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Large wood and sediment storage in a mixed bedrock-alluvial stream, western Montana, USA

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ABSTRACT

Sediment storage by instream wood in forested mountain streams mediates sediment movement from hillslopes through the channel network and can alter channel morphology at multiple spatial scales. Mixed bedrock-alluvial channels are prevalent in mountain stream networks, yet the distribution and geomorphic impact of large wood within these streams are poorly understood. To estimate how the distribution of large wood in a mixed bedrock-alluvial stream relates to sediment storage, we measured and characterized large wood, and we surveyed the volume of associated sediment within a stream in the Bitterroot Mountains, Montana. The upstream portion of the study reach is predominantly alluvial and the downstream portion has significant bedrock exposure along the channel bed and banks. Wood volume and sediment storage in the mixed bedrock-alluvial subreach are 50% and 15%, respectively, of those measured in the alluvial subreach. Most wood is organized into jams, and two channel-spanning jams within the upstream subreach account for 50% and 80% of the reach-averaged wood and sediment volume, respectively. The volume of sediment stored by wood in the full reach is the same order of magnitude as the estimated annual bedload export. Our study highlights the interactions among channel form and the fluxes and storage of wood and sediment. Wood that forms channel-spanning jams, which store a disproportionate amount of wood and sediment in the study reach, may accentuate differences between alluvial and bedrock-dominated subreaches in mountain stream networks, by promoting sediment deposition and storage upstream and by reducing sediment supply to downstream reaches.

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1. Introduction

Sediment connectivity in channel networks depends not only on sediment supply and transport capacity but also on the location, volume, and residence time of sediment deposits (Fryirs, 2013; Hoffmann, 2015). In mountain streams where hillslope-channel coupling is strong and sediment transport capacity tends to be high, instream wood can mediate sediment connectivity by altering transport capacity and contributing to sediment storage, complementing storage in bars, behind boulders, and on floodplains (Megahan, 1982; May and Gresswell, 2003; Fisher et al., 2010; Wohl and Scott, 2017). Understanding of the temporal and spatial (e.g., across channel types; Jerin, 2019) variability in how instream wood affects sediment connectivity is limited, however, despite recent advances (Wohl and Scott, 2017). In contrast, the influence of wood on pool formation and other aspects of stream morphology and aquatic habitat is well documented (e.g., Bisson et al., 1987; Montgomery et al., 1995; Gurnell et al., 2002). Emerging recognition that channel-spanning jams and other wood and sediment in riverine corridors are key sites for carbon storage and processing (Wohl et al., 2012; Beckman and Wohl, 2014; Wohl et al., 2017) provides further impetus for investigating wood-induced sediment storage.

The distribution of wood within stream reaches, laterally across floodplains, and downstream through the channel network affects its potential for storing sediment and governs its influence on sediment routing (Wohl et al., 2019a). In forested mountain streams, wood structures change predictably with increasing drainage area (Nakamura and Swanson, 1993; Wohl and Jaeger, 2009). In steep headwater streams, large wood tends to be immobile and forms steps where it enters the channel (Wohl et al., 1997; Scott et al., 2014), storing sediment in wedges upstream of embedded wood (Marston, 1982; Wohl et al., 1997). Wood pieces alter the local water-surface gradient, increase effective step height when interlocked with boulders, reduce upstream velocities, and generate form drag and spill resistance (Wilcox et al., 2006; Church and Zimmermann, 2007; Wilcox and Wohl, 2007), all of which alter sediment transport capacity and induce sediment storage. As drainage area increases, greater transport capacity promotes wood mobility and jam formation (Abbe and Montgomery, 2003). Wood jams create hydraulic roughness, decrease flow velocity, and contribute

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to sediment deposition (Manga and Kirchner, 2000; Davidson, 2011), and the volume of sediment storage generally correlates with jam size (Eaton and Hassan, 2013). Marginal and channel-spanning jams can also promote overbank deposition during high flows (Jeffries et al., 2003; Oswald and Wohl, 2008).

The formation, persistence, and geomorphic impact of wood jams depend in part on channel type and valley geometry (Massong and Montgomery, 2000; Abbe and Montgomery, 2003; Wohl, 2011; Wohl and Beckman, 2014). Where transport capacity is high, jams may be unstable, diminishing their long-term potential for storing sediment (Eaton and Hassan, 2013; Wohl and Jaeger, 2009). For example, in transitional or mixed bedrock-alluvial channels, boulders and bedrock may suspend large wood, thereby limiting its interactions with bedload. Alternatively, boulders and bedrock may facilitate jam formation by racking up large wood and stabilizing key pieces (Faustini and Jones, 2003). Wood in sufficient volume (e.g., in channel-spanning logjams) can shift a bedrock or mixed bedrock-alluvial reach to an alluvial reach (Montgomery et al., 1996; Wohl, 2011). Storage of wood and sediment is disproportionately high in third- and fourth-order streams compared to other parts of headwater networks (Pfeiffer and Wohl, 2018).

Reviews on connectivity in river systems (Fryirs, 2013; Wohl, 2017; Wohl et al., 2019b) highlight the need for more quantitative insights into wood-induced sediment storage in mountain streams, including to advance understanding of hillslope-channel coupling; sensitivity of mountain streams to, and downstream propagation of, disturbances; ecogeomorphic feedbacks; and management. Few reach-scale studies in forested mountain streams have considered the relative magnitude of sediment stored by individual large wood pieces and log jams of various sizes. Furthermore, most studies of sediment stored in association with large wood have been conducted in gravel-bed streams in wet, temperate coastal environments, especially the Pacific Northwest of North America (e.g., Swanson and Lienkaemper, 1978; Marston, 1982; Bilby and Ward, 1989; Faustini and Jones, 2003). Compared to that region, mountain streams in the intermountain western U.S. contain smaller and more mobile wood due to lower forest-stand density and average tree diameter (Wohl and Goode, 2008; Wohl and Jaeger, 2009).

Here we investigated how the distribution of large wood (piece length ≥ 1 m and diameter ≥ 0.1 m) influences sediment storage in a mixed bedrock-alluvial stream. We tested the hypothesis that large wood stores more sediment per unit wood volume where it forms channel-spanning jams compared with small jams and individual pieces, which produce less form drag than jams and thus have lower potential for storing sediment. We measured wood, sediment, and channel morphology and modeled one-dimensional hydraulics and sediment transport to contextualize observed patterns in wood and sediment storage. This approach provided a thorough assessment of wood and sediment storage and their interactions in a mixed bedrock-alluvial stream.

2. Study area

Our study site is Lost Horse Creek, a stream in the Bitterroot Mountains of western Montana (Fig. 1), where granitic rocks of the Idaho batholith predominate (Foster et al., 2001). The Bitterroot Mountains are oriented north-to-south and comprise a series of west-to-east trending canyons that bear the topographic imprint of Pleistocene glaciation (Alden, 1953). The extensive bedrock exposure, abundance of talus, and coarse valley fill in the Bitterroot are consistent with other post-glacial landscapes (Hoffmann, 2015). Where soil-mantled hillslopes occur, they support mixed coniferous forests dominated by Douglas fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), and Engelmann spruce (*Picea engelmannii*).

Within Lost Horse Creek we focused on a 720 m, third-order reach at about 1650 m elevation that drains 37 km^2 (Fig. 1). Four avalanche slide paths (Stauffer, 1976), the largest of which abuts the upstream end of the study reach, likely contribute to the stream's wood volume. The basin has not been harvested in the past century (BNF, 2016). In 1988, a moderate- to high-severity fire burned about 25% of the basin draining to our study reach (USGS and USFS, 2018). Average annual precipitation is 1600 mm (PRISM, 2018). Precipitation is greatest from November to January, and July to September are the driest months (NRCS, 2019). Lost Horse Creek is ungaged but has a snowmelt-driven flow regime, with peak flows in May and June. Our field data collection occurred in 2017 and 2018, during a period of above-average snowfall and runoff. Peak snow water equivalent (SWE) was ~140% of normal in 2017 and ~ 200% of normal in 2018. At the nearest US Geological Survey gaging

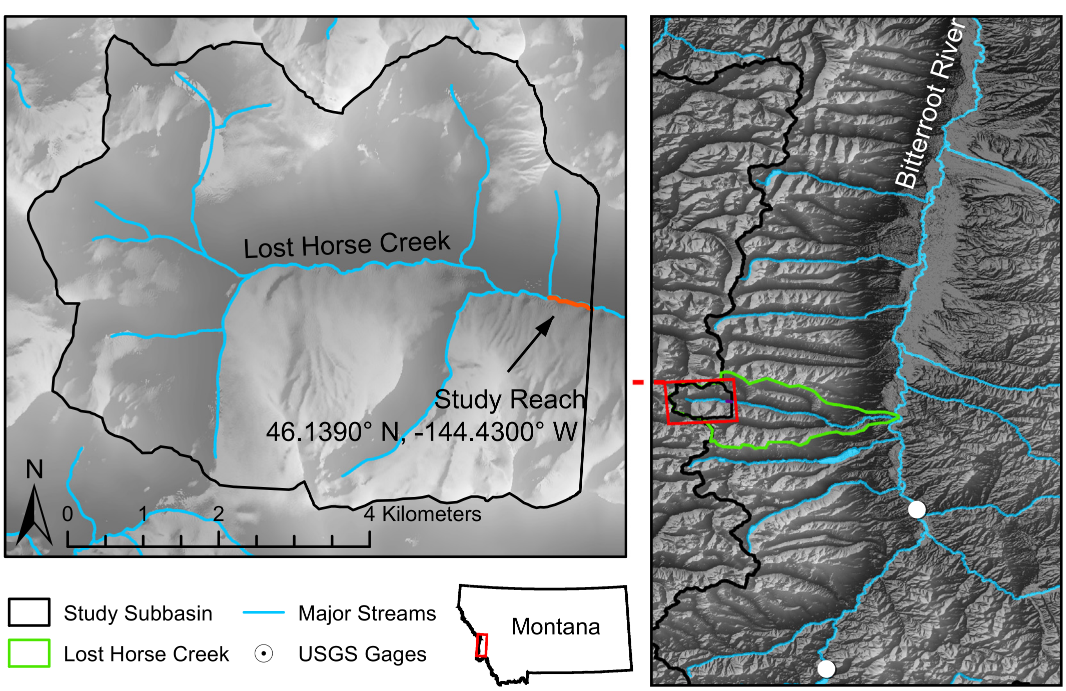

Fig. 1. Study site on Lost Horse Creek in the Bitterroot Mountains, Montana; location in Bitterroot River basin and nearby US Geological Survey (USGS) gaging stations are shown on right.

stations (Fig. 1; West Fork Bitterroot near Conner, MT, #12342500; Bitterroot River near Darby, MT, #12344000), the 2017 and 2018 peak discharges had recurrence intervals of just over 2 and 5 years, respectively (USGS, 2018).

Lost Horse Creek contains steep, bouldery, mixed bedrock-alluvial reaches, and low-gradient (<0.01), alluvial, gravel- and cobble-bedded reaches. Our study reach reflects these broader patterns. The upper half of the reach is alluvial, and it transitions from a pool-riffle to a plane-bed channel type (Fig. 2). Downstream, it is a mixed bedrock-alluvial stream with cascade and step-pool morphology.

3. Materials and methods

3.1. Channel morphology and hydraulics

To characterize the geomorphic and hydrologic context of our wood and sediment-storage analyses, we measured topography, bed-material size, and discharge, and we completed associated modeling of flow and sediment dynamics. To measure channel and valley morphology, we used a bare-earth digital elevation model (DEM) from airborne LiDAR (Benjaram, 2016) and an orthomosaic from a drone survey, both completed in fall 2016. We delineated the channel, active floodplain, and valley margins, and we used the resulting polygons to calculate channel width, entrenchment (valley area/channel area), confinement (active floodplain/channel area), and sinuosity. To distinguish between and characterize the alluvial and mixed bedrock-alluvial subreaches, we surveyed the bed slope, channel dimensions, and bed-material size (D) throughout our study reach. We used a total station to survey bed topography along a longitudinal profile of the thalweg and 11 equally spaced cross sections. To measure the surface grain size, we completed modified Wolman pebble counts at every other cross section, in which we measured the b-axis diameter of 200 particles using a gravelometer. We then calculated D_{16}, D_{50}, and D_{84}, i.e., the grain size below which 16, 50, and 84% of the bed material is finer, respectively.

We combined field measurements and nearby gage data to estimate flow magnitudes and frequencies. To measure stage, we installed pressure transducers, recording at 15-minute intervals, at the downstream and upstream ends of our study reach in spring 2017 and 2018. We also measured the discharge with a SonTek FlowTracker ADV at a range of wadeable flows. We developed stage-discharge relations from these data, which we used to estimate discharge for the portion of the 2017 and 2018 water years for which stage was monitored.

To understand spatial and temporal variations in hydraulics and transport capacity and channel-floodplain flow connectivity in our study reach, we ran the one-dimensional HEC-RAS (Hydrologic Engineering Center's River Analysis System) model. We used the LiDAR-based DEM of the floodplain and field surveys of the main channel as topographic input. We simulated discharges ranging from baseflow up to the 2018 peak. HEC-RAS provided information on differences across discharges and between subreaches in boundary shear stress, $\tau_o = \rho g R S_f$, where ρ is water density, g is gravitational acceleration, R is hydraulic radius, and S_f is friction slope. We then used shear stress values, in combination with bed-material size measurements, to calculate dimensionless shear stresses, $\tau^* = \tau_o / [(\rho_s - \rho)gD]$, where ρ_s is sediment density and D is set equal to D_{50}, as a measure of the competence of flows to transport sediment.

To estimate annual sediment export, for comparison with our measurements of sediment-storage volume, we used Bedload Assessment for Gravel-bed Streams (BAGS) (Pitlick et al., 2009). We employed the Parker (1990) surface-based equation, which is suitable for bed-material conditions in our study reach, to calculate sediment transport rates. Input data for sediment-transport calculations included reach-average channel dimensions, S_f (as calculated in HEC-RAS), bed-material size distribution, and a flow duration curve that we developed from discharge estimates during 2018.

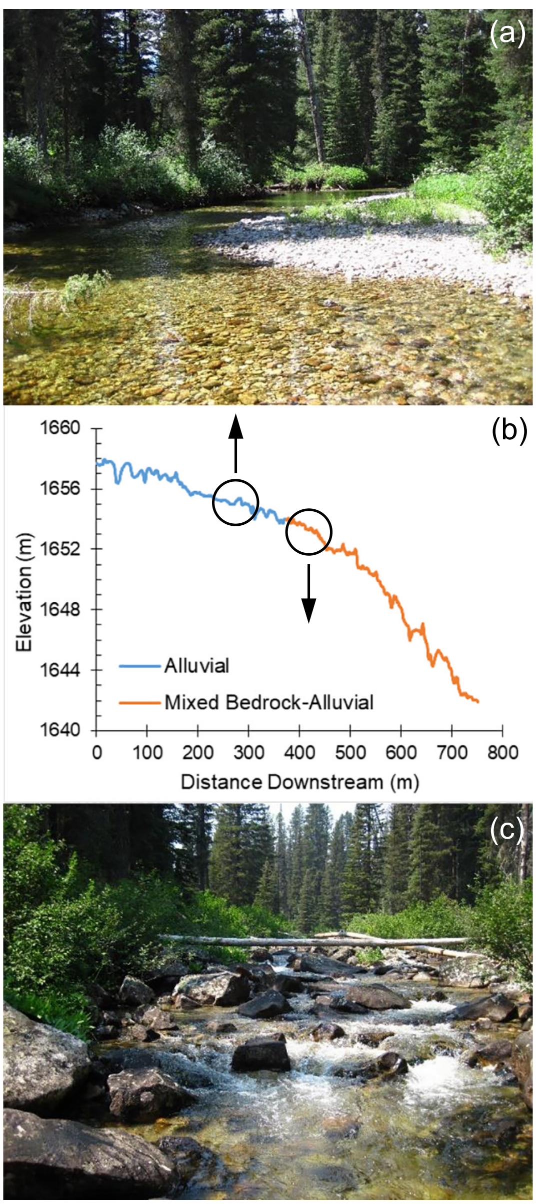

Fig. 2. Lost Horse Creek study reach, including: (a) alluvial subreach, (b) water-surface longitudinal profile generated from LiDAR-based DEM, and (c) mixed bedrock-alluvial subreach. Image locations are circled on longitudinal profile. Flow is from background to foreground.

3.2. Large wood distribution

To determine how large wood volume and distribution relate to channel type, we measured and characterized instream wood during summer 2017. We measured the length and mid-length diameter of each piece that extended at least 1 m into the bankfull channel and had a diameter ≥ 0.1 m. From these measurements, we calculated the volume of each piece by treating each log as a cylinder. We classified each piece as single or part of a jam (three or more pieces of wood that are in contact). Wood volume between the alluvial and mixed bedrock-alluvial domains was then compared by dividing the total wood volume by the subreach length and area (including wood volume where individual pieces were not measured, as described below).

To quantify wood organized in jams, we estimated the total volume of each jam from the sum of individual piece volumes. Where it was impractical to survey individual pieces within a jam, we estimated the wood volume from the aerial extent, thickness, and porosity (void space) (Livers et al., 2020). We surveyed the perimeter and top of the jam with a total station. By assuming a zero slope beneath the jam, the volume was calculated as the product of the surface area and height, adjusted for visually estimated porosity. The distribution of wood between subreaches was compared by calculating the proportion of wood volume in jams, the average volume of each jam, and the jam frequency (number of jams divided by subreach length).

To provide further insights into the relative mobility of large wood, and thus its potential for storing sediment over time, we also evaluated metrics related to large wood retention including decay, accumulation, stability, and source. We noted whether each piece had a rootwad and its level of decay (rotten, decayed, bare, limbs, bark, needles/leaves; after Wohl et al., 2010). We documented any features associated with wood accumulation (jam, living tree/rootwad, buried in bank, boulder, bedrock, bar, buried in bed, none), stability (drifted, bridge, collapsed bridge, ramp, buried, pinned), and source (unknown, riparian, hillslope, floated, bank undercutting) (Wohl et al., 2010). Subreach differences in categorical attributes were compared using chi-squared tests for independence.

3.3. Sediment stored by wood

We quantified sediment in wood-forced riffles, bars, and pools within the active channel. We surveyed sediment in riffles and bars during summer 2017. To estimate the volume of coarse bed material stored by log bed-steps and jams, we treated each wood-forced sediment deposit with a surface area ≥ 1 m^2 as a wedge defined by breaks in channel gradient and bed-material size. To determine its dimensions, we surveyed the perimeter and the elevation of the bed surface immediately upstream and downstream of the log or jam. We considered features wood-forced if one or more pieces of the involved wood were at an oblique angle or perpendicular to the main flow.

We estimated the volume of sediment stored in bars similarly to how we estimated the volume of wood jams (Section 3.2). We surveyed the perimeter and top of the bar, and calculated the volume from the derived surface area and average height. The volume of fine bed material (<2 mm) stored in each pool was determined by probing sediment depth in a gridded pattern (Lisle and Hilton, 1992). First, we surveyed the perimeter. Then, we strung a tape across the longest dimension of the deposit to facilitate systematic probing with the aid of a 1 m^2 PVC frame. To determine deposit thickness, we pounded a steel rod into the fine sediment until the depth of refusal, assumed to coincide with the underlying coarse bed material. Depending on the surface area of the deposit, we probed sediment depth at a spacing of either 0.25 or 1 m. For deposits exceeding 20 m^2, random soundings were performed in a zig-zag pattern across the length of the tape for a total of about 20. We estimated the volume from the surface area and average deposit thickness.

We compared sediment stored by wood between the alluvial and mixed bedrock-alluvial domains by dividing the total sediment volume by the subreach length and area.

To compare the geomorphic influence of individual pieces, small jams, and channel-spanning jams, we calculated the total volume of sediment stored by each feature type. We also divided the total volume of sediment by the cumulative volume of wood in individual pieces, small jams, and channel-spanning jams, a metric known as the large wood particulate storage index (LWPSI) (Pfeiffer and Wohl, 2018).

4. Results

4.1. Channel morphology and hydraulics

Channel and valley morphology mediate the distribution of wood and sediment in the study reach. The alluvial and mixed bedrock-alluvial subreaches show marked differences in both the valley-scale attributes of entrenchment, confinement, and lateral connectivity and the channel-scale attributes of sinuosity, slope, and bed-material size (Table 1). The valley and active floodplain narrow and steepen from upstream, where multiple side channels are present that are hydrologically connected to the main channel at near-bankfull flows, to downstream, where the channel is single thread and has reduced lateral connectivity to its floodplain (Fig. 3). Bedrock influence, bed-material size, and slope all increase downstream of a valley-bottom constriction at the transition between subreaches (Fig. 3). These differences drive variations in hydraulics (Table 1). Bankfull shear stresses are 33 N/m^2 and 170 N/m^2 in the alluvial and mixed bedrock-alluvial subreaches, respectively, according to HEC-RAS modeling (detailed HEC-RAS results are presented in Welling, 2019). The corresponding dimensionless shear stress (τ^*) values at bankfull are 0.041 and 0.11 in the alluvial and mixed bedrock-alluvial subreaches, respectively.

4.2. Large wood and sediment storage

Patterns of wood and sediment storage reflect the subreach variations in hydraulics and valley and channel morphology described above. Wood volume in the alluvial subreach is double that of the mixed bedrock-alluvial subreach. By volume, most wood occurs in jams, and the channel-spanning jams account for about 50% of the wood volume (Table 2, Fig. 4). Jam frequency does not vary by subreach, but average jam volume, which is strongly influenced by the presence of two channel-spanning jams, is three times larger in the upstream subreach.

There are subreach differences in the general source, rootwad presence, level of decay, and accumulation of large wood pieces (chi-squared tests, $\alpha = 0.05$) (Fig. 5). The proportion of pieces of riparian origin in the downstream, mixed bedrock-alluvial subreach is double that of the upstream, alluvial subreach. Large wood pieces are four times as likely to have a rootwad in the upstream subreach. Although most large wood shows evidence of significant decay (decayed or rotten), the proportion of decayed wood is about 1.5 times as large, and the proportion of bare wood is about half as large in the upstream subreach. More pieces are associated with bedrock, boulders, islands, or live trees/rootwads in the downstream subreach, and more pieces are buried in the banks or not associated with an obvious geomorphic feature or structural element in the upstream subreach.

Sediment stored by wood in the upstream subreach is six times the volume measured in the downstream subreach (Table 3). About half of the sediment stored by wood consists of fine sediment, all of which occurs in the upstream subreach. Greater sediment stored by wood

Table 1
Attributes of full study reach and mixed bedrock-alluvial and alluvial subreaches.

	Entrenchment[a]	Confinement[b]	Sinuosity[c]	Bed slope	Bed-material size (mm)			Velocity (m/s)[d]	Depth (m)[d]	Shear stress (N/m^2)[d]
					D_{16}	D_{50}	D_{84}			
Full study reach	9.6	4.6	1.2	0.017	13	64	160	1.0	0.57	100
Mixed bedrock-alluvial	7.9	3.3	1.1	0.031	26	93	220	1.4	0.54	170
Alluvial	11	5.7	1.4	0.0097	14	50.	96	0.65	0.60	33

[a] Valley width/channel width.
[b] Floodplain width/channel width.
[c] Reach/valley length.
[d] For bankfull discharge (12 m^3/s), as determined by HEC-RAS modeling.

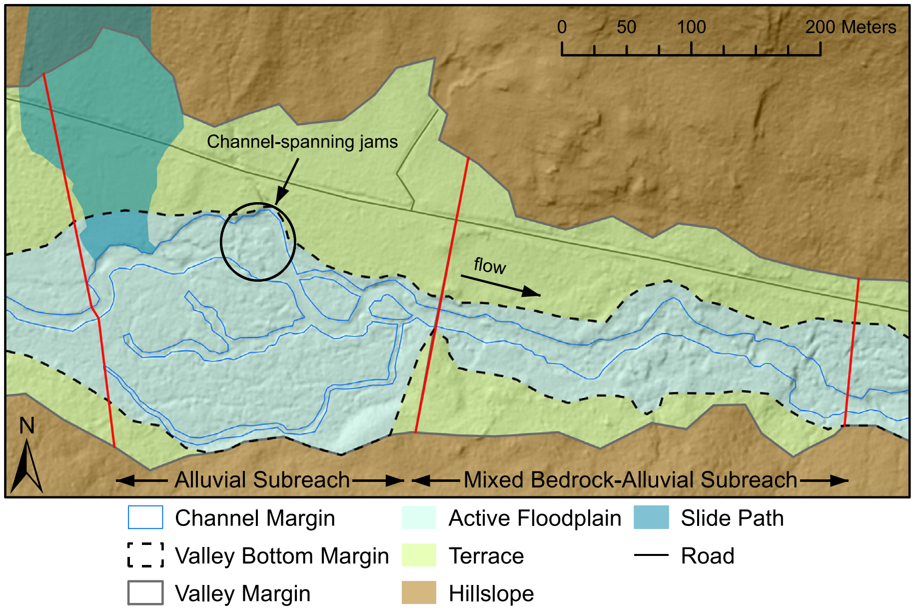

Fig. 3. Geomorphic map of study site, illustrating downstream valley narrowing and shift from alluvial, multi-thread subreach in upstream portion to mixed-bedrock-alluvial, single-thread and confined subreach in downstream portion. The transition between subreaches, which are delineated on map by red lines, occurs at a valley-bottom constriction. Other key geomorphic features are an avalanche slide path in upper left and floodplain side channels along upstream subreach.

correlates with both larger wood volume and the efficiency with which large wood stores sediment (Tables 2 and 3).

Channel-spanning and small jams account for about 75% and 20%, respectively, of all sediment stored in association with wood (Fig. 4). The former store relatively more fine sediment, and the latter store more coarse sediment. Large wood pieces store less than 5% of each of the fine and coarse sediment volume. Channel-spanning and small jams account for more of the total wood volume and have a higher sediment-storage efficiency than do individual pieces. The LWPSI for pieces, small jams, and channel-spanning jams is 0.12 ± 0.08, 0.34 ± 0.05, and 0.9 ± 0.2, respectively.

5. Discussion

5.1. Reach-scale wood and sediment dynamics

Mountain streams typically have high capacities to transport sediment and wood, with dimensionless shear stresses commonly exceeding expected mobility thresholds for alluvial rivers (Church, 2006). Yet they retain sediment and wood, to degrees that vary temporally and spatially, thus providing habitat complexity and mediating the routing of these materials to downstream reaches. Our study reach exemplifies this apparent conundrum. Despite high individual piece mobility and the sediment supply-limited condition of the reach, wood and sediment storage are significant.

Wood volume in the study reach is consistent with values reported for other streams in the Intermountain West. The measured wood volume of 160 m^3/ha is within the range of 39–303 m^3/ha for subalpine streams of similar width and drainage area in Yellowstone National Park, Wyoming (Wohl and Scott, 2017). It is also within the range of 12–415 m^3/ha for subalpine streams in Rocky Mountain National Park, Colorado (Wohl and Cadol, 2011), but it exceeds the range of 0.06–29 m^3/ha observed in montane streams in the same region (Wohl and Jaeger, 2009), which are more similar in width to Lost Horse Creek. The ranges of wood volume cited here are large, highlighting the highly variable nature of wood loading as a function of channel-reach morphology, hydroclimatology, wood recruitment, and management (Wohl et al., 2019a).

Spatial variability in forest-stand composition and hydrologic regime contribute to regional differences in large wood distribution

Table 2
Large wood volume and distribution by reach and subreach.

	Full study reach	Mixed bedrock-alluvial	Alluvial
Wood volume (m^3)[a,b]	220 ± 20	68 ± 5	150 ± 20
Wood volume (m^3/100 m)[a,b]	30. ± 4	19 ± 2	40. ± 6
Wood volume (m^3/ha)[a,b]	160 ± 20	110 ± 10	220 ± 30
Proportion of wood in jams (m^3/m^3)	0.8	0.8	0.9
Proportion of wood in channel-spanning jams (m^3/m^3)	0.5	0	0.8
Jam frequency (number/100 m)[c]	6.2 (45)	6.2 (22)	6.3 (23)
Average jam volume (m^3/jam)[b,c]	4.1 ± 0.5 (45)	2.4 ± 0.2 (22)	5.7 ± 0.9 (23)
Average jam volume excluding channel-spanning jams (m^3/jam)[b,c]	1.6 ± 0.1 (43)	2.4 ± 0.2 (22)	0.91 ± 0.03 (23)
Average volume of channel-spanning jams (m^3/jam)[b,c]	60 ± 10 (2)	NA	60 ± 10 (2)

[a] Wood volumes combine data from measurements of individual large wood pieces (588 total) and from jams surveyed with a total station.
[b] Uncertainties are based on our assumption that we measured each of 588 large wood pieces to the nearest 0.1 m in length and 0.01 m in diameter; these uncertainties were then propagated to wood volumes. Where jam volumes were determined from the sum of individual piece volumes, uncertainties were estimated as per individual piece measurements. Where total station measurements were used, we assigned an uncertainty to jam volume calculations by (1) assuming total station measurements of surface area were accurate to ±10%, (2) assuming visual estimates of porosity were accurate to ±0.1, (3) calculating the standard deviations of multiple height measurements across the jam, and (4) propagating the uncertainties in surface area, height, and porosity to jam volume.
[c] Parenthetical values show sample size; i.e., number of jams.

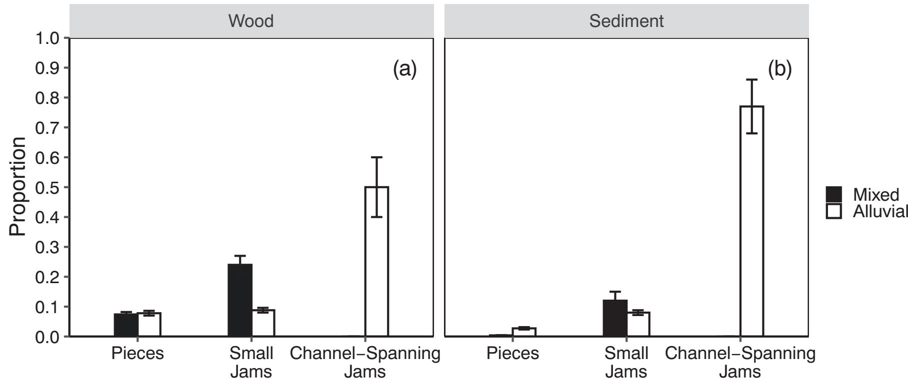

Fig. 4. Categorical data, by subreach, for individually surveyed wood: (a) general source, (b) level of decay, (c) subsource of riparian wood; these data are a subset of (a) to provide more information about wood of riparian origin, (d) stability, (e) rootwad presence, and (f) features associated with piece accumulation. p-Values from chi-squared tests are included and frequencies are indicated below each bar. When there are more than two factor levels, significance of chi-square tests for each level are depicted as follows *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$ and n/a when sample size was insufficient for testing. Some pieces were assigned to multiple stability or accumulation types, so chi-square tests were only performed at the factor level.

within drainage networks. This is apparent not only at broad physiographic scales (Gurnell et al., 2002; Ruiz-Villanueva et al., 2016), but also within regions including the Intermountain West. For example, in the Colorado Front Range, subalpine areas tend to have greater forest stand density, slightly smaller tree diameters, more snowmelt-dominated hydrology, and higher wood loading than lower-elevation montane portions of channel networks, where increased rainfall influence on hydrographs can increase the likelihood of overbank flooding (Wohl and Jaeger, 2009; Polvi et al., 2011). Furthermore, variation in climate-driven disturbance regimes can lead to divergent patterns in large wood distribution even among streams of the same forest type (Wohl et al., 2018). In New Mexico and Colorado, streams with a snowmelt-driven flow regime had higher wood loads and more jams compared to streams with peak flows due to rainfall, and more frequent fires and debris flows (Wohl et al., 2018). Lost Horse Creek receives more precipitation than many regions in the Intermountain West, and the proportion of wood within jams is higher compared to streams of similar drainage area and stream order. Therefore, conceptual and quantitative models specific to hydroclimatic regions, including the northern Rockies, may be needed to better understand patterns of large wood distribution and in turn, how shifts in climate and hydrology may affect wood regimes.

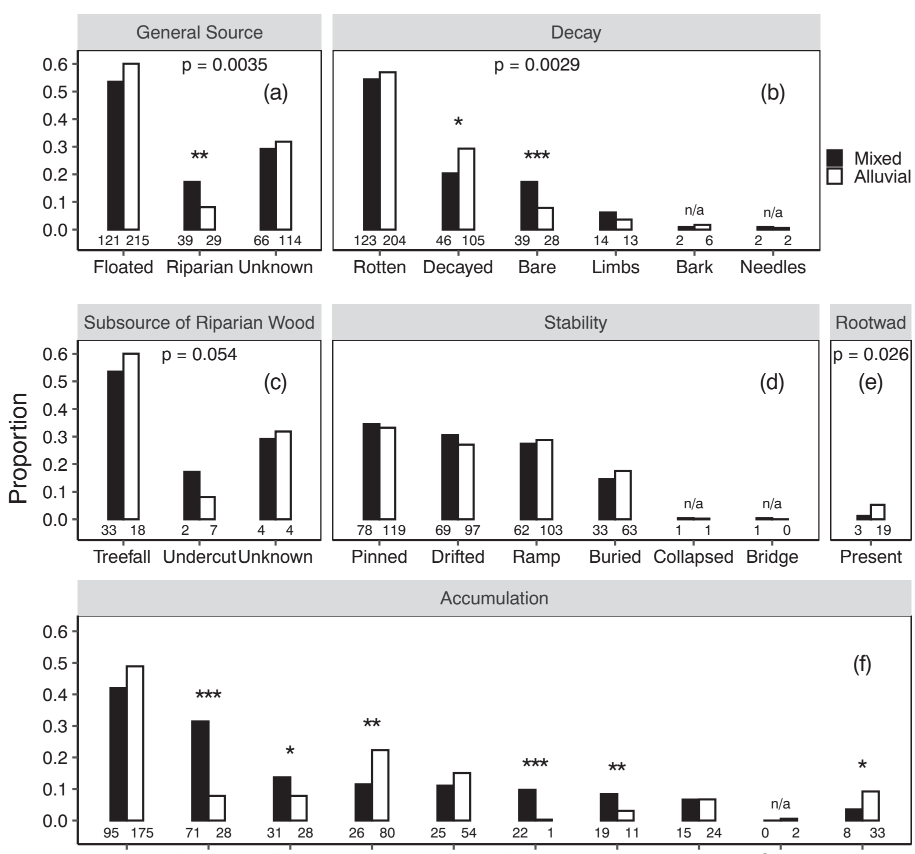

Fig. 5. (a) Reach-scale large wood and (b) associated sediment storage in pieces, small jams, and channel-spanning jams within mixed bedrock-alluvial (black) and alluvial subreaches (white), illustrating the disproportionate role of channel-spanning jams in storing sediment.

Table 3
Fine and coarse sediment stored in association with wood by reach and subreach, where values show mean, uncertainty, and sample size (number of surveyed deposits, in parentheses) for each metric.[a,b]

	Full study reach	Mixed bedrock-alluvial	Alluvial
Sediment volume (m^3)	124 ± 9 (40)	15 ± 3 (10)	109 ± 8 (30)
Sediment volume (m^3/100 m)	17 ± 2 (40)	4.2 ± 0.9 (10)	30 ± 3 (30)
Sediment volume (m^3/ha)	90 ± 10 (40)	24 ± 5 (10)	160 ± 20 (30)
Coarse sediment volume (m^3)	58 ± 6 (27)	15 ± 3 (10)	43 ± 4 (17)
Fine sediment volume (m^3)	66 ± 7 (13)	0	66 ± 7 (13)
LWPSI (m^3 sediment/m^3 wood)[c]	0.57 ± 0.08	0.22 ± 0.05	0.7 ± 0.1

[a] Multiple sediment deposits were surveyed for some wood pieces and jams.
[b] Uncertainties were calculated similarly to our approach for wood jam volumes; we (1) assumed total station measurements of surface area were accurate to ±10%, (2) calculated the standard deviations of multiple depth measurements across each deposit, and (3) propagated the uncertainties to sediment volume.
[c] Large wood particulate storage index.

Sediment stored by wood, most of which occurs in the alluvial subreach of our study site, is the same order of magnitude as annual bedload export. Stream surveys in the Pacific Northwest and South America have produced similar results (Marston,1982; Andreoli et al., 2007). This is particularly remarkable given the larger piece diameter and corresponding stability of wood in these coastal mountain streams (Braudrick and Grant, 2000; Ruiz-Villanueva et al., 2016).

5.2. Subreach differences in wood and sediment storage

The low wood volume in our mixed bedrock-alluvial (downstream) subreach compared to the alluvial subreach likely reflects both greater transport capacity and reduced supply in the downstream reach. Large wood metrics indicate that the overall distribution of wood is similar between subreaches with most pieces transported from upstream. Although the greater confinement of the downstream subreach suggests strong hillslope-channel coupling and potential for wood delivery to the channel from flanking hillslopes, we found no evidence of this supply pathway. The disproportionate volume of wood stored by the channel-spanning jams suggests that jams effectively trap wood in the upstream reach, amplifying observed subreach differences in wood storage.

Subreach differences in sediment stored by wood are even more pronounced than differences in subreach wood volumes. Sediment trapping and storage by wood jams in the upstream subreach reduces sediment supply to the downstream subreach, in a setting where sediment supply is likely already low compared to transport capacity. Moreover, the high transport capacity of the steeper downstream subreach suggests that much of the sediment that enters this subreach is evacuated. At the same time, the mixed bedrock-alluvial channel contains more large wood pieces that are suspended on boulders or bedrock and/or parallel to the direction of flow; storing little to no sediment as a result. These factors conspire to maintain discontinuous alluvial cover, an overall paucity of fine sediment, and lower sediment storage by wood in the downstream, mixed bedrock-alluvial subreach.

Differences in subreach wood and sediment volumes are consistent with patterns observed in other mountain streams. Past studies indicate that channel confinement, sinuosity, and number of channels are key predictors of wood volume. Wood volume tends to be larger in low-gradient, unconfined reaches compared to steep, confined reaches (Nakamura and Swanson, 1994; Wohl, 2011). Enhanced trapping and recruitment of large wood in multi-thread reaches, which are common where the stream is unconfined, lead to greater wood storage.

As with subreach differences in wood volume, sediment stored by wood depends on channel type. Wood stores 160 m^3 sediment/100 m in a bedrock-controlled reach of Mack Creek, a third-order stream in the western Cascade Range, Oregon, while the boulder-bed reach just downstream contains 500 m^3 of sediment/100 m (Nakamura and Swanson, 1993). Where large wood pieces are smaller in diameter, sediment stored by wood may vary to an even greater degree with channel type. Wohl and Beckman (2014) estimate that sediment stored by wood averages 1.4 m^3/100 m in low-gradient unconfined reaches and 21 m^3/100 m in steep confined reaches in subalpine streams in the Colorado Front Range. Although bedrock is discontinuously exposed along the bed and banks of these cobble and boulder-bed streams (Wohl and Cadol, 2011), they did not explicitly relate wood and sediment volumes to alluvial cover.

5.3. Jams, wood, and sediment storage

Jams store more sediment per unit volume of wood than do individual pieces, and channel-spanning jams are particularly effective at storing sediment. This finding is consistent with previous studies that find the organization of wood into jams correlates with increased sediment storage (Pfeiffer and Wohl, 2018; Nakamura and Swanson, 1993), and that channel-spanning jams store sediment at higher rates compared with other types of jams (Mao et al., 2008). Results also support the widespread observation that channel-spanning jams play a disproportionate role in wood and sediment storage in river networks (Montgomery et al., 1996; Massong and Montgomery, 2000; Wohl and Beckman, 2014).

The two channel-spanning jams within the low-gradient, less-confined subreach are the only site in the reach where the channel is multi-thread (Fig. 3). At flood stage, these jams dissipate flow energy and form a backwater, inundating portions of the floodplain and routing flow into side channels. We measured significant coarse and fine sediment storage within active channels and observed wood-forced sediment deposition in adjacent floodplain channels. HEC-RAS modeling of snowmelt-driven flows provides evidence that wood-forced changes in channel planform and associated hydraulics contribute to high wood retention and sediment storage. The flow area is much greater and the depth, velocity, and shear stress are significantly lower in the wood-forced multi-thread channel, as modeled using HEC-RAS. Declining shear stress leads to sediment deposition, and lower velocity and relative wood submergence promote jam persistence, even during high-flow years such as those during our study period. These observations support the positive feedback loop proposed in Wohl (2011) that explains how channel-spanning jams in low-gradient, unconfined reaches facilitate long-term wood and sediment storage.

Despite the strong influence of wood jams on sediment storage in our study area, we did not observe forced alluvial channels in Lost Horse Creek. In forced alluvial channels, which are common in the Pacific Northwest, wood jams "force" alluviation of reaches that would be predicted as bedrock based on drainage area-slope relations (Massong and Montgomery, 2000). The absence of forced alluvial channels in our study area likely reflects a combination of lower wood and sediment supply and smaller wood than in many Pacific Northwest streams. Similar to the Pacific Northwest, however, sediment storage in jams, by reducing sediment supply to downstream reaches, may increase the prevalence or persistence of bedrock or mixed-bedrock alluvial morphologies downstream of jams, even where slope-area relationships predict alluvial beds (Massong and Montgomery, 2000).

5.4. Wood, sediment storage and connectivity in headwater streams

Sediment is relatively scarce in mixed bedrock-alluvial channels, such that instream wood and associated sediment storage may play a disproportionate role in the creation of aquatic habitat. Consequently, habitat created by wood may be sensitive to riparian forest harvest or direct removal of instream wood (Livers et al., 2018). Placement of large wood can be an effective restoration tool (e.g., Elosegi et al., 2017), particularly where it reflects the local geomorphic setting (Roni et al., 2014), allows for wood mobility, and is accompanied by passive restoration of wood regimes (Wohl et al., 2019a). In mixed bedrock-alluvial channels, jams are more likely to be stable and store more sediment than individual pieces. The placement of wood near boulders or bedrock outcrops may trigger feedbacks that increase both the volume and residence time of gravel and finer sediment.

Instream wood and sediment dynamics can determine the extent to which hillslope disturbances, such as fire, beetle kills, timber harvest, and roads, propagate from headwater streams to downstream portions of the channel network that are ecologically and economically important (Lancaster et al., 2001; Short et al., 2015; Gasser et al., 2019). Headwater streams may, on the one hand, serve as transport reaches for sediment delivered from hillslopes, implying resilience in form and function to elevated sediment delivery from road networks, timber harvest, and other sources of chronic sediment input. On the other hand, anthropogenic disturbances that increase sediment delivery (e.g., clearcutting and streamside roads) may also reduce wood supply to headwater streams. Because of the key role of wood for storing sediment, as documented here, the basic sediment budget equation (input − output = change in storage; Dietrich and Dunne, 1978) indicates that reductions in wood supply, wood volume, and wood-induced sediment storage would magnify the effect of increased sediment inputs, with respect to sediment export to downstream reaches. In contrast, maintenance of instream wood in headwater streams may buffer downstream reaches of channel networks from headwater sediment disturbances. Feedbacks among wood and sediment delivery from hillslope disturbances, channel morphology, the volume and residence time of sediment storage in headwaters, and sediment fluxes in and out of headwater reaches highlight the influence of wood on sediment cascades (e.g., Fryirs, 2013) and sediment connectivity from hillslopes to downstream reaches.

Future research into how episodic wood and sediment inputs alter the transport efficiency of mixed bedrock-alluvial channels would inform forest management, stream restoration, and evaluation of the sensitivity of streams to climate-change-induced shifts (Goode et al., 2012) in these disturbances. As with many areas of surface-process studies, emerging tools will facilitate improved quantification of wood and sediment volume over broader temporal and spatial scales. These include airborne and terrestrial LiDAR (Kasprak et al., 2012; Yochum et al., 2014), Unmanned Aerial Vehicles and structure from motion (Sanhueza et al., 2019), geochemical tools for determining the residence time of wood (Ruiz-Villanueva et al., 2016) and sediment (Koiter et al., 2013), and numerical modeling simulations of wood and sediment routing and connectivity (e.g., Eaton and Hassan, 2013; Gilbert and Wilcox, 2020).

6. Conclusions

Channel type influences overall storage of wood and sediment in channels. Previous research has primarily focused on differences in wood and sediment volumes with channel width, slope, and confinement. This study highlights the importance of alluvial cover, the extent of which determines basic stream type, in governing sediment stored by wood. In a ~1 km reach of Lost Horse Creek, wood and sediment dynamics differ between alluvial and mixed bedrock-alluvial subreaches. Low wood and sediment volumes in the mixed bedrock-alluvial subreach correlate with the channel's high transport capacity. Consistent with previous research, thresholds in wood and sediment storage and positive feedback loops involving channel-spanning jams underlie observed differences in wood and sediment storage. Two channel-spanning jams within the low-gradient, less-confined alluvial subreach fundamentally alter channel morphology and store a majority of wood and sediment within the study reach.

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Declaration of competing interest

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

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Data availability

Data are available as appendices to Welling (2019; https://scholarworks.umt.edu/etd/11336/).

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