphic processes, preserves old OC. Statistical modeling of OC stocks suggests that biogeomorphic processes and the legacy of past erosion regulate the modern distribution of OC in river networks. Our results suggest that although mountain rivers may accumulate large OC stocks relatively rapidly, those stocks are highly sensitive to alterations in soil and wood retention, implying both short- and long-term feedbacks between retentiveness and the distribution of OC between the land and atmosphere.

Plain Language Summary

Carbon stored on the land has the potential to be released to the atmosphere and act as a greenhouse gas, influencing global climate. To predict future climate, it is imperative to understand where and how much carbon is stored across the landscape to understand how much carbon might be released to and/or sequestered from the atmosphere in the future. We quantify carbon storage in downed wood and soil in mountain river valley bottoms, finding that mountain river valley bottoms are high magnitude carbon storage zones on the landscape, and that the legacy of past glaciation, climate, and modern erosional and depositional processes regulate the age and quantity of stored OC. Our results imply that human actions can change how much carbon is stored in mountain river valley bottoms, and how it is stored there. Understanding the distribution of carbon across the landscape, especially in carbon-rich zones such as valley bottoms, requires an understanding of both the historic and modern processes shaping the landscape and vegetation.

1 Introduction

Organic carbon (OC) stored in soil and organic material in freshwater systems is substantial (Aufdenkampe et al., 2011) and varies in both spatial distribution (Battin et al., 2008; Scott & Wohl, 2018a; Sutfin et al., 2016; Sutfin & Wohl, 2017; Wohl, Hall, et al., 2017) and residence time (Barnes et al., 2018; Omengo et al., 2016). Carbon dynamics in these systems can thus strongly regulate carbon emissions to and sequestration from the atmosphere (Berner, 1990; Stallard, 1998), regulating global climate. Although numerous measurements have been made of the radiocarbon age of particulate OC in transport, especially in large river basins (Barnes et al., 2018; Schefuß et al., 2016; Tao et al., 2015; Xue et al., 2017), the stock and corresponding age of OC stored in river corridors (Harvey & Gooseff, 2015) have yet to be quantified on broad scales.

OC that enters the fluvial network can either be stored, commonly as downed wood or soil (Sutfin et al., 2016), or exported. Erosion regulates the fate of OC (Doetterl et al., 2016;

Hilton, 2017; Wang et al., 2017) and whether that OC is stored long-term in sedimentary sinks (Blair & Aller, 2012) or respired to the atmosphere by microbes (Falloon et al., 2011; Jobbágy & Jackson, 2000). Modeling indicates that sedimentation dynamics should regulate the age of OC in floodplain soils (Torres et al., 2017), complementary to the idea that geomorphic processes regulate OC concentrations in those soils (Lininger et al., 2018; Scott & Wohl, 2018a; Sutfin & Wohl, 2017; Wohl, Hall, et al., 2017) and wood loads in valley bottoms (Scott & Wohl, 2018b).

Despite the importance of erosion and the transport of wood and soil in determining the fate of OC in river networks, there is still a need for extensive quantification of the valley bottom OC stock and its age. Here, we quantify the OC stock in downed wood and floodplain soil in four mountain river basins across the western United States. We also quantify the age of this OC stock with an expansive sample of radiocarbon dates of floodplain soil bulk carbon. In doing so, we present a novel characterization of an important component of the terrestrial carbon pool and determine the role of mountain river basins in terrestrial carbon dynamics. We contextualize this characterization in terms of the geomorphic and geologic history of the study basins to draw broad, testable inferences regarding the interactions between climate, geomorphology, and OC dynamics in valley bottoms.

2 Methods

We quantified the valley bottom OC stock in wood and soil across the entirety of the river network in four disparate watersheds (Figure 1). The Middle Fork Snoqualmie, in the central Cascade Range of Washington, has a mean annual precipitation of 3.04 m (Oregon State University, 2004), 2079 m of relief, a 407 km^2 drainage area, and erosion rates ranging from 0.05 to 0.33 mm/yr (Reiners et al., 2003). The MF Snoqualmie exhibits glaciogenic topography with small glaciers still evident in headwaters and dominantly thick forests of fir and hemlock, with thinner, younger forests lower in the basin where clearcut logging was widespread over the last century. The Big Sandy, in the Wind River Range of Wyoming, exhibits a mean annual precipitation of 0.72 m (Oregon State University, 2004), 1630 m of relief, a 114 km^2 drainage area, and erosion rates that are likely significantly lower than those in basins studied in Washington, based on erosion rates < 0.1 mm/yr in nearby ranges (Garber, 2013; Kirchner et al., 2001). Similar to the MF Snoqualmie, the Big Sandy exhibits broad, glacially carved valleys and recently extensive glaciers (with remnants near summits), but generally sparse, parkland forests (Fall, 1994) of pine, spruce, and fir with broad grassy meadows. The Sitkum and South Fork Calawah basins, in the Olympic Mountains of Washington, exhibit similar precipitation (3.61 and 3.67 m, respectively; Oregon State University, 2004), drainage area (112 and 85 km^2, respectively), identical 1024 m relief, and exhumation rates between 0.3 and 0.7 mm/yr (Brandon et al., 1998). Both basins exhibit deeply incised fluvial canyons, likely due to a lack of glacial erosion. Despite their similarity, the Sitkum has been extensively clearcut since the 1940s, whereas the SF Calawah is relatively pristine, residing in Olympic National Park (designated in 1938).

To simplify our presentation of results, we categorize these basins by climate and geomorphic legacy with respect to whether the valley bottoms display dominantly glaciogenic or fluviogenic topography. We term the MF Snoqualmie, with its moderate erosion rate, wet climate, and glaciogenic lakes and broad valley bottoms as the *wet glaciogenic* basin. In contrast, we term the Big Sandy, with its low erosion rate, semi-arid climate, and glaciogenic broad valley bottoms as the *semi-arid glaciogenic* basin. Finally, we term the Sitkum and SF Calawah, which exhibit the highest erosion rate, wettest climate, but most fluvially incised, narrow valley bottoms as the *wet fluviogenic* basins. We further subset the Sitkum as the *logged* wet fluviogenic basin and the SF Calawah as the *unlogged* wet fluviogenic basin.

We stratified and randomly sampled OC stocks and valley bottom characteristics in summer 2016 (both fluviogenic basins and the semi-arid glaciogenic basin) and summer 2017 (wet glaciogenic basin). Sample design methodology is described in Text S1. Due to our sampling methodology, we distinguish sites in the wet glaciogenic basin by those stratified by slope (covering the entire basin) and those stratified by floodplain type (covering only the largest floodplains). At each sample site in all four basins, we measured the total channel and floodplain wood load in jams and individual pieces within a reach surrounding the site defined as either 100 m or 10 channel widths, whichever was shorter (see Scott & Wohl (2018b) for detailed wood load measurement methodology). We converted total wood volume per unit area to wood OC mass per unit area (stock) by assuming a density based on estimated decay classes assigned to wood pieces and jams in the field (Harmon et al., 2011) and the approximation that half of the wood mass is carbon (Lamlom & Savidge, 2003). We also took a single soil core at a location on the floodplain of each site judged to be representative of the floodplain as a whole, if soil was present. We did not observe floodplain soils in the fluviogenic basins that were sufficiently fine textured to core, and as such, we consider those basins to store negligible soil OC. Wet glaciogenic basin sites stratified by floodplain type were not explicitly associated with a reach, so we did not measure wood load at those sites.

At all sites where floodplain soil was present, cores were collected to refusal or approximately 1 m depth. OC stock estimation methods are given in Text S2. Five cores in the semi-arid glaciogenic basin, 12 cores in the wet glaciogenic basin sites stratified by slope, and 11 cores in the wet glaciogenic basin sites stratified by floodplain type did not reach refusal, indicating that we generally sampled the entirety of the floodplain soil pool.

Additional field measurements (listed in Table S1) were inconsistent across basins because field protocol evolved during the course of the study. We measured confinement and channel bed slope in all basins. We estimated a proxy for stream power by multiplying the drainage area, bed slope, and average basin-wide annual precipitation (Oregon State University, 2004) at each reach. We also measured bankfull width and depth in the wet glaciogenic basin, bankfull width in the fluviogenic basins (generally equivalent to valley bottom width, because almost all reaches were tightly confined by their valley walls), and valley bottom width in the semi-arid glaciogenic basin. In the wet glaciogenic basin, we classified dominant bedform (Montgomery & Buffington, 1997), classified streams as being either multithread or single thread, and noted whether grasses, shrubs, or trees were present at each soil core site. We also visually classified the dominant channel bed material as either sand (< 2mm), pebble (2-64 mm), cobble (64-256 mm), boulder (> 256 mm), or bedrock. We did not measure channel-specific variables for floodplain-stratified sites in the wet glaciogenic basin, because such sites were not clearly associated with a specific reach. We used a 10 m DEM and National Land Cover Database data (Homer et al., 2015) to measure elevation, the mean slope of the basin draining to each reach (including hillslopes and channels), canopy cover, land cover classification, and drainage area.

We randomly sampled across individual soil samples in the glaciogenic basins (the only two with floodplain soil) to select samples to be analyzed for ^{14}C age. We randomly selected 11 soil samples in each of the four wet glaciogenic basin slope strata that had soil samples (the highest gradient stratum had so few samples that exhibited floodplain soil that we excluded it). We randomly selected four samples from each of the wet glaciogenic basin floodplain type strata as well. In the semi-arid glaciogenic basin, we randomly selected six samples from each of the unique combinations of drainage area class and confinement strata. If too little soil was left after LOI analysis, we replaced the random sample with one of similar characteristics, if possible. This resulted in a total of 121 samples split between the glaciogenic basins that we analyzed for radiocarbon age.

We dried each radiocarbon sample in an oven at 100 °C for 24 hours before sending samples to DirectAMS (Zoppi et al., 2007) for radiocarbon dating of bulk sediment, integrating all carbonaceous sources in the sample and providing an estimate of the distribution of age of all carbon that would be measured in a process such as LOI. We used OxCal 4.3 (Ramsey, 2001) to calibrate samples using both the IntCAL13 (Reimer et al., 2013) and Bomb13NH1 (Hua et al., 2013) calibration curves, depending on the uncalibrated radiocarbon age. Our modeling and data reporting utilize the best estimate of the median age of the bulk carbon in each sample, based on the most appropriate calibration curve. This allowed us to estimate the distribution of age of the carbon stock measured in each study basin.

We compared our measured OC stocks in the wet glaciogenic basin to upland OC stocks in downed wood and soil using data from Smithwick et al. (2002), who measured those OC pools for uplands in the Washington Cascades. Methods used in this comparison are detailed in Text S3.

We statistically modeled (see Text S4 for details) OC stock, the radiocarbon age of floodplain soil OC, and soil depth (a proxy for more valley bottom soil retention) using the R statistical package (R Core Team, 2017). All uncertainties presented represent 95% confidence intervals (CI) on estimates. To test for buried, high-OC concentration layers at depth, we compared each buried soil sample to the sample above it using the criterion that a peak in OC at depth should have an OC concentration 1.5 times that of the overlying sample and be above 0.5% (Appling et al., 2014).

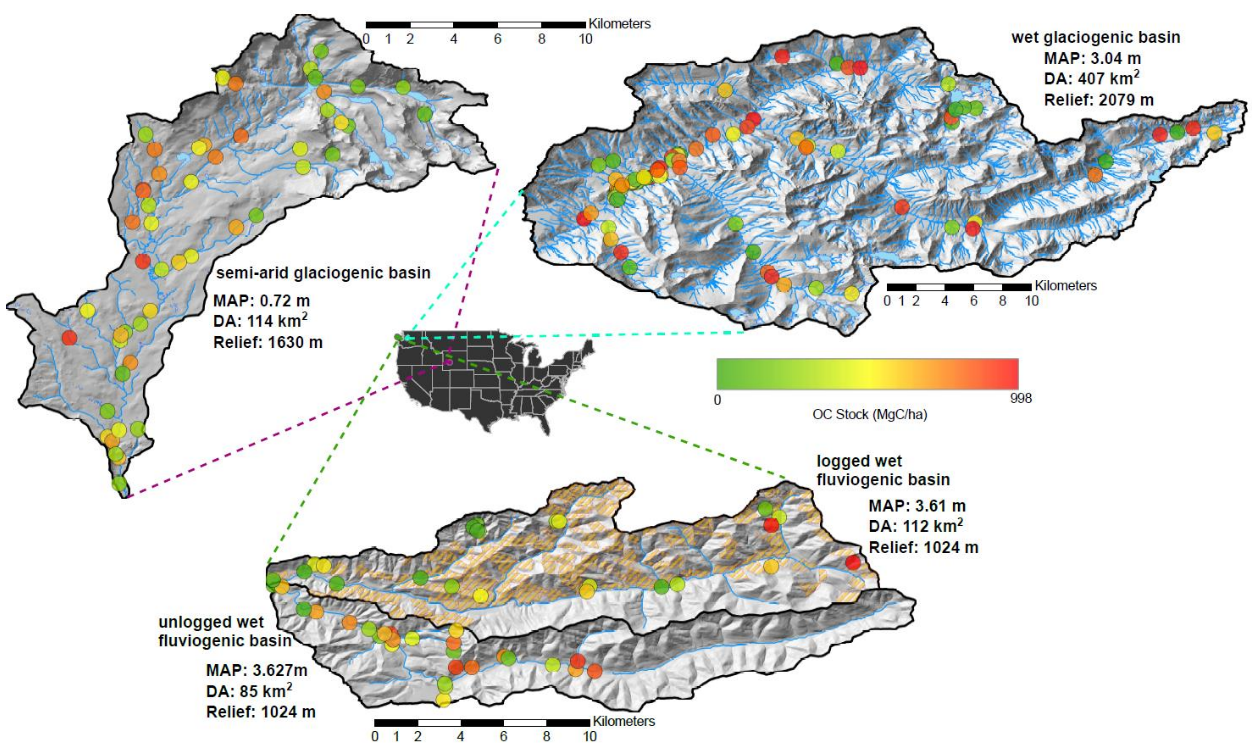


Figure 1. Map showing the location, topography, sampling sites, and stream network of the sampled basins. Clockwise, from upper left: Big Sandy (semi-arid glaciogenic) watershed, Wyoming; MF Snoqualmie (wet glaciogenic) watershed, Washington; Sitkum (logged wet fluviogenic, north) and SF Calawah (unlogged wet fluviogenic, south) watersheds, Washington. Circles represent sampling locations, colored by total OC stock (wood and soil). The orange overlay in the Sitkum basin represents areas that have experienced recorded clearcut timber harvest. Mean annual precipitation (MAP), drainage area (DA), and relief are given for each basin.

3 Results

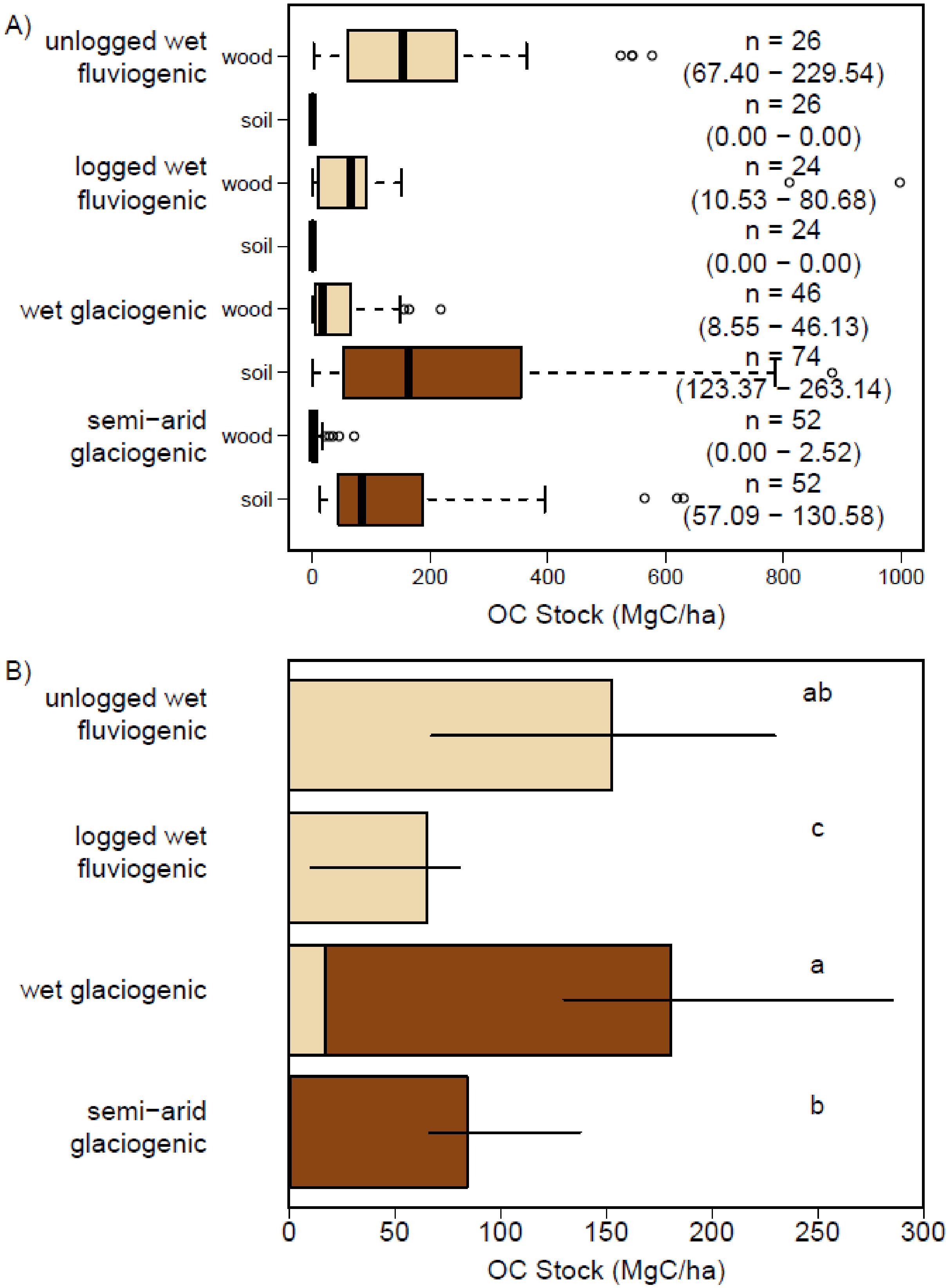
Figure 2a and Table S2 show OC stocks in wood and soil for each basin. Both wet, fluviogenic basins store only wood, with negligible soil (Figure 2b). In the two glaciogenic basins that store OC in soil and wood, the proportion of OC stored in soil is significantly different ($p < 0.0001$) between the semi-arid glaciogenic basin ($n = 52$, 95% CI on median between 0.95 and 1.00) and wet glaciogenic basin ($n = 44$, 95% CI on median between 0.00 and 0.90). Variability in wood load (linearly related to wood OC stock) in all three basins is discussed in detail in Scott & Wohl (2018b).

Soil OC stock across both glaciogenic basins is dominantly controlled by soil moisture and soil depth. In wet glaciogenic basin sites stratified by slope, soil OC stock ($n = 44$, adjusted $R^2 = 0.87$, $p < 0.0001$, cube root transform) is controlled by moisture content ($\beta = 0.014 \pm 0.0057$), soil depth ($\beta = 0.069 \pm 0.011$), and whether the reach is multithread ($\beta = 1.59 \pm 0.97$). Soil OC stock in wet glaciogenic basin sites stratified by floodplain type ($n = 30$, adjusted $R^2 = 0.67$, $p < 0.0001$, no transform) is controlled by soil depth ($\beta = 3.35 \pm 1.15$) and moisture ($\beta = 1.17 \pm 0.37$). Soil OC stock in semi-arid glaciogenic basin sites ($n = 52$, adjusted $R^2 = 0.81$, $p < 0.0001$, cube root transform) is similarly controlled by soil depth ($\beta = 0.26 \pm 0.0066$) and moisture ($\beta = 0.0093 \pm 0.0024$). All modeling results are summarized in Table S3.

Soil depth, a primary control on OC stock, is dominantly controlled by confinement and channel bed slope. Modeling soil depth as a proxy for soil retention in wet glaciogenic basin sites stratified by floodplain type yielded no significant results. Soil depth in wet glaciogenic basin sites stratified by slope ($n = 44$, adjusted $R^2 = 0.56$, $p < 0.0001$, cube root transform) is controlled by channel bed slope ($\beta = -4.79 \pm 2.14$) and whether the stream is unconfined ($\beta = 1.05 \pm 0.64$). Soil depth in semi-arid glaciogenic basin sites ($n = 52$, adjusted $R^2 = 0.56$, $p < 0.0001$, cube root transform) is controlled by elevation ($\beta = -0.00073 \pm 0.00080$), channel bed slope ($\beta = -1.68 \pm 1.20$), and whether the stream is unconfined ($\beta = 0.48 \pm 0.49$).

Comparing wet glaciogenic basin sites ($n = 74$, 95% CI on median between 123.37 and 263.14) to comparable upland sites ($n = 10$, 95% CI on median between 59.90 and 204.80) measured by Smithwick et al. (2002), we find that valley bottom soil and downed wood may store higher OC stocks than are stored in coarse downed wood and soil in uplands ($p = 0.11$) Using estimates of valley bottom area and the total area of our wet, glaciogenic study basin, we find that valley bottoms (2159^{+2795}_{-878} ha) take up only 5^{+7}_{-2} % of the total land surface area, but store 12^{+14}_{-9} % ($0.79^{+2.89}_{-0.69}$ Tg OC) of the total OC mass in the basin, indicating that valley bottoms, at least in this basin, are disproportionately important relative to the land area they occupy in storing OC. However, we note that uncertainties in these estimates are large and overlapping, indicating that more data are necessary to fully evaluate this finding. We were unable to find comparable upland data for other study basins.

Floodplain soil OC is moderately old (10^2 yr) in these study basins, and its age is dominantly controlled by sample depth below the ground surface, confinement, and whether the sample is a peak in the vertical profile of OC (Figure S1). We found no significant difference in median radiocarbon age of floodplain OC between the two study basins. Bulk carbon in soils sampled in the semi-arid glaciogenic basin (median age 126^{+260}_{-126} yr BP) and wet glaciogenic basin (median age 425^{+179}_{-314} yr BP) ranges in age from modern (≤ 0 years before 1950) to 6179 yr BP, and the median OC age across both basins is 185^{+269}_{-75} yr BP (Data Set S1, Figure S1). In wet glaciogenic basin soil samples stratified by slope ($n = 44$, adjusted $R^2 = 0.57$, $p < 0.0001$, no transformation), sample depth below ground surface ($\beta = 15.39 \pm 6.26$) and whether the sample exhibited a peak in the vertical profile of OC ($\beta = 665.76 \pm 500.87$) controlled median radiocarbon age. In wet glaciogenic basin soil samples stratified by floodplain type ($n = 20$, no transformation), only depth below ground surface was found to directly correlate to radiocarbon age (Spearman $\rho = 0.41$, 95% CI between 0.22 and 0.58). In semi-arid glaciogenic basin soil samples ($n = 57$, adjusted $R^2 = 0.47$, $p < 0.0001$, no transformation), sample depth below ground surface ($\beta = 21.32 \pm 8.20$) and whether the reach was unconfined ($\beta = 392.98 \pm 337.09$) controlled median radiocarbon age.



A)
unlogged wet fluviogenic
logged wet fluviogenic
wet glaciogenic
semi−arid glaciogenic
wood
soil
n = 26
(67.40 − 229.54)
n = 26
(0.00 − 0.00)
n = 24
(10.53 − 80.68)
n = 24
(0.00 − 0.00)
n = 46
(8.55 − 46.13)
n = 74
(123.37 − 263.14)
n = 52
(0.00 − 2.52)
n = 52
(57.09 − 130.58)
0
200
400
600
800
1000
OC Stock (MgC/ha)
B)
ab
c
a
b
0
50
100
150
200
250
300
OC Stock (MgC/ha)

239

Figure 2. Boxplot of OC stock in wood (tan) and soil (brown) for each basin. Boxplots (A) show distribution of data, including the lack of soil in the SF Calawah and Sitkum (unlogged and logged wet fluviogenic basins, respectively). Bold lines represent median, box represents interquartile range, dashed lines represent 1.5 times the interquartile range, and circles represent outliers. Sample size (n) and 95% confidence interval on median estimates (shown in parentheses) are given for each group. Stacked bar plots (B) show the median total OC stock for each basin, separated into wood (tan) and soil (brown). Error bars represent the 95% CI on the median. Letters a-c represent significant differences based on combined examination of 95% CI and pairwise Wilcoxon rank-sum tests. Note that the unlogged and logged wet fluviogenic basins contain negligible floodplain soil, and hence a zero value for soil OC stock.

4 Discussion

Increased soil retention (both in terms of valley width and soil depth) leads to the preservation of older OC and a higher mass of OC by storing deep soil over a larger area. Along with likely storing more soil OC than uplands (Lininger et al., 2018; Wohl et al., 2012), a nearly 200 yr BP median age shows that floodplain soils store OC over moderate timescales, preventing fast respiration to the atmosphere. In addition, deep burial in floodplain deposits where microbial respiration is likely inhibited can lead to biospheric OC storage on timescales of up to 10^3 years (median age of buried OC peaks is 1056 yr BP, with a 95% CI ranging from modern to 2750 yr BP), even in these mountainous rivers. Modeling of floodplain soil OC age indicates that buried samples tend to be significantly older than samples near the surface, and buried OC-rich layers (preserved OC peaks in the vertical soil profile) in the wet glaciogenic basin tend to be older than other samples. (We were unable to test this for the semi-arid glaciogenic basin due to a lack of preserved OC peaks at depth.) In the semi-arid glaciogenic basin, OC from unconfined streams is generally older than that from confined streams, indicating that unconfined streams likely have a longer floodplain turnover time, allowing buried OC to be preserved. Essentially, packets of soil OC that are more shielded from the atmosphere (deeply buried) and from rapid lateral migration (in reaches with wider valleys and presumably slower floodplain turnover times) can be preserved longer than shallower soils in confined valleys that are eroded more rapidly. This indicates that burial of soil OC in wide, retentive valley bottoms is the dominant process in preserving old OC in these basins, a trend that fits with both modeling (Torres et al., 2017) and field observations (Barnes et al., 2018).

Net changes in wood and soil retention due to activities such as grazing in the semi-arid glaciogenic basin or forest harvest in the wet glaciogenic basin have likely caused substantial redistribution of OC and potential sequestration lower in the network (Wohl, Hall, et al., 2017; Wohl, Lininger, et al., 2017; Wohl & Scott, 2016). A century-scale turnover (assuming stocks are currently in steady state) of the majority of the substantial floodplain soil OC pool indicates that changes in soil retention and resulting storage of OC (e.g., due to land use change) should be tightly linked to OC respiration rate to the atmosphere over moderate timescales. Although OC likely turns over more rapidly in the mountainous basins studied here, it may be stored for longer periods of time lower in the river network after being eroded (Doetterl et al., 2016; Van Oost et al., 2012; Wang et al., 2017), depending on erosion and sedimentation dynamics (Schook et al., 2017; Torres et al., 2017). Changes in retention of the mountain river valley bottom OC stock may have rapid (due to generally short turnover times) and substantial (due to its high magnitude) effects on the distribution of OC between the atmosphere and terrestrial storage. Our modeling indicates that soil depth, a proxy for retention, is largely a function of erosivity (the efficiency of soil erosion and transport downstream), with wider, lower gradient valley bottoms storing deeper soils and more OC, and thus presenting a greater potential OC source if soil retention is decreased via disturbance. Wood load variability is likely a function of wood supply, governed by climate and land use, and spatial heterogeneity, which regulates how efficiently valley bottoms can trap wood (Scott & Wohl, 2018b).

Our comparison of disparate basins shows that where there is an abundant source of wood (e.g., wet basins with dense forests), wood acts as a substantial OC pool (Scott & Wohl, 2018b). However, where forests are sparse (e.g., the semi-arid glaciogenic basin), soil is by far the dominant valley bottom OC pool. When taken in the context of radiocarbon analyses of OC in larger rivers (Barnes et al., 2018; Schefuß et al., 2016; Xue et al., 2017), our results indicate substantially faster soil OC cycling in mountainous, headwater basins, in contrast to sites lower in river networks, where burial of OC may lead to longer OC preservation (Blazejewski et al., 2009; Ricker et al., 2013). However, soil burial in any portion of the network can lead to old OC ages (on the order of 10^3 yr). Burial of wood in floodplains, which can lead to exceptionally long-term preservation, likely only occurs in unconfined, wider reaches. Wood retention is also likely easier and more commonly managed (Roni et al., 2015) than soil (Bullinger-Weber et al., 2014), as wood trapping structures or direct wood placement can both enhance wood loads. The partitioning of OC between wood and soil has direct implications for best management practices in terms of restoring OC stocks to anthropogenically influenced valley bottoms. For instance, our results imply that attempting to increase soil OC stock in wet, fluviogenic basins such as the Sitkum would likely be ineffective due to the naturally low soil retention in such a basin with deeply incised, narrow valleys. Restoring wood there, however, would likely increase the OC stock substantially, if the unlogged wet, fluviogenic basin in this study is representative of potential wood OC stocks. Still, a major uncertainty exists in terms of where wood is most stable on the landscape.

Climate, by influencing forest characteristics and resulting litter input rates to soils and wood supply to channels, acts as a first-order control on the partitioning of OC between floodplain soil and wood as well as the total valley bottom OC stock. In both the wet and semi-arid glaciogenic basins, floodplain soils store more OC stock than downed wood. However, if we take the unlogged wet fluviogenic basin as an example of wood loads in a pristine basin in the Pacific Northwest, it appears possible that wood OC stock can be of comparable magnitude to soil OC stock (in the wet glaciogenic basin). This implies a strong potential for increasing the OC stock in wood in the wet glaciogenic basin, in which wood loads are likely decreased as a result of logging (Scott & Wohl, 2018b). It is also important to note the significant difference between soil OC stocks in the wet versus semi-arid glaciogenic basin. Both of these basins have similar soil retention, as measured by soil depth ($p = 0.85$), but OC concentrations in the wetter basin can be substantially higher than those in the semi-arid basin, potentially due to difference in OC inputs resulting from differing rates of litter input (Scott & Wohl, 2018a).

Comparing the distribution of OC between wood and soil in these basins reveals a strong impact of basin morphology, which is a result of uplift rate, erosion rate and style, and climate. Where valley bottoms are narrow, likely due to a high precipitation rate and accompanying rates of fluvial incision, valleys store negligible amounts of soil, but forests grow dense and wood OC stock can be extremely high, as long as trees go unharvested and can be recruited to channels, as in the two study basins in the Olympics (Scott & Wohl, 2018b). In the semi-arid glaciogenic basin, low uplift rate, glaciogenic valleys, and dry climate correspond to broad valley bottoms but sparse forests, resulting in almost negligible wood OC stock (Scott & Wohl, 2018b) and only moderate soil OC storage, likely due primarily to low rates of litterfall input (Scott & Wohl, 2018a). Where the climate is wet, uplift is moderately high, but valleys are widened by recent glaciation, we observe both broad valley bottoms and dense forests, leading to substantial OC stocks in soil in the wet glaciogenic basin. Given that the wet glaciogenic basin has been extensively logged, it is likely that total OC stocks there were much higher than either the wet fluviogenic or semi-arid glaciogenic basins until the last century. Valley bottoms of the wet glaciogenic basin represent a peak in potential OC stock due to dense forests; wide, retentive valley bottoms; and high rates of OC input from vegetation.

5 Conclusion

The legacies of glaciation and tectonics, combined with geomorphic processes, determine the distribution, magnitude, and age of the OC stock in mountain river valley bottoms. Here, we show through extensive field measurement that this OC pool is highly variable both spatially and temporally, but that geomorphic processes largely explain that variation. Burial and preservation of OC-rich soil is essential to preserving soil OC past the median age of around 200 years in these floodplains. Deeper soils in unconfined valleys, especially those that were unusually OC-rich, reach ages up to a few thousand years. Valley bottom geometry, forest stand characteristics (directly affected by land use), and climate interact to regulate the retention of both wood (Scott & Wohl, 2018b) and soil. This implies that managing the substantial valley bottom OC stock necessitates a careful consideration of geomorphic process and form. Future examination of carbon sequestration efforts in river corridors (e.g., Bullinger-Weber et al., 2014) will test this inference by determining the rate and magnitude at which OC can be restored to floodplain soils in varying environments.

The century-scale age of much of the soil OC measured in these basins implies a close coupling between soil retention and the distribution of OC across the landscape and between the land and atmosphere. The alteration of valley bottom morphology and soil retention likely influences the fate of OC sequestered in high primary productivity (Schimel & Braswell, 2005) mountain ranges over short (Wohl, Hall, et al., 2017; Wohl, Lininger, et al., 2017) and long (Berner, 1990; Molnar & England, 1990) timescales. Changes in soil retention likely alter how much OC reaches downstream water bodies that may sequester OC over longer timescales, thus altering the respiration of that OC to the atmosphere. Future work to quantify the residence time and decay rate of wood in valley bottoms and its eventual fate when exported, in addition to examination of the sources and fate of soil OC, will further constrain and illuminate this feedback.

Acknowledgements

This work was funded by NSF grant EAR-1562713 and a National Geographic Society Young Explorer Grant. We thank the Quileute tribe and Olympic National Park for access to field sites in the Olympics. We thank Ellen Daugherty for assistance in field work, Sarah Lowe for assistance processing soil samples, and Katherine Lininger for discussion and review that improved the manuscript. Data can be found in Data Set S1 and the Colorado State University Digital Repository (https://hdl.handle.net/10217/187763).

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