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Disturbance legacies of historic tie-drives persistently alter geomorphology and large wood characteristics in headwater streams, southeast Wyoming

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ABSTRACT

Instream wood is recognized as an integral component of stream morphology in forested areas. However, few studies have evaluated the legacy effects of historic wood removal activities and associated impacts on channel morphology, contemporary wood loading, and recruitment. This study investigates the role of historic tie-driving, a widespread channel disturbance legacy, in shaping present-day stream channel conditions in southern Wyoming. Geomorphic and riparian surveys were used to assess the extent of disturbance and degree of recovery within three sets of paired tie-driven and non-driven study reaches. Tie-driven streams were narrower, shallower, and had low cross-sectional roughness and higher width-to-depth ratios when compared to non-driven streams. Study reaches in first-order tie-driven streams were characterized by predominantly plane-bed morphologies and an extremely low abundance of wood compared to paired, non-driven reaches. Wood loads in second-order tie-driven reaches were similar to non-driven reaches, but overall wood distribution varied and was more likely to accumulate in jams. Existing wood loads in tie-driven reaches exhibited a narrower range of geomorphic functions and were less stable overall, although the relative state of decay was similar across all reaches. Basal area, stream power, and reach slope were identified as key mechanisms driving wood retention in the study reaches. The results of this study suggest that contemporary channel morphology and wood loads continue to reflect disturbance histories but have not yet been affected by other contemporary disturbances expected to influence wood loads such as bark beetle infestations.

1. Introduction

While billions of dollars have been invested in stream restoration in the United States, restoration efforts may not be producing the desired ecosystem improvements, indicating a disconnect between river science and river restoration practice (Bernhardt et al., 2005; Palmer, 2009). The reliance on reference reaches to provide a baseline or target condition for restoration projects compounds other shortcomings related to restoration techniques. Reference reaches, or minimally impaired systems that approximate characteristic stream function, are often used as templates to guide many restoration projects and management initiatives. Reference reaches are chosen based on a variety of considerations including their ability to represent pre-disturbance conditions (Brookes, 1987) as well as similarities in morphology (Rosgen, 1994), physiographic qualities (Montgomery et al., 1995), and more recently, analytical characteristics that capture process-based dynamics instead of form-based features (Downs and Simon, 2001). However, the selection of reference reaches requires an understanding of historic system conditions as well as future response trajectories. Given the spatial extent and history of human impacts on stream systems (Gregory, 2006), altered systems derived from past disturbance events (hereafter referred to as disturbance legacies) underlie much of our contemporary understanding of what constitutes *natural* stream function (Walter and Merritts, 2008; Burchsted et al., 2010; Downs and Simon, 2011).

One aspect of fluvial geomorphology that is often overlooked in the reference stream selection process is the role of large wood (LW). The scientific study of the functional role of LW in streams has a rich theoretical foundation in terms of channel form and of process-based implications for stream systems (e.g., Keller and Swanson, 1979; Lienkaemper and Swanson, 1987; Marston et al., 1995; Brooks and Brierley, 2002; Flores et al., 2011). The geomorphic impacts of LW are numerous and include the alteration of flow patterns (Gippel, 1995; Daniels and Rhoads, 2004), storage of organic matter and sediment (Lisle, 1995; Thompson, 1995; Montgomery et al., 2003; Daniels, 2006), and controls on bedform morphology (Montgomery et al., 1995). Considerable effort has focused on recruitment mechanisms and patterns (Downs and

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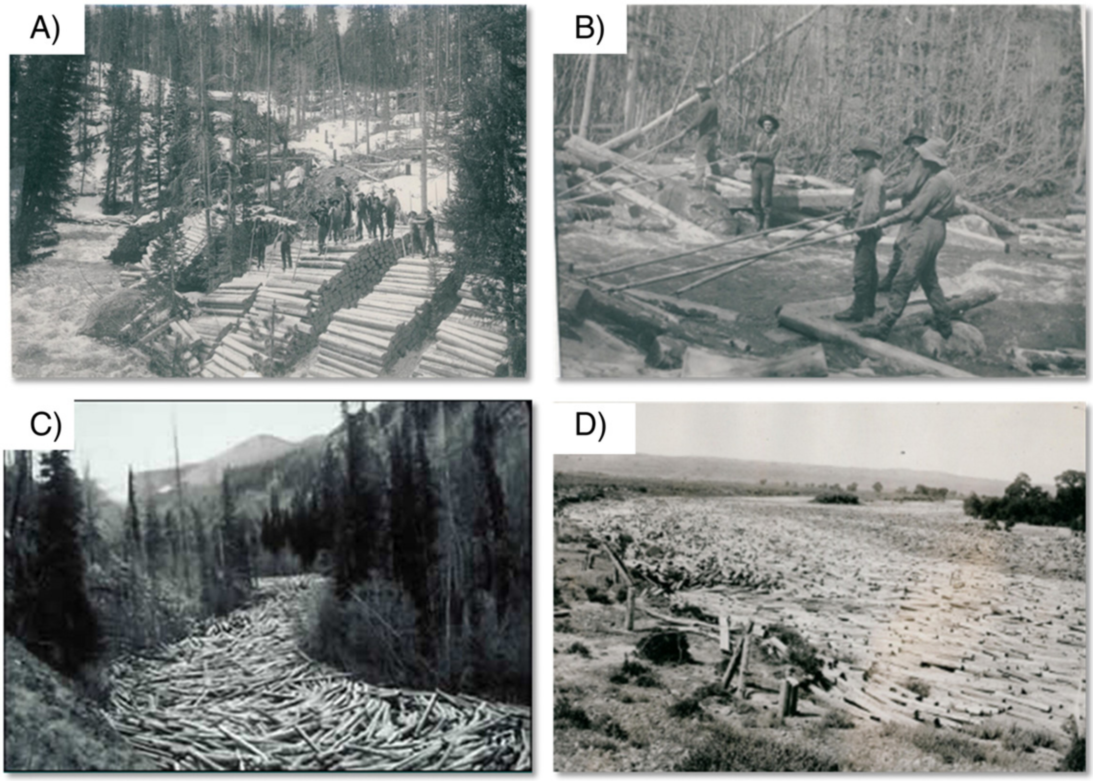

Fig. 1. Tie-driving in the Medicine Bow National Forest, southeast Wyoming. (A) Railroad ties were cut and stored in the riparian area adjacent to the stream channel. (B) Ties were floated downstream following peak flow. (C) Extensive tie jams were a routine event during drives. (D) Ultimately, tie drives accumulated in larger rivers to be delivered to processing centers downstream. Photographs courtesy of the Grand Encampment Museum.

Simon, 2001; Webb and Erskine, 2003) as well as transport potential (Abbe and Montgomery, 1996). Longitudinal patterns of wood throughout stream networks vary based on network position and have been attributed to a variety of drivers, including channel gradient, channel width, stream power, and drainage area (Wohl and Jaeger, 2009) — although local variations in channel and valley morphology can mask these drivers (Wohl and Cadol, 2011). This body of work has served as an integral foundation for understanding ecological functions such as habitat diversity and nutrient retention (Bilby and Likens, 1980; Bisson et al., 1987; Gurnell et al., 1995). Large wood has also received attention from the management community given the significant channel responses to wood removal and additions (Piégay et al., 2005; Chin et al., 2008; Lassettre and Kondolf, 2012). Despite the recent increase in research on wood dynamics over the last several decades, relatively little is known about wood loading in systems not subjected to pervasive historic anthropogenic disturbances.

Table 1
Observed responses in channel geomorphology to channel modifications related to timber floating activities.

Modification	Longitudinal	Cross-sectional	Planform	Sediment properties	Hydraulics
In-channel wood removal		– Widening and aggradation[a]	– Lower diversity of bedforms[a]		
Splash dams		– Channel incision[a] – Decreased floodplain connectivity[c]	– Fewer pools – Lower diversity of bedforms[a,b,c,d] – Decreased sinuosity[d] – Inundated riparian area[d]	– Increased erosion and scouring[b] – Bed armoring[a] – Decreased range of sediment sizes[b]	– Increased flooding upstream of dam[d] – Altered flow regime downstream of dam[d]
Feeder flumes			– Decreased sinuosity[d]		– Reduced hyporheic exchange[d] – Dewatering of backwaters, side channels, or other reaches[d] – Altered flow regime downstream of flume inlet and outlet[d]
Boulder removal	– Reduced channel roughness[d]	– Homogeneous channel depth[d] – Reduced channel roughness[d]			
Channelization	– Reduced channel roughness[d]	– Reduced channel width[e] – Decreased floodplain connectivity[e]	– Decreased sinuosity[e] – Homogeneity of bedforms[c,e]	– Loss of fine grain sediment[e]	– Altered flow regimes and decreased flood frequencies [c,d] – Increased flow velocity[e]

[a] Comiti (2012).
[b] Miller (2010).
[c] Helfield et al. (2007).
[d] Nilsson et al. (2005).
[e] Gardeström et al. (2013).

Instream wood loads can be influenced by a multitude of factors, including geomorphic disturbances such as mass wasting events (Lancaster et al., 2003; Montgomery et al., 2003; Wohl et al., 2009), riparian disturbances (Wallace et al., 2001), as well as historic and contemporary human impacts such as beaver extirpation (Burchsted et al., 2010), timber harvesting (Gurnell et al., 2000), urbanization (Finkenbine et al., 2000; Segura and Booth, 2010), and navigation (Angradi et al., 2009; Philips and Park, 2009). In the absence of human influence, instream wood loads typically reflect a balance among input rates, species decay rates, and export rates (Benda et al., 2003), the latter of which is partly determined by the transport capacity of the stream (Swanson et al., 1976; Gurnell et al., 2000; Wohl and Goode, 2008). Headwater streams, especially in mountainous regions, are generally associated with high wood loadings because of adjacent dense riparian forests, steep slopes, and the limited transport capacity of their characteristically small channels. Wood loads in low-order streams are closely coupled to riparian and hillslope characteristics as well as geomorphic retention mechanisms, while hydrologic properties play less of a role in transport. Although determining the residence time of instream wood is difficult, several studies in the western United States have found that some pieces of wood will remain unmoved for 70–100 years, and records exist of pieces lasting in the channel for ~250 years (Swanson et al., 1976; Murphy and Koski, 1989). Few studies have examined wood residence time explicitly, but it is generally understood that piece dimensions relative to the size of the channel and the potential for integration within the channel influence mobility (Wohl and Goode, 2008).

This paper focuses on the legacy of tie-driving, also known as timber floating, which is an extensive historic anthropogenic disturbance along the Front Range of the Rocky Mountains that has largely gone unstudied. As railroads reached the Rocky Mountains during the mid-1800s, streams were used as the primary method for transporting railroad ties, as was common throughout the United States (e.g., Sedell et al., 1991; Wohl, 2001). Timbers were harvested and cut into ties across the forested land, including riparian areas, and through all seasons. Ties were stored on floodplains and within stream channels throughout the year until the high spring flows could carry the wood loads downstream in what were referred to as tie drives (Fig. 1). Modifications

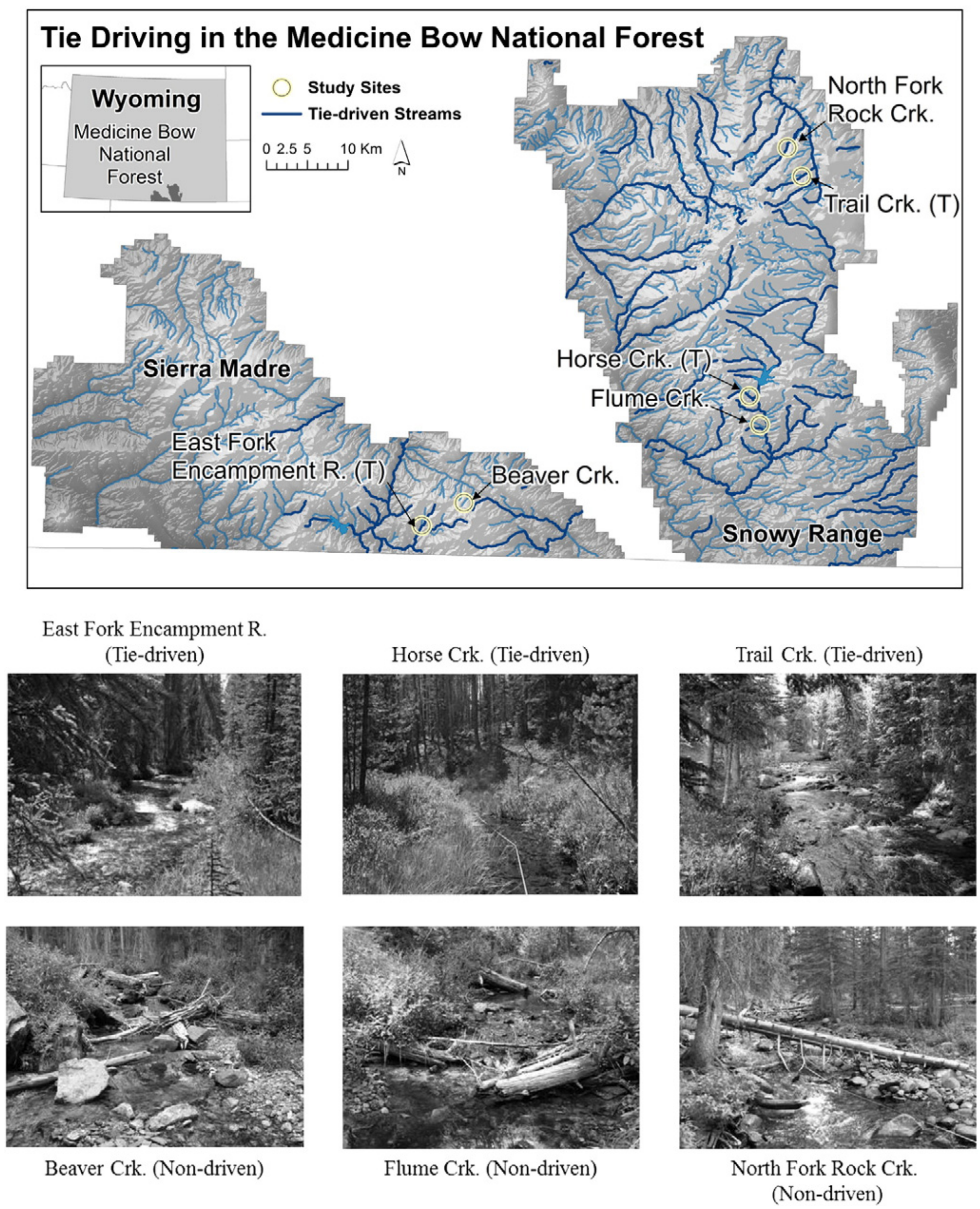

Fig. 2. Location of tie-driven streams and study reaches in the Medicine Bow National Forest, southeast Wyoming. Heavy lines indicate all known tie-driven streams. The photographs compare tie-driven and non-driven conditions for each pair of study reaches.

necessary to make streams drivable included the clearing of riparian vegetation for tie storage and passage; the removal of existing LW, debris jams, and boulders; and the construction of surge dams and feeder flumes to increase flow. Young et al. (1994) inventoried individual bedforms, censused LW (pieces ≥2 m long with mean diameters ≥15 cm), and sampled riparian vegetation (trees ≥20 cm diameter at breast height) to evaluate the effects of tie drives on streams in southern Wyoming. They found that stream channels that had previously been tie-driven had a fewer pools, lacked LW, and were characterized by riparian forests with low stem densities and limited streamside shrub cover. Decreased wood loads owing to historic tie-driving and contemporary management activities have also been observed in the Bighorn National Forest in northern Wyoming (Nowakowski and Wohl, 2008). However, detailed information regarding morphodynamic differences, the functional role of instream wood, and recruitment potential of additional wood is needed to fully articulate the extent, magnitude, and legacy effects of tie-driving.

The geomorphic implications of timber floating and associated practices such as the use of splash dams have been studied in other regions including Oregon, USA (Miller, 2010), Sweden (Dahlstrom et al., 2005), and the Italian Alps (Comiti, 2012). Study results have shown consistent channel responses to the construction of splash dams, channelization, and other structural alterations, particularly effects on channel geometry, planform, and hydraulic alterations (Table 1). In addition to alterations in channel structure, evidence also suggests that logging activities in the riparian area can have lasting impacts on the channel as well. In both Oregon and Washington, riparian logging has altered LW recruitment and has led to altered distribution of LW piece size classes, altered spatial distribution of LW along stream networks, increased sediment transport and channel widening, fewer and less deep pools, and increased riffle length (Czarnomski et al., 2008; Mellina and Hinch, 2009). Research along streams in coastal Maine demonstrates an overall loss in geomorphic heterogeneity associated with historic hillslope and riparian logging (Magilligan et al., 2008). The work presented here focuses on the removal of LW from the channel and investigates the effects of this legacy on contemporary channel morphology in a variety of dimensions.

Our primary research objective is to examine the geomorphic response of low-order streams to the removal of LW associated with historic tie-driving. We used geomorphic, instream wood, and riparian surveys to evaluate differences between tie-driven and non-driven headwater stream reaches in the Medicine Bow National Forest, southeast Wyoming. We hypothesized that tie-driven streams would be characterized by simplified channel morphology, less dense and younger stands of riparian trees, and lower instream wood loading. We addressed four response variable categories with respect to tie-driving legacies: (i) channel morphology; (ii) frequency, volume, and size of instream LW; (iii) function of instream LW; and (iv) riparian–channel wood recruitment relationships.

2. Regional setting

The Medicine Bow National Forest is located in the Rocky Mountains of southern Wyoming, USA, and includes the Sierra Madre and Snowy Mountain ranges. The underlying geology of the area ranges in origin from granitic, metasedimentary, and metavolcanic rocks to glacial deposits in the higher elevations (Love and Christiansen, 1985). Elevations within the Medicine Bow National Forest boundary range from 2170 to

Table 2
Variables recorded for each piece of instream large wood (LW; from Wohl et al., 2010).

Variable	Categories	Description
Stability: potential mobility of piece, as defined by number of anchor points	0 — no ends	Neither end of the wood is anchored in a bank or other structure
	1 — one end	One end is anchored in the bank or other structure
	2 — two ends	Both ends are anchored in place
Decay class: qualitative assessment of piece age	0 — rotten	Soft wood that can be broken apart easily
	1 — decayed	Soft wood that cannot be pulled apart easily
	2 — bare	Little to no bark present
	3 — limbs	Limbs are intact and may have some or most of the bark intact
	4 — bark	Bark is intact
	5 — needles	Green or brown needles or leaves still attached
Function: process-based descriptor of the geomorphic contribution of the piece	0 — drift	Sitting on a bar with both ends within active channel
	1 — bridge	Both ends above active channel, center suspended above
	2 — collapsed bridge	Two ends on bank, broken in the middle
	3 — ramp	One end in channel, other end out of active channel
	4 — incorporated	Portion of wood is buried in channel (may or may not be a step)
Structure: individual channel feature that contributes to the retention of the piece	1 — debris jam	part of a jam of 3 or more pieces
	2 — tree/rootwad	Associated with a living tree or rootwad
	3 — boulder	Associated with a boulder in the stream
	4 — meander	Caught on the outside of a meander
	5 — bar	Sitting on a point or mid-stream bar
	6 — bedrock	Caught on bedrock
	7 — beaver dam	Part of a beaver dam
	8 — bank	Imbedded in the bank, buried by soil or bank materials
	9 — log step	Forms a step in the stream
	10 — buried in bed	Portion of log is buried in channel bed, but is NOT functioning as a step
	0 — none/other	Something else (specify)
Channel type: the larger morphologic unit where the piece is found	1 — pool	Flat surface, deep with a downstream control
	2 — riffle	Shallow, finer grained 1–2% slope
	3 — glide	Between pool and riffle, no downstream control
	4 — rapid	(Plane bed) 2.5–4% slope, poorly defined steps, moderately steep
	5 — step/pool	Well-defined step-pool structure
	6 — cascade	Very steep, fall, irregular step-pool morphology
	7 — other	Explain in comments area
Source: assessment of recruitment source	0 — unknown	Source of wood cannot be determined
	1 — riparian	Source of wood appears from relatively flat surface adjacent to stream channel
	2 — hillslope	Wood originates from steeper landform — either a depositional feature (moraine) or valley wall
	3 — floated	Origin of wood is from upstream and has been transported into place
	4 — avalanche	Wood appears to have been transported by moving snow
	5 — other	Other clearly defined source — explain in comments section

3640 m. Both the Snowy Range and Sierra Madre were glaciated during the Pleistocene resulting in numerous till fields, moraines, and lakes throughout the area (Dillon et al., 2005).

The majority of annual precipitation in the region falls as snow between October and May and mean annual precipitation varies from ~28 cm at low elevations to 669 cm at the highest elevations. Average annual temperatures range from a low of −1.31 °C to a high of 11.65 °C with January typically being the coldest month and July being the warmest (PRISM Climate Group). The flow regime throughout the area is snowmelt dominated, and peak flow usually occurs in June.

Forests are typically dominated by a mixture of lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and aspen (*Populus tremuloides*) that vary in relative abundance depending on elevation and aspect (Dillon et al., 2005). Published estimates of stand age suggest that within the Sierra Madre and Snowy ranges, only 15% to 30% of trees are more than 150 years old and therefore stands qualifying as old-growth (generally thought to be between 200 and 300 years old in spruce–fir dominated regimes) are very limited (Dillon et al., 2005). Stream channel morphology in the area is consistent with channel morphology in other mountainous regions (Montgomery and Buffington, 1997) and highly dependent on gradient and the geomorphic influence of instream wood (Wohl and Goode, 2008; Wohl and Merritt, 2008). Typical channel types associated with streams in the region include step–pool, plane-bed, and pool–riffle channels (Wohl and Merritt, 2008). Common natural disturbances in the study region include wildfire, bark beetle outbreaks, and debris flows; while human disturbances range from historic activities such as removal of beaver, placer mining, and tie-driving; to present day activities related to resource management, development, and recreation (Wohl, 2001, 2006; Dillon et al., 2005).

3. Methods

3.1. Selection of study reaches

We adopted a paired-reach sampling design, with two pairs (four reaches) in the Snowy Range and one pair (two reaches) in the Sierra Madre (Fig. 2). Reach pairs were located in close proximity to control for localized differences in geology, elevation, and riparian forest structure that may confound detection of differences in channel morphology associated with disturbance conditions. Each reach-pair consists of one tie-driven reach and one non-driven reach. Because of the extensive history of human activity within the National Forest, tie-driven streams were determined on the basis of tall and decayed stumps, abandoned cabins close to the reach, and other indications of prior logging activity. None of the study reaches were located in areas where the riparian community would qualify as old-growth. Non-driven streams were determined based on the quantity and age of existing wood loads in the channel and riparian area, the presence of large boulders or knickpoints near the study reach, and any other geologic feature that would prohibit the passage of ties during high flow events. Each identified stream was cross-checked with the historical records of tie-driving compiled by Young et al. (1994). There are historical records of tie-driving that correspond with two of the non-driven reaches. However, field evidence indicated that any tie-drives occurred downstream of the chosen study reach locations based on the site selection criteria listed above. Study watersheds were evaluated for disturbances (e.g. blow-downs, fire, beaver dams) that would impact wood loading or other geomorphic processes using a combination of historic records, aerial and satellite imagery, and field reconnaissance. Selection of study reaches was further constrained by common physiographic criteria including stream order, reach slope, geomorphic characteristics of valley bottoms, and surficial geology. Paired study reaches were selected to be as physically analogous as possible, with the exception of tie-driven-related attributes.

3.2. Field methods

Along each sampling reach, we surveyed 30 evenly spaced cross sections and one centerline longitudinal profile extending 30 channel widths in length using a stadia rod and level (Simon and Castro, 2003). Reach lengths were scaled according to average bankfull width in order to account for differences in stream size. Beaver Creek, East Fork Encampment River, Flume Creek and Horse Creek each have 90 m long reaches and North Fork Rock and Trail Creeks have 210 m long reaches (Fig. 2). Stream reaches were sampled in July and August 2012 following peak snowmelt flows. Channel geometry was calculated for the bankfull portion of each cross section and reaches were classified following Montgomery and Buffington (1997) into categories for pool–riffle, plane-bed, step–pool, and cascade channel sequences. Each reach

Table 3
Description of control and response variables used in the multiple regression analyses. Control variables are grouped by category.

Response variables

Variable	Description (units)
$Piece_{Tot}$	Number of pieces per study reach (#)
$Piece_{Load}$	Number of pieces/channel area (m^2)
Vol_{Tot}	Total volume of wood per study reach (m^3)
Vol_{Load}	Total volume/channel area (m^3/m^2)

Control variables

	Abbreviation	Variable (units)	Description
Physiographic	Drive	Drive	Categorical (non-driven = 1, tie-driven = 2)
	Elev	Elevation (m)	Continuous; derived from 10-m resolution digital elevation models
	Area	Drainage area (km^2)	Continuous; watershed area upstream from study reach delineated using 10-m resolution digital elevation models
Riparian	StDe	Stem density (stems ha^{-1})	Continuous; calculated from riparian plot data
	BaArea	Basal area (m^2 ha^{-1})	Continuous; calculated from riparian plot data and includes all trees sampled
	BaDead	Basal area of dead trees (m^2 ha^{-1})	Continuous; calculated from riparian plot data and includes only dead trees sampled
	PDead	Proportion of dead trees (%)	Continuous; percentage of dead trees within sampled plots
Geomorphic	ChW	Average channel width (m)	Continuous; calculated from surveyed cross sections
	R	Roughness (σ_z)	Continuous; standard deviation of bed elevation measurements obtained from surveyed cross sections
	W	Total stream power	Continuous; calculated from the equation $W = gQ_2S$ where g is the specific weight of water (9800 N/m^2), Q_2 is the peak flow rate with a 2-year return frequency, and S is the reach slope (m/m); values of Q_2 were estimated using regional regression equations (Lowham, 1976)
	S	Reach slope	Continuous; obtained from surveyed longitudinal profile (m/m)

Table 4
Study reach characteristics.[a]

Reach (pair)	Disturbance condition	Stream order	Riparian plots (no.)	A_{Basin} (km^2)	E (m)	A_{Reach} (m^2)	L (m)
Beaver Creek (A)	Non	1	2	2.66	2884	336.0	92.3
East Fork Encampment River (A)	Tie	1	2	4.27	2728	305.3	91.4
Flume Creek (B)	Non	1	2	3.47	2698	231.0	88.5
Horse Creek (B)	Tie	1	2	7.28	2835	275.3	90.25
North Fork Rock Creek (C)	Non	2	3	14.24	2948	1476.8	208.0
Trail Creek (C)	Tie	2	4	8.26	2991	1478.0	225.0

[a] A_{Basin} = contributing drainage area; E = elevation; A_{Reach} = area of reach calculated from reach length and average bankfull width; L = reach length.

was also mapped at the habitat unit scale (i.e. individual, discrete bedforms). Substrate size distributions were visually estimated for each morphologic unit using a randomly placed 0.5 m × 0.5 m gridded plot (Gordon et al., 2004). The same operator performed all of the visual estimates of substrate cover to minimize measurement error (Daniels and McCusker, 2010). Riparian forest stand characteristics were sampled in 0.05-ha circular plots (2 to 4 plots per reach), which were established adjacent to the stream channel in locations that were representative of the variation in forest structure along the entire study reach. Within each plot, information recorded on all live and dead trees (≥5 cm diameter at breast height, DBH) included species, DBH, and evidence of bark beetle incidence and damage. Infestation by bark beetles is responsible for recent, widespread tree mortality throughout the Rocky Mountain region (Jenkins et al., 2008; Raffa et al., 2008) and was recorded in order to gain insight on the trajectories of future wood loading in the study reaches.

A wood census was completed for all pieces of LW within the bankfull channel that were longer than 1 m and at least 10 cm in diameter following the level I metrics suggested by Wohl et al. (2010). For each piece of instream wood occurring within each reach, the total length, length of the portion within the channel, and two end diameters were measured. The volume of each piece within the channel was calculated using Eq. (1) (Lienkaemper and Swanson, 1987):

$$\text{Volume} = \frac{\pi\left(D_1{}^2 + D_2{}^2\right)L}{8} \quad (1)$$

where D_1 and D_2 are the end diameters (m) for each piece and L is the piece length within the channel (m). Calculated piece volumes were summed to quantify wood loads for each reach. Because the total piece lengths were not used, calculated volumes and reach wood loads do not include the volume of wood outside of the stream channel. Instream stability, structural associations, and piece function (see Table 2 for category definitions) were recorded for each LW piece to compare process-based characteristics of existing wood loads between tie-driven and non-tie-driven reaches. Decay class and recruitment source were recorded to relate riparian condition with instream wood loads (see Table 2 for category definitions).

3.3. Data analysis

We used Analysis of Variance (ANOVA) to test for differences in channel morphology and LW piece dimensions between tie-driven and non-driven study reaches. Channel width, average depth, and cross-sectional area were scaled by watershed area to enable comparisons across watersheds. Normality was assessed using the Shapiro–Wilk test prior to running each ANOVA. To meet assumptions of normality, the following variables were log transformed: channel width (scaled), average channel depth (scaled), cross-sectional area (scaled), width-to-depth ratios (W:D), average LW piece diameter, and average in-channel LW volume. Total LW piece length and in-channel piece length did not meet normality assumptions after transformation so they were compared using the Kruskal–Wallis test, a non-parametric ANOVA. To assess differences in the functional characteristics of LW, categorical variables associated with the wood census metrics were analyzed using χ^2 analyses.

We used simple linear regression analyses to evaluate relationships between wood loads and control variables representing physiographic, riparian, and geomorphic conditions that have been shown to influence LW recruitment to streams. Control and response variables used in the regression analyses are described in Table 3. Four variations of wood loading metrics (sensu Wohl and Jaeger, 2009) were used as response variables to examine differences in the frequency and volume of LW pieces in each study reach and to standardize those values by study reach area to account for loading differences across sites. Control variables representing physiographic, riparian, or geomorphic categories (Table 3) were run individually as opposed to a multiple linear regression because of the low sample size (n = 6). We used $\alpha = 0.05$ and $\alpha = 0.1$ to determine model significance.

4. Results

Study reach characteristics are summarized in Table 4. Of the six reaches sampled, only one pair, Trail Creek and North Fork Rock Creek, was located along second-order streams. Riparian tree species composition reflected the dominant species found in the area: lodgepole pine (*P. contorta*), Engelmann spruce (*P. engelmannii*), and subalpine fir (*A. lasiocarpa*). Approximately 39.0% to 71.6% of the basal area (in North Fork Rock Creek and Beaver Creek, respectively) was

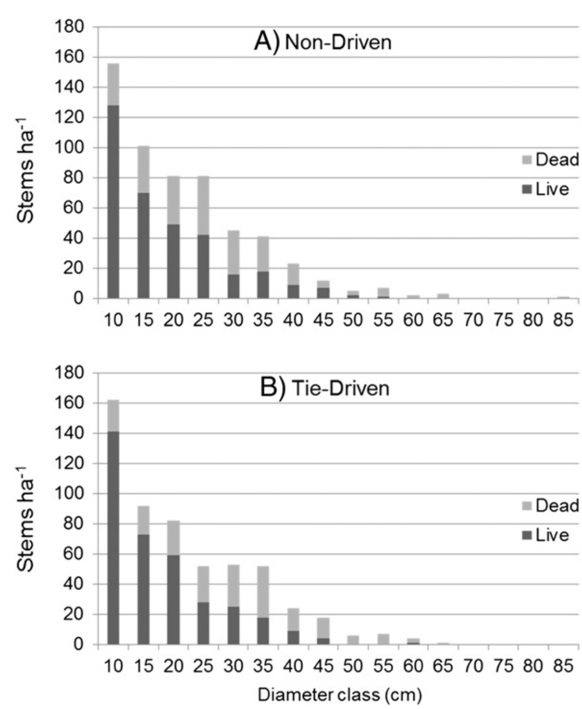

Fig. 3. Density (stems ha^{-1}, live and dead, ≥10 cm DBH) for stems of all species by diameter class (5-cm increments) for non-driven and tie-driven riparian plots. Species sampled include subalpine fir, lodgepole pine, and Engelmann spruce.

Table 5
Mean channel geometry metrics. Reach values represent averages over 30 surveyed cross-sections for each study reach (n = 30).[a]

Reach (pair)	Disturbance condition	S (m/m)	W (m)	D (m)	Area (m^2)	W:D	R_{XS}	R_{LONG}
Beaver Creek (A)	Non	0.06	3.64 ± 0.15 (2.2–5.38)	0.3 ± 0.02 (0.16–0.59)	1.003 ± 0.1 (0.4–2.38)	13.25 ± 0.92 (5.78–26.91)	16.94 ± 0.98 (10.57–29.67)	1.6
East Fork Encampment River (A)	Tie	0.04	3.34 ± 0.1 (2.03–4.6)	0.16 ± 0.01 (0.08–0.25)	0.503 ± 0.03 (0.22–0.82)	22.73 ± 1.47 (12.86–42.33)	9.19 ± 0.50 (4.52–15.84)	0.9
Flume Creek (B)	Non	0.02	2.61 ± 0.12 (1.5–4.08)	0.29 ± 0.02 (0.14–0.57)	0.630 ± 0.05 (0.2–1.29)	10.02 ± 0.66 (3.7–19.98)	16.02 ± 0.82 (9.7–26.85)	1.2
Horse Creek (B)	Tie	0.02	3.05 ± 0.1 (2.25–4.1)	0.27 ± 0.02 (0.14–0.55)	0.69 ± 0.04 (0.3–1.14)	12.41 ± 0.82 (4.52–21.76)	14.46 ± 0.86 (8.36–27.41)	0.5
North Fork Rock Creek (C)	Non	0.04	7.1 ± 0.28 (3.15–12.4)	0.42 ± 0.03 (0.11–0.72)	2.814 ± 0.22 (0.81–5.79)	20.13 ± 2.15 (4.4–71.76)	20.17 ± 1.04 (9.88–35.28)	2.5
Trail Creek (C)	Tie	0.04	6.54 ± 0.3 (3.4–10.2)	0.41 ± 0.02 (0.23–0.76)	2.401 ± 0.16 (1.02–5.85)	17.38 ± 1.36 (7.27–38.17)	21.70 ± 1.19 (12.27–35.85)	2.5

[a] S = channel gradient obtained from surveyed longitudinal profiles; W = average bankfull channel width; D = average bankfull depth; A = average cross-sectional area; W:D - = average width-to-depth ratio; R_{XS} = average cross-sectional roughness represented as the standard deviation of surveyed bankfull depths; R_{LONG} = longitudinal channel roughness represented as the standard deviation of depths surveyed along the thalweg.

composed of dead trees, with lodgepole pine killed by mountain pine beetle within the last 8 years and Engelmann spruce recently killed by spruce beetle (Colorado State Forest Service, 2012; Dwire et al., in press). The distribution of tree diameter size classes is indicative of uneven aged cohorts of riparian trees across non-driven and tie-driven reaches. Approximately 84% of live trees in non-driven and in tie-driven sites had DBH values of 25 cm or less, while 60% of dead trees in non-driven sites and 45% of dead trees in tie-driven sites fell in this category (Fig. 3).

4.1. Morphological conditions

On average, channel dimensions are similar when study reaches are compared within the same stream order (Table 5). First-order reaches have bankfull widths of ~3 m with average depths ranging from 0.16 to 0.3 m. Second-order reaches are almost twice as wide with average depths just over 0.4 m. However, results from the ANOVA tests indicate that both scaled and unscaled metrics of channel geometry differ between tie-driven and non-driven reaches (Table 6). When scaled by watershed area and log-transformed to meet assumptions of normality, non-driven reaches were significantly wider (Fig. 4A; Table 6; $p < 0.001$), deeper (Fig. 4B; Table 6; $p < 0.001$), and had greater cross-sectional area (Fig. 4C; Table 6; $p < 0.001$) than tie-driven reaches. Non-driven reaches also have significantly smaller W:D ratios (Fig. 4D; Table 6; $p < 0.01$) and significantly higher cross-sectional roughness values (Fig. 4E; Table 6; $p < 0.001$). Longitudinal roughness values were not significantly different between tie-driven and non-driven streams (Fig. 5).

Table 6
Results of ANOVA and Kruskal–Wallis tests testing differences in geomorphologic variables between tie-driven and non-driven study reaches; the ANOVA was run on log transformed variables to meet assumptions of normality.

ANOVA			
	Ndf, Ddf	F	Pr (>F)
Morphology			
LogWidth_Scaled	1, 178	12.16	0.0006**
LogDepth_Scaled	1, 178	28.73	0.0006**
LogArea_Scaled	1, 178	23.33	0.0006**
LogW:D	1, 178	9.419	0.002*
LogRough	1, 178	14.07	0.0002**
LW dimensions			
$Diameter_{Avg}$	1, 136	1.593	0.209
$Volume_{Channel}$	1, 136	0.092	0.763
Krukal–Wallis			
	Ndf	Chi-squared	Pr (>F)
LW dimensions			
$Length_{Total}$	1	1.1601	0.2814
$Length_{Channel}$	1	4.1055	0.0427^

** indicates significance at the $p < 0.001$ level; * at the $p < 0.01$ level; and ^ at the $p < 0.05$ level.

Habitat units were inventoried to assess morphological heterogeneity associated with tie-driven and non-driven reaches (Fig. 5; Table 7). Habitat units characterizing the study reaches include pools, riffles, runs, steps, and cascade morphologies. A greater proportion of tie-driven reaches were characterized by riffle or run morphologies compared to their non-driven site pairs (Table 7). In general, a smaller percentage of total reach area in tie-driven streams was composed of pool features compared to non-driven reaches, with the exception of Horse Creek (Table 7). Tie-driven reaches also had a smaller percentage of area characterized by high gradient morphologies such as steps and cascades (Table 7). In East Fork Encampment River, three out of four pools are associated with wood-forced morphology while in Trail Creek, six out of nine pools are associated with wood-forced morphology (Fig. 5).

The substrate across all habitat units is relatively coarse and is characterized by size classes representing cobbles and boulders, with sparse patches dominated by gravels (Fig. 6). Differences in the distribution of grain sizes between tie-driven and non-driven reaches were not significantly different (p value >0.1), even when morphologic unit type was taken into account (Table 7). Additionally, the geometric mean — which captures the central tendency of the grain size distributions while accounting for extremes in the sample distribution — did not differ between tie-driven and non-driven reaches (Table 7; p value >0.1).

4.2. Characteristics of instream large wood

With the exception of Trail Creek, tie-driven reaches have substantially fewer pieces of instream wood, translating to overall lower wood loads (Table 8). Trail Creek and its non-driven site pair, North Fork Rock Trail Creek, are both second-order streams and had similar quantities of wood pieces within the study reaches. However, Trail Creek is somewhat unique in that it had the highest riparian basal area, which was mostly comprised by standing dead trees. The majority of instream wood found in the Trail Creek reach was concentrated in four jams that formed along recently downed trees (Fig. 5). In North Fork Rock Creek, instream wood was found in two jam formations; but these jams did not appear to have an impact on morphology, and most pieces were more evenly distributed throughout the reach (Fig. 5).

Average total piece length ranges from ~5 to 9 m across all reaches with fairly consistent average diameters (Table 8; Fig. 7). The exception is Horse Creek, which only had two pieces of instream wood in the study reach and also had the lowest basal area. The average diameters for the two LW pieces are 19 and 7.95 cm; however, it is difficult to accurately compare these values to the rest of the basin, given the small sample size. Normalized values of average LW piece diameter or volume of

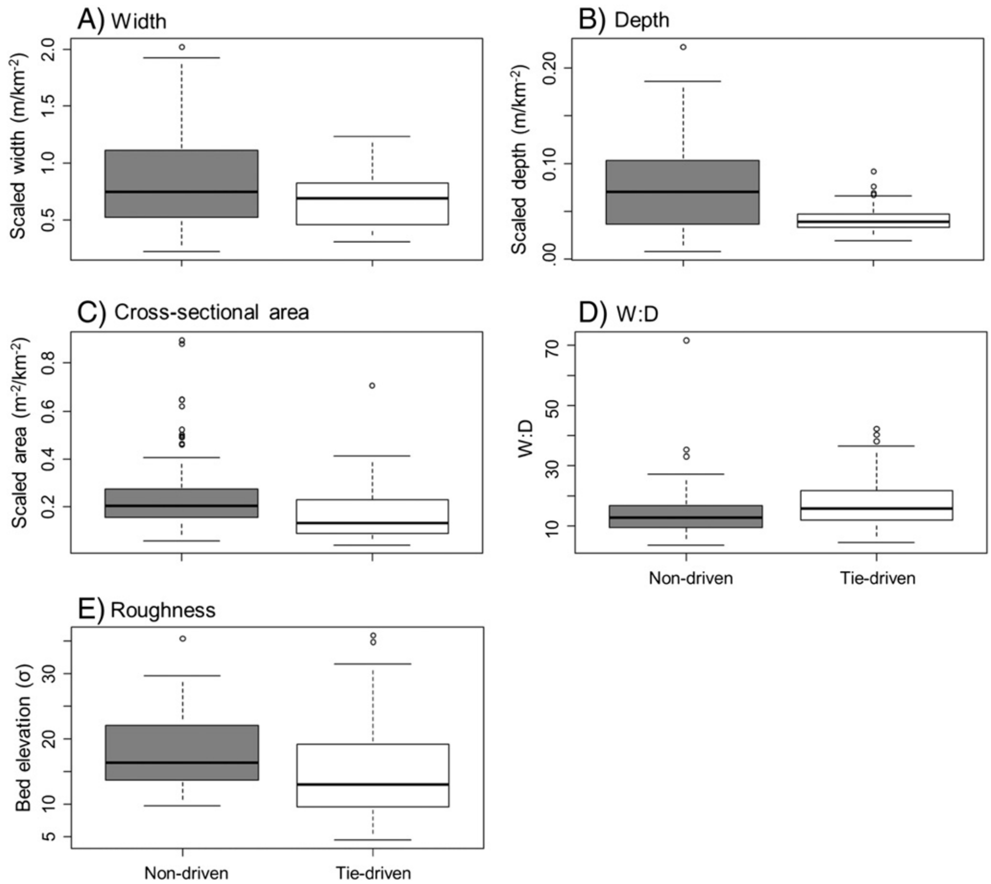

Fig. 4. Box plots comparing scaled values of (A) channel width, (B) average depth, and (C) cross-sectional area as well as (D) width-to-depth rations (W:D) and (E) cross-sectional roughness values between non-driven and tie-driven sites. Roughness was calculated as the standard deviation of surveyed bed elevations. Gray boxes signify the non-driven reach within the study pair.

LW pieces within the channel between disturbance conditions were not significantly different (Table 6). The Kruskal–Wallis nonparametric test revealed that total piece length was not significantly different between non-driven and tie-driven streams; however, the length of LW within the channel of tie-driven reaches was significantly longer than pieces within the channel of non-driven reaches (Table 6; Fig. 7). Taken together, the similarities in instream wood dimensions as represented by diameter and total length reflect the traits of the dominant riparian tree species and suggest that the primary recruitment mechanism for the study streams has been individual tree mortality (Benda et al., 2003).

Wood census metrics differed significantly between tie-driven and non-driven reaches, indicating notable differences in the functional and structural role of instream LW pieces (χ^2 tests, Fig. 8). The stability of wood pieces, as indicated by the number of anchored piece ends (0, 1, 2), differed significantly between disturbance conditions with more pieces in the non-driven reaches being anchored at two ends (Fig. 8A; χ^2 (2, n = 138) = 7.33, $p < 0.05$). Non-driven study reaches also had more pieces in a greater range of decay classes (Fig. 8B; χ^2 (5, n = 138) = 12.02, $p < 0.05$). In tie-driven reaches, no pieces were observed in the *rotten* decay class; and 16% of all pieces retained limbs, bark, and needles, indicating that they were recently recruited to the channel. The frequencies of piece function, which infers the morphologic role that each piece plays in the channel, were also different between non-driven and tie-driven reaches. In non-driven reaches, 33% of the pieces were acting as ramps compared to 52% in tie-driven reaches (Fig. 8C; χ^2 (4, n = 138) = 17.21, $p < 0.01$). Additionally, 16% of the pieces inventoried in non-driven streams were incorporated into the channel, while no incorporated pieces were inventoried for tie-driven streams. Structural associations of LW pieces indicate the types of instream features that retain wood. Pieces in non-driven reaches were associated with a wider variety of channel structures (Fig. 8D; χ^2 (7, n = 138) = 20.18, $p < 0.01$). In both non-driven and tie-driven reaches, the most common structural associations were stream banks (33% and 47%, respectively) and debris jams (30% and 34%, respectively). Tie-driven reaches had no log steps, while six log steps were inventoried for non-driven streams. Approximately 19% of LW pieces inventoried in non-driven reaches were identified as having structural associations other than the main categories listed in Table 2. These pieces were primarily ramps and bridges that were held in place by trees in the riparian area. Large wood pieces in the tie-driven reaches were associated with a wider range of channel types compared to non-driven reaches (χ^2 (7, n = 138) = 23.75, $p < 0.001$). The majority of wood pieces were associated with riffle morphologies in non-driven (77%) and tie-driven (63%) reaches. Approximately 35% of LW pieces in tie-driven reaches were found in pools compared to only 11% in non-driven reaches. Sources of LW between non-driven and tie-driven reaches were not significantly different. In non-driven streams, 11% of the pieces were contributed from the hillslope, 37% were from the riparian area, and 42% of pieces were from unknown sources. In tie-driven reaches, 28% of the pieces were contributed from the hillslope, 36% were from the riparian area, and 36% of pieces were from unknown sources.

4.3. Relations among wood loads, riparian and geomorphic variables

Basal area was significantly correlated with the total number of instream wood pieces ($Piece_{Tot}$; $p < 0.1$, $R^2 = 0.48$) and total wood volume (Vol_{tot}; $p < 0.05$, $R^2 = 0.61$) across all study reaches (Table 9). Basal area was the only riparian variable that explained a significant portion of the variation for these LW metrics. Stream power (*W*;

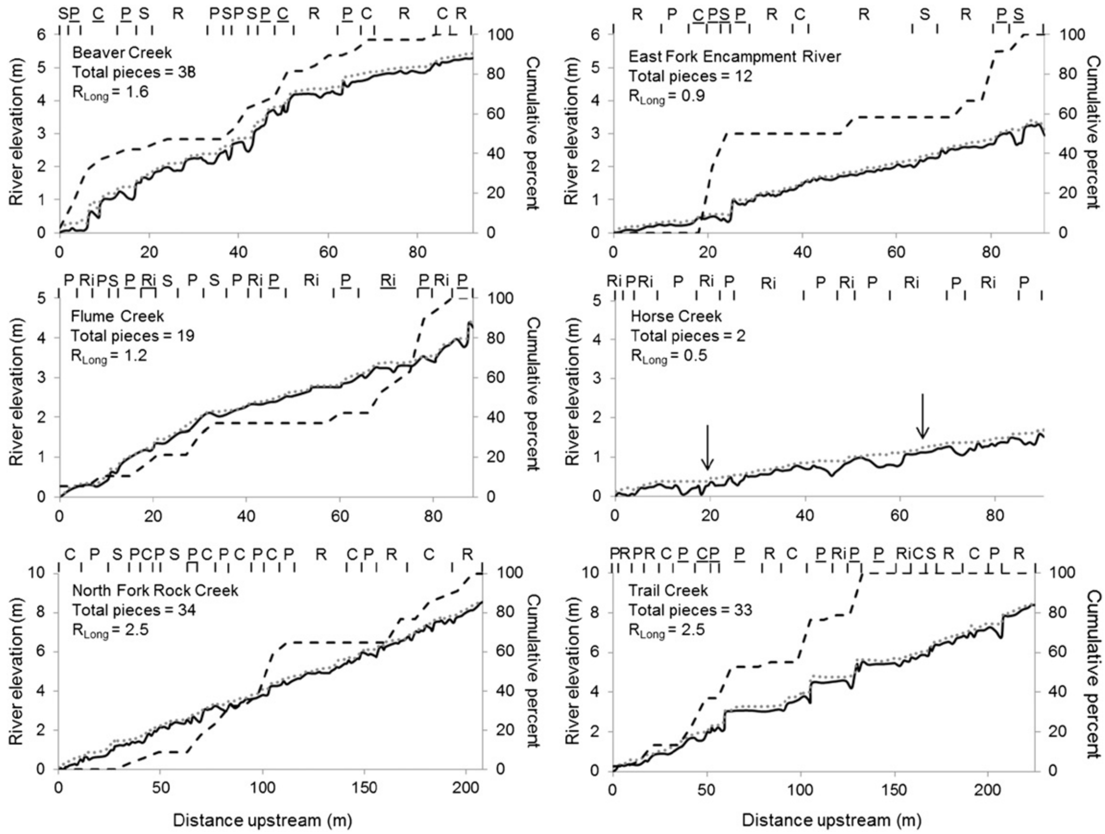

Fig. 5. Longitudinal profiles of all reaches with cumulative accumulation of all inventoried in-channel wood. Bed elevations are shown with a solid black line, water surface elevations are shown with a gray dotted line, and cumulative frequencies of wood loads are shown with a black dashed line. Because of the low number of pieces (n = 2) for Horse Creek, the locations of each piece are shown instead of cumulative frequency. Habitat units are identified at the top of the graph, and wood-forced morphologies are denoted with an underline. Codes for habitat units are as follows: C = cascade, P = pool, R = run, Ri = riffle, S = step.

$p < 0.1, R^2 = 0.43$) and reach slope (S; $p < 0.1, R^2 = 0.49$) were correlated with total volume of instream wood for each study reach (Table 9). Reach slope was the only control variable significantly related to total volume standardized by unit area (Vol_{Load}; $p < 0.05, R^2 = 0.64$). No variables were significantly correlated with wood load per reach area ($Piece_{Load}$; Table 9).

5. Discussion

Comparisons between non-driven and tie-driven stream reaches indicate that tie-driven reaches are significantly more narrow and shallow and have lower cross-sectional areas compared to non-driven reaches. Additionally, they are characterized by significantly lower cross-sectional roughness and higher width to depth ratios. Non-driven reaches were significantly wider, deeper, and had a larger cross-sectional area and greater cross-sectional roughness values compared to tie-driven pairs. The variety of habitat units across sites reflects the range of morphologic types expected of mountain streams (Montgomery and Buffington, 1997). However, tie-driven streams were dominated by runs or riffles and had proportionally fewer pools compared to non-driven streams, although substrate conditions were similar. Overall, tie-driven streams were associated with lower wood loads and altered load characteristics. Although the dimensions of individual wood pieces are similar, LW in tie-driven streams tends to be younger than those in non-driven streams, and the majority of wood is arranged as ramps. The lack of bedforms associated with LW incorporated in the channel such as log steps and the predominance of plane-bed features found in tie-driven reaches are consistent with Young et al. (1994). Their results indicate that tie-driven channels were largely dominated by plane-bed features with fewer discrete channel units than non-driven reaches (Young et al., 1994). They also identified instream wood as a morphologic control for pool formation in their reference (non-driven) reaches and note the lack of log steps in tie-driven reaches. Direct comparisons between the frequency of channel units and specific riparian stand parameters could not be made because of differences in channel inventory and riparian sampling methods.

5.1. Morphologic conditions

The simplified channel morphology associated with tie-driven reaches, as represented by altered channel geometry, lower cross-sectional roughness, and low diversity of bedforms typifies the result of adjustments made over the course of decades following the practice of tie-driving. Previous studies examining the effects of LW removal on stream channels have found increases in water velocity (Gregory and Davis, 1992), enhanced scouring of fine sediments (Beschta, 1979), and decreased frequency and size of pools (Lisle, 1986; Richmond and Fausch, 1995; Díez et al., 2000). Increases in velocity and bedload movement that result from wood removal can lead to the straight, featureless bed characteristics of plane-bed morphologies as the channel adjusts between transport-limited and supply-limited phases of sediment loading (Heede, 1985; Montgomery and Buffington, 1997). Reaches characterized as pool-riffle have transitioned to plane-bed channels following events of increased sediment supply, although plane-bed channel morphology is ultimately associated with sediment supply limited conditions such as bed armoring (Lisle, 1995; Wohl and Cenderelli, 2000). The heightened transport capacity associated with extended plane-bed reaches has been shown to impact rates of wood removal and increase wood recruitment in downstream reaches (Downs and Simon, 2001). The presence of instream wood is an

Table 7
Habitat unit characteristics for each study reach.[a]

Site	F	A	$A_{\%}$	D_{16}	D_{50}	D_{84}	D_g
Beaver Creek (A: non-driven)							
Cascade	4.3	20.5 (±5.9)	19.2	95.8 (±17.5)	180.5 (±33.6)	316.0 (±40.0)	172.8 (±27.0)
Pool	6.5	10.4 (±1.4)	22.7	17.0 (±3.8)	69.9 (±14.1)	128.4 (±14.0)	44.7 (±7.3)
Run	4.3	34.1 (±3.1)	53.1	37.1 (±2.1)	87.9 (±5.3)	142.1 (±11.2)	71.2 (±3.5)
Step	4.3	4.1 (±0.3)	5.1	49.1 (±5.8)	190.5 (±50.0)	236.5 (±42.5)	105.0 (±15.0)
E.F. Encampment River (A: tie-driven)							
Cascade	2.2	15.0 (±3.4)	13.1	33.2 (±3.0)	62.0 (±7.8)	160.1 (±16.7)	72.8 (±7.0)
Pool	4.4	10.0 (±1.7)	11.6	29.5 (±4.2)	50.9 (±8.0)	148.6 (±19.4)	59.5 (±3.5)
Run	4.4	55.8 (±8.1)	65.2	59.8 (±6.4)	105.8 (±5.7)	236.5 (±49.8)	117.1 (±18.1)
Step	4.4	11.5 (±2.4)	10.0	22.2 (±3.4)	94.0 (±8.6)	155.1 (±11.5)	55.6 (±5.1)
Flume Creek (B: non-driven)							
Pool	10.1	6.8 (±1.3)	32.9	31.4 (±4.0)	86.0 (±13.8)	157.7 (±21.5)	66.2 (±7.3)
Riffle	6.7	12.3 (±1.8)	50.8	23.8 (±5.3)	66.8 (±7.5)	123.1 (±4.7)	48.7 (±4.4)
Step	3.4	5.9 (±1.6)	16.3	81.9 (±28.3)	104.5 (±26.5)	176.2 (±16.5)	106.1 (±24.8)
Horse Creek (B: tie-driven)							
Pool	8.8	16.9 (±3.0)	39.6	66.5 (±20.0)	111.0 (±20.2)	181.3 (±17.5)	100.5 (±17.1)
Riffle	8.8	25.7 (±6.6)	60.4	24.4 (±3.8)	49.9 (±9.6)	148.3 (±22.6)	58.6 (±8.8)
N.F. Rock Creek (C: non-driven)							
Cascade	2.9	114.7 (±20.8)	46.2	65.6 (±3.3)	138.8 (±14.4)	192.9 (±13.0)	111.3 (±5.3)
Pool	3.8	38.6 (±4.0)	20.7	91.1 (±18.1)	153.8 (±17.6)	203.0 (±12.1)	130.4 (±15.6)
Run	1.4	150.6 (±11.9)	30.3	100.1 (±16.2)	141.0 (±16.4)	205.7 (±20.0)	140.8 (±16.7)
Step	1.0	20.8 (±4.5)	2.8	127.8 (±17.0)	186.0 (±10.4)	218.0 (±12.3)	165.6 (±16.0)
Trail Creek (C: tie-driven)							
Cascade	2.2	97.9 (±7.3)	34.2	51.3 (±3.2)	107.8 (±9.3)	192.0 (±3.6)	98.7 (±3.6)
Pool	3.6	22.6 (±2.3)	12.6	66.2 (±17.1)	92.4 (±15.4)	144.9 (±12.7)	93.1 (±15.0)
Riffle	0.8	69.1 (±2.8)	9.7	64.0 (±0)	83.5 (±2.0)	116.6 (±3.5)	86.3 (±1.3)
Run	1.7	143.5 (±19.9)	40.1	47.0 (±3.3)	94.5 (±11.5)	163.3 (±15.6)	87.4 (±7.2)
Step	0.9	24.5 (±1.8)	3.4	139.4 (±3.5)	218.0 (±0)	256.0 (±0)	188.8 (±2.4)

[a] F = frequency of each habitat unit in reach per 100 m of channel length; A = average area of habitat units (m^2); $A_{\%}$ = cumulative percent of area occupied by each respective unit; D_{16} = grain size for the 84th percentile; D_{50} = median grain size; D_{84} = grain size for the 84th percentile; D_g = geometric mean, computed as $[(D16)(D84)]^{0.5}$.

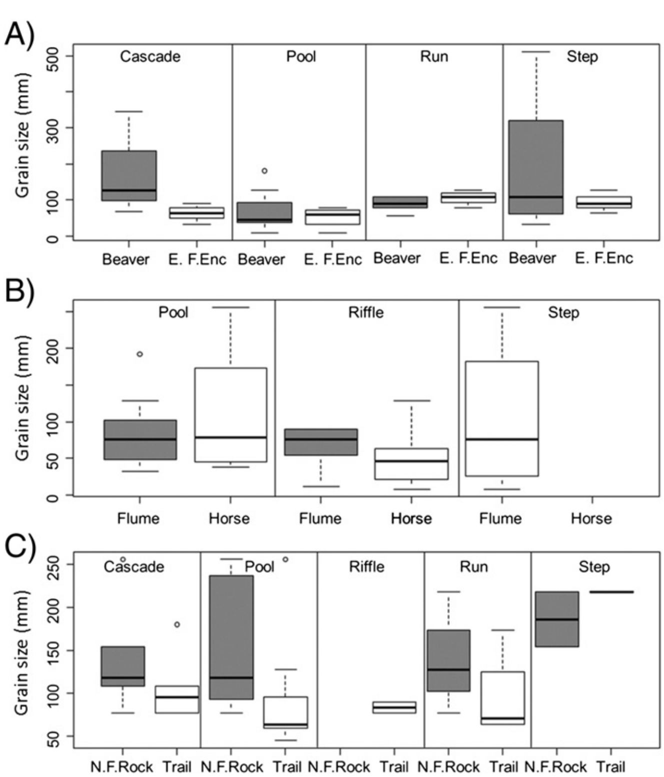

Fig. 6. Box plots displaying grain size distributions per habitat unit for paired reaches. Gray boxes signify grain size distributions for the non-driven reach within the study pair. The dark black line within the box plots denotes D_{50}.

important morphological control on sediment storage, particularly finer size classes (Díez et al., 2000; Montgomery et al., 2003), so a lack of wood can exacerbate armoring and facilitate the export of fine sediment. Given the geomorphic parameters, the present condition of tie-driven streams is characterized as wood supply-limited channels that provide little resistance during times of high flow. This increased transport capacity likely prolongs channel recovery under normal sediment delivery conditions as material is flushed out during peak flows.

5.2. Characteristics of instream large wood

In the Medicine Bow National Forest, the number and volume of instream wood pieces remain remarkably low in first-order tie-driven streams and are accumulating in jams in the second-order tie-driven reach. Without human influence, instream LW removal rates reflect wood decay rates, mechanical breakdown through abrasion and fragmentation, and the overall transport capacity of the channel. Mountain headwater streams are often associated with high wood loads because of their limited transport capacity (Jones et al., 2011) and are frequently characterized by reaches of log step sequences and wood incorporated in the channel (Hyatt and Naiman, 2001). The total volume and volume per unit area of LW in tie-driven streams are low, suggesting that wood-loading patterns reflect the impact of wood removal necessary for tie-driving. However, the limited wood present in tie-driven channels seems to have a larger geomorphic contribution than wood in the non-driven reaches. Localized transitions in habitat units within tie-driven channels were more frequently associated with the presence of wood, as indicated by the difference in the pools associated with wood in tie-driven reaches. The presence of wood in tie-driven reaches results in localized but distinct differences in morphology. In non-driven reaches, wood is more evenly distributed so that the introduction of new pieces into the channel does not influence channel form as noticeably.

Table 8
Reach averages of existing instream wood loads; jams are defined as having a minimum of three LW pieces that are in contact with one another.[a]

Site (Pair)	Disturbance condition	Stream order	Piece total	Proportion in jam (%)	$Wood_{Load}$	Total $wood_L$	Channel $wood_L$
Beaver Creek (A)	Non	1	38	26.3	0.11	7.11 ± 1.1 (1.0–27.9)	2.95 ± 0.39 (1–10.7)
East Fork Encampment River (A)	Tie	1	12	0	0.04	5.62 ± 1.42 (1.0–16.5)	3.12 ± 0.79 (0.5–9.1)
Flume Creek (B)	Non	1	19	31.5	0.08	4.62 ± 1.12 (1.2–22)	2.32 ± 0.28 (0.5–6.2)
Horse Creek (B)	Tie	1	2	0	0.01	1.95; 9.5*	1.95; 4*
North Fork Rock Creek (C)	Non	2	34	32.3	0.02	8.36 ± 0.87 (1.0–19.1)	3.62 ± 0.47 (0.5–11.2)
Trail Creek (C)	Tie	2	33	48.5	0.02	9.24 ± 1.2 (1.9–32.2)	4.27 ± 0.48 (1.4–13.1)

[a] $Wood_{Load}$ = number of pieces per m^2; Total $wood_L$ = average total piece length (m); Channel $wood_L$ = average piece length within the bankfull channel (m). *Total $wood_L$ and Channel $wood_L$ for Horse Creek are raw piece dimensions.

Extensive investigations of wood loads in streams of the Colorado Front Range suggest that despite local and basin scale variability, predictable patterns of wood loading correspond to network position (Wohl and Jaeger, 2009). Rates of wood input coupled with geomorphic characteristics combine to create zones of transport limitation where wood loads are high, supply limitation where wood loads are low, and transition areas characterized by high frequencies of jams (Wohl and Jaeger, 2009). However, in Medicine Bow National Forest the practice of tie-driving was so widespread that almost every major drainage basin was affected and has resulted in conditions that contradict this framework. Differences in piece stability and decay class between tie-driven and non-driven reaches indicate that wood in non-driven streams is less mobile, which is consistent with expected transport-limited conditions. Large wood in tie-driven streams is less stable and younger, on average. In our study, much of the LW in older decay classes in tie-driven reaches were pieces located in the various jams in Trail Creek (Fig. 8B). The accumulation of wood in these jams, in a second-order tie-driven reach, suggests that the legacy of wood removal upstream may result in more effective wood transport than might be expected. Channel banks were the most common structural association for LW pieces in tie-driven and in non-driven streams, which is likely an artifact of the narrow channels relative to the length of many recruited wood pieces. Bank associations do not necessarily imply stability as shorter and thinner pieces can move under high flow conditions unless additional structures are present such as riparian vegetation and boulders that can retain the piece. Given the prevalence of tie-driving in the area, it is possible that many headwater streams are effectively supply-limited systems that actively export a portion of recruited wood.

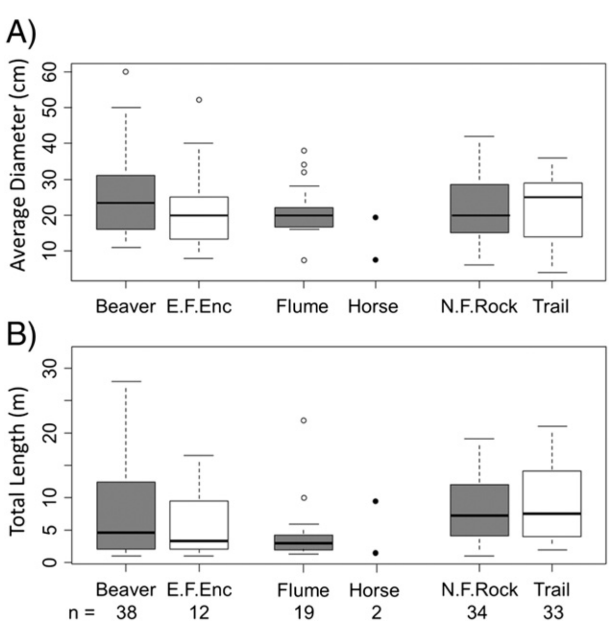

Fig. 7. Box plots of (A) mean piece diameter and (B) total piece length by study reach. Boxes with gray shading correspond to non-driven reaches, while white boxes correspond with tie-driven reaches. Mean diameter is the average of the two measured end diameters for each piece. Raw values are plotted for Horse Creek (n = 2) because only two pieces were found in the study reach. Average diameter and total length between tie-driven and non-driven reaches were not significantly different between tie-driven and non-driven reaches.

Previous studies of wood loads in Rocky Mountain Front Range streams indicate that larger quantities of wood are associated with increases in watershed area (Richmond and Fausch, 1995). However, wood loads in our reaches did not correspond to this pattern and overall were on the low end of those found in streams of the Colorado Front Range and Wyoming (Table 10). Instream wood is a more significant geomorphic mechanism in non-driven reaches as shown by the higher proportion of pieces incorporated in the channel and found in jam formations. While log steps and jams have been identified as the primary wood-based mechanisms inducing channel adjustments in mountain streams (Wohl and Goode, 2008; Beckman and Wohl, 2014), ramp formations were the predominant mechanism contributing to the variety of bedforms in tie-driven reaches. Ramps, or LW pieces that are partially in the channel, were prevalent in tie-driven reaches, yet they represent a limited influence on channel morphology overall. However, ramps deflect flow, help break up bed armoring in localized areas, and contribute to the development of jams. They also represent the initial stage of wood reintroduction following the recovery of the riparian area (Vaz et al., 2013).

5.3. Relations among wood loads, riparian and geomorphic variables

Wood recruitment mechanisms in mountain streams are dominated by topography and operate at episodic (landslides, blowdowns, etc.) or continuous (bank erosion, tree mortality) rates (Downs and Simon, 2001; Jones et al., 2011). Large-scale controls on wood recruitment can be categorized as forest characteristics, hydrological processes, geomorphic controls, and management activities (Gurnell et al., 2000). In headwater streams, forest structure and geomorphic controls are the predominant influences on wood recruitment as flow is usually not powerful enough to transport existing pieces. Generally, the frequency of instream wood decreases as channel width increases because of lower storage capacity and the decreased transport potential of the channel (Montgomery et al., 1995; Baillie et al., 2008). However, we observed that the largest wood loads were associated with the widest reach in tie-driven streams. This pattern further corroborates the observation that first-order tie-driven streams may be effective at LW transport despite their relatively small size.

Similarities in piece length and diameter between tie-driven and non-driven reaches suggest that tree mortality is an important recruitment process as most of the LW pieces sampled represented mature tree size classes. The positive correlation between basal area and the

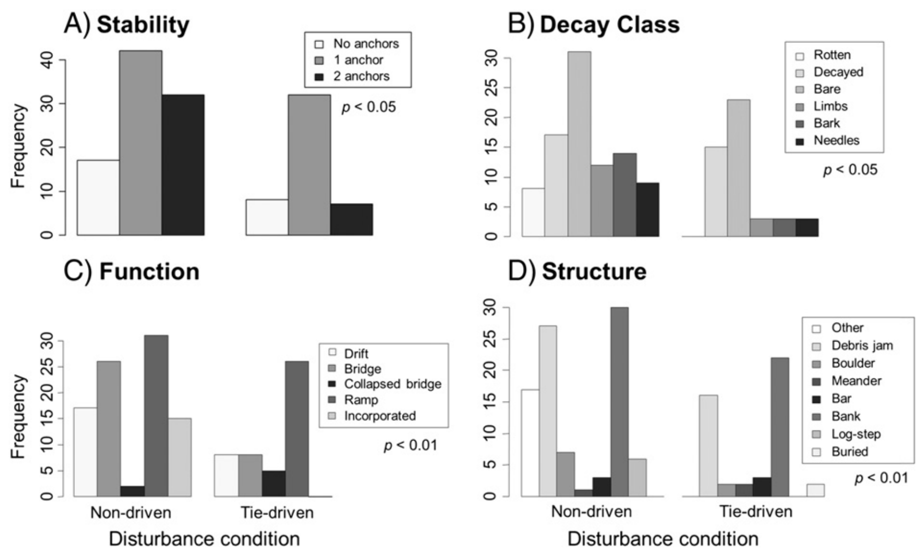

Fig. 8. Piece frequencies for instream wood characteristics for tie-driven and non-tie-driven study reaches. All p-values represent the results of χ^2 analyses on group difference.

total number of pieces (Table 9) supports the relationships associated with wood recruitment to the stream channel. Increases in the volume of LW loads are related to the tree size within the adjacent riparian area. When larger scale recruitment controls are considered, a variety of riparian and geomorphic controls influence wood frequency and volume. Basal area and metrics of transport potential (stream power and slope) were much stronger predictors of wood recruitment than physiographic controls representing basin conditions. However — in other studies investigating wood loads — recruitment sources, stand age, and local channel and valley morphology have been identified as dominant controls (Wohl and Cadol, 2011). In this study, no significant relationship between wood load per channel area and drainage area was found, which contradicts expected wood loading relationships associated with position in the network (Table 2; Table 9). Previous work has shown that lower order streams are associated with greater wood loads per area because of transport limitations associated with smaller channels (Wohl and Jaeger, 2009). The tie-driven streams in this study reflect the opposite: the first-order reaches had less wood when compared to the second-order reaches. Given the pervasiveness of tie-driving, wood loads throughout the Medicine Bow National Forest are undoubtedly altered from what would be considered an undisturbed state.

Investigations into wood loads in the Rocky Mountain Front Range indicate that local variability is a stronger determinant of LW piece frequency at the reach-scale than at the basin-scale controls (Wohl and Cadol, 2011). In this study, the number of LW pieces and local channel roughness in the cross-sectional and longitudinal directions was not significantly related. While channel roughness was significantly different between non-driven and tie-driven reaches, the lack of a direct linear relationship between wood loading and roughness suggests that roughness is likely a secondary factor regulating channel transport capacity and wood retention. Stream power and reach slope were both found to have strong correlations with metrics of wood storage (Table 9), particularly as they relate to piece volume. Stream power and reach slope are drivers that influence the transport capacity of the channel.

Interestingly, the riparian variables that were not significantly related to wood loads (Table 2) across study reaches suggest that LW recruitment dynamics lags behind forest recovery in the riparian area and the recovery of wood loads within the channel (Benda et al., 2003). The wood loads presented here fall well below many of the estimates made for streams within old growth riparian conditions (Table 10), which may indicate a disruption in wood recruitment. Wood loads were not correlated with stem density, the basal area of standing dead trees, or the proportion of standing dead trees in the riparian area. The lack of relationship between stem density and wood loads indicates

Table 9
Linear models assessing relationships relating wood-loading metrics (response variables) to geomorphic and riparian control variables.

Response variable	Control variable	p-Value	Adj. R^2
$Piece_{Tot}$	BaArea	0.08^	0.48
$Piece_{Load}$	n/a		
Vol_{Tot}	BaArea	0.04*	0.61
	W	0.1^	0.43
	S	0.07^	0.49
Vol_{Load}	S	0.03*	0.64

* Indicates significance at $p < 0.05$.
^ Indicates significance at $p < 0.1$.

Table 10
Summary of wood loads in other Rocky Mountain streams; type designations refer to descriptors of riparian condition used in the original publication.

Region	Type	Pieces/ 100 m	Source
Yellowstone National Park and Shoshone National Forest, Wyoming	Undisturbed	63	Zelt and Wohl (2004)
	Disturbed	61	
Bighorn National Forest, Wyoming	Managed	13	Nowakowski and Wohl (2008)
	Unmanaged	42	
	Combined	27	
	Combined	17	
Arapaho and Roosevelt National Forests, Colorado	Oldgrowth	18	Richmond and Fausch (1995)
	Oldgrowth	50	
	Oldgrowth	24	
	Oldgrowth	33	
	Oldgrowth	46	
	Oldgrowth	54	
	Oldgrowth	37	
	Oldgrowth	32	
	Oldgrowth	59	
	Oldgrowth	60	
	Oldgrowth	64	
	Disturbed	22	
	Disturbed	26	
	Disturbed	16	
	Disturbed	2	
This study	Tie-driven	13	
	Tie-driven	2	
	Tie-driven	15	
	Non-driven	41	
	Non-driven	21	
	Non-driven	16	

that channel condition and transport processes are determining wood retention. The lack of relationship between instream wood loads and the dead basal area or proportion of dead riparian trees attributed to beetle-caused mortality is striking (Table 8; Fig. 3). These results show that wood recruitment in the study streams has not yet responded to the recent bark beetle infestations in the area, consistent with results found in northern Colorado (Ryan et al., 2014).

5.4. Legacies and implications of tie-driving across the Medicine Bow Mountains

The legacies of historic tie-driving within the study area include altered system components such as geomorphic forms, wood loading, and riparian conditions throughout the study region. Tie-driving has not occurred in this region since the 1940s, and in some areas since the early 1900s, yet channel adjustments and wood loading are still in the early stages of recovery. Like other pervasive historic stream disturbances such as mill dams in the northeast (Walter and Merritts, 2008) and logging in coastal Maine (Magilligan et al., 2008) and in the Pacific Northwest (Bilby and Ward, 1991), tie-driving has altered the dominant channel forms and processes characterizing streams in the Medicine Bow Mountains. The alteration of these ecosystems is notable given the area's role as a significant location for recreation and its history of management within the twentieth century. Reference streams that exhibit non-driven conditions may be of little use as targets for management objectives on tie-driven streams. Differences in morphology, and associated processes such as sediment and wood transport, will complicate channel manipulations conducted at the reach scale. For example, engineered log steps are frequently used to promote pool development and habitat heterogeneity. However, placement within a tie-driven reach could result in local scouring and the eventual undercutting of the structure. Management decisions regarding fish passage, habitat availability, and sediment control must be made with the understanding that many streams in the forest may not respond as expected to strategies implemented at the reach scale, particularly if tie-driving legacies are pervasive across the network in question.

Looking forward, channel response rates in the region may increase given the prevalence of bark-beetle-caused tree mortality throughout the area. The mountain pine beetle and spruce beetle are responsible for the vast majority of tree mortality in the area (Colorado State Forest Service, 2012). In this study, the proportion of standing dead trees attributed to beetle kill in the riparian areas sampled ranged from 41% to 89% (in Beaver Creek and Flume Creek, respectively). This constitutes a large pool of recruitable wood in the near future and may represent a reset in terms of wood recruitment to streams at a large scale (Dwire et al., in press). Once LW recruitment begins to occur, future wood loads and channel response may very well obscure the legacies of tie-driving with the coming decades.

6. Conclusions

Tie-driving represents a pervasive and long-lasting disturbance to stream channel morphology and wood loading and continues to influence the ability of affected channels to retain LW. Tie-driven channels in the Medicine Bow National Forest display simplified morphology as characterized by extensive plane-bed reaches and low abundance of instream wood loads. Evidence of the impacts associated with tie-driving is supported by significant differences in channel geometry, wood loads, and wood recruitment potential. The degree of channel response and recovery of wood loading appears to occur at different rates depending on stream order; first-order tie-driven streams are characterized by supply limitation, while second-order systems are accumulating wood. Despite the extensive literature examining the role of instream wood, this study is one of few that addresses channel response following extensive historic disturbance related to tie-driving, including wood load removals and channel simplification.

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References

Abbe, T.B., Montgomery, D.R., 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regul. Rivers Res. Manag. 12, 201–221.

Angradi, T.R., Bolgrien, D.W., Jicha, T.M., Pearson, M.S., Taylor, D.L., Hill, B.H., 2009. Multispatial-scale variation in benthic and snag-surface macroinvertebrate assemblages in mid-continent US great rivers. J. N. Am. Benthol. Soc. 28 (1), 122–141.

Baillie, B.R., Garrett, L.G., Evanson, A.W., 2008. Spatial distribution and influence of large woody debris in an old-growth forest river system, New Zealand. For. Ecol. Manag. 256 (1), 20–27.

Beckman, N.D., Wohl, E., 2014. Carbon storage in mountainous headwater streams: the role of old-growth forest and logjams. Water Resour. Res. http://dx.doi.org/10.1002/2013WR014167.

Benda, L., Miller, D., Sias, J., Martin, D., Bilby, R., Veldhuisen, C., Dunne, T., 2003. Wood recruitment processes and wood budgeting. In: Gregory, S.V., Boyer, K.L., Gurnell, A.M. (Eds.), The Ecology and Management of Wood in World Rivers. American Fisheries Society, Symposium, Bethesda, Maryland 37, pp. 49–73.

Bernhardt, E.S., Palmer, M.A., Allan, J.D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S.C., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Katz, S., Kondolf, G.M., Lake, P.S., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L., Powell, B., Sudduth, E., 2005. Synthesizing U.S. river restoration efforts. Science 308, 636–637.

Beschta, R.L., 1979. Debris removal and its effects on sedimentation in an Oregon Coast Range stream. Northwest Sci. 53 (1), 71–77.

Bilby, R.E., Likens, G.E., 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61 (5), 1107–1113.

Bilby, R.E., Ward, J.W., 1991. Characteristics and function of large woody debris in streams draining old-growth, clearcut, and second-growth forests in southwestern Washington. Can. J. Fish. Aquat. Sci. 48, 2499–2508.

Bisson, P.A., Bilby, R.E., Bryant, M.D., Dolloff, C.A., Grette, G.B., House, R.A., Murphy, M.L., Koski, K.V., Sedell, J.R., 1987. Large woody debris in forested streams in the Pacific Northwest: past, present and future. In: Salo, E.O., Cundy, T.W. (Eds.), Streamside Management: Forestry and Fishery InteractionsProceedings of the Symposium, February 12–14, 1986, Seattle, Washington, College of Forest Resources, Contribution 57. University of Washington, Washington, pp. 143–190.

Brookes, A., 1987. Restoring the sinuosity of artificially straightened stream channels. Environ. Geol. Water 10 (1), 33–41.

Brooks, A.P., Brierley, G.J., 2002. Mediated equilibrium: the influence of riparian vegetation and wood on the long-term evolution and behaviour of a near-pristine river. Earth Surf. Process. Landf. 27 (4), 343–367.

Burchsted, D., Daniels, M.D., Thorson, R., Vokoun, J., 2010. The river discontinuum: applying beaver modifications to baseline conditions for restoration of forested headwaters. Bioscience 60 (11), 908–922.

Chin, A., Daniels, M.D., Urban, M.A., Piegay, H., Gregory, K.J., Bigler, W., Boyer, K., Butt, A., Grabel, J., Gregory, S.V., LaFrenz, M., Laurencio, L.R., Wohl, E., 2008. Perceptions of wood in rivers and challenges for stream restoration in the United States. Environ. Manag. 41 (6), 893–903.

Colorado State Forest Service, 2012. 2012 Report on the Health of Colorado's forests: Forest Stewardship through Active Management. Available from csfs.colostate.edu/pages/pub-csfs2.html (accessed 5 Feb 2014).

Comiti, F., 2012. How natural are Alpine mountain rivers? Evidence from the Italian Alps. Earth Surf. Process. Landf. 37 (7), 693–707.

Czarnomski, N.M., Dreher, D.M., Snyder, K.U., Jones, J.A., Swanson, F.J., 2008. Dynamics of wood in stream networks of the western Cascades Range, Oregon. Can. J. For. Res. 38, 2236–2248. http://dx.doi.org/10.1139/X08-068.

Dahlstrom, N., Jonsson, K., Nilsson, C., 2005. Long-term dynamics of large woody debris in a managed boreal forest stream. For. Ecol. Manag. 210 (1–3), 363–373.

Daniels, M.D., 2006. Distribution and dynamics of large woody debris and organic matter in a low-energy meandering stream. Geomorphology 77 (3–4), 286–298.

Daniels, M.D., McCusker, M.H., 2010. Operator bias characterizing stream substrates using Wolman pebble counts with a standard measurement template. Geomorphology 115 (1), 194–198.

Daniels, M.D., Rhoads, B.L., 2004. Effect of LWD configuration on spatial patterns of three-dimensional flow in two low-energy meander bends at varying stages. Water Resour. Res. 40 (11), W11302. http://dx.doi.org/10.1029/2004WR003181.

Díez, J.R., Larrañaga, S., Elosegi, A., Pozo, J., 2000. Effect of removal of wood on streambed stability and retention of organic matter. J. N. Am. Benthol. Soc. 621–632.

Dillon, G.K., Knight, D.H., Meyer, C.B., 2005. Historic range of variability for upland vegetation in the Medicine Bow National Forest, Wyoming. RMRS-GTR-139. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO (85 pages).

Downs, P.W., Simon, A., 2001. Fluvial geomorphological analysis of the recruitment of large woody debris in the Yalobusha River network, Central Mississippi, USA. Geomorphology 37 (1–2), 65–91.

Dwire, K.A., Hubbard, R., Bazan, R., 2014. Comparison of riparian and upland forest stand structure and fuel loads in beetle infested watersheds, southern Rocky Mountains. For. Ecol. Manag. (in press, submitted to).

Finkenbine, J.K., Atwater, J.W., Mavinic, D.S., 2000. Stream health after urbanization. J. Am. Water Resour. Assoc. 36 (5), 1149–1160.

Flores, L., Larranaga, A., Diez, J., Elosegi, A., 2011. Experimental wood addition in streams: effects on organic matter storage and breakdown. Freshw. Biol. 56 (10), 2156–2167.

Gardeström, J., Holmqvist, D., Polvi, L.E., Nilsson, C., 2013. Demonstration restoration measures in tributaries of the Vindel river catchment. Ecol. Soc. 18 (3), 8. http://dx.doi.org/10.5751/ES-05609-180308.

Gippel, C.J., 1995. Environmental hydraulics of larger woody debris in streams and rivers. J. Environ. Eng. 121 (5), 388–395.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J., Nathan, R.J., 2004. Stream Hydrology: An Introduction for Ecologists. John Wiley and Sons, West Sussex, England.

Gregory, K.J., 2006. The human role in changing river channels. Geomorphology 79 (3–4), 172–191.

Gregory, K.J., Davis, R.J., 1992. Coarse woody debris in stream channels in relation to river channel management in woodland areas. Regul. Rivers Res. Manag. 7 (2), 117–136.

Gurnell, A.M., Gregory, K.J., Petts, G.E., 1995. The role of course woody debris in forest aquatic habitats: implications for management. Aquat. Conserv. Mar. Freshwat. Ecosyst. 5, 143–166.

Gurnell, A.M., Petts, G.E., Harris, N., Ward, J.V., Tockner, K., Edwards, P.J., Kollmann, J., 2000. Large wood retention in river channels: the case of the Fiume Tagliamento, Italy. Earth Surf. Process. Landf. 25, 255–275.

Heede, B.H., 1985. Channel adjustments to the removal of log steps: an experiment in a mountain stream. Environ. Manag. 9, 427–432.

Helfield, J.M., Capon, S.J., Nilsson, C., Jansson, R., Palm, D., 2007. Restoration of rivers used for timber floating: effects on riparian plant diversity. Ecol. Appl. 17 (3), 840–851.

Hyatt, T.L., Naiman, R.J., 2001. The residence time of large woody debris in the Queets River, Washington, USA. Ecol. Appl. 11 (1), 191–202.

Jenkins, M.J., Herbertson, E., Page, W., Jorgensen, C.A., 2008. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. For. Ecol. Manag. 254, 16–34.

Jones, T.A., Daniels, L.D., Powell, S.R., 2011. Abundance and function of large woody debris in small, headwater streams in the Rocky Mountain foothills of Alberta, Canada. River Res. Appl. 27 (3), 297–311.

Keller, E.A., Swanson, F.J., 1979. Effects of large organic material on channel form and fluvial processes. Earth Surf. Process. Landf. 4 (4), 361–380.

Lancaster, S.T., Hayes, S.K., Grant, G.E., 2003. Effects of wood on debris flow runout in small mountain watersheds. Water Resour. Res. 39 (6). http://dx.doi.org/10.1029/2001WR001227.

Lassettre, N.S., Kondolf, G.M., 2012. Large woody debris in urban stream channels: redefining the problem. River Res. Appl. 28 (9), 1477–1487. http://dx.doi.org/10.1002/rra.1538.

Lienkaemper, G.W., Swanson, F.J., 1987. Dynamics of large woody debris in old-growth Douglas-fir forests. Can. J. For. Res. 17, 150–156.

Lisle, T.E., 1986. Effects of woody debris on anadromous salmonid habitat, Prince of Wales Island, southeast Alaska. N. Am. J. Fish Manag. 6 (4), 538–550.

Lisle, T.E., 1995. Effects of course woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington. Water Resour. Res. 31 (7), 1797–1808.

Love, J.D., Christiansen, A.C., 1985. Geologic Map of Wyoming. US Geological Survey.

Lowham, H.W., 1976. Techniques for Estimating Flow Characteristics of Wyoming Streams. U.S. Geological Survey, Water Resources Division, Cheyenne (Print).

Magilligan, F.J., Nislow, K.H., Fisher, G.B., Wright, J., Mackey, G., Laser, M., 2008. The geomorphic function and characteristics of large woody debris in low gradient rivers, coastal Maine, USA. Geomorphology 97, 467–482.

Marston, R.A., Girel, J., Pautou, G., Piegay, H., Bravard, J.P., Arneson, C., 1995. Channel metamorphosis, floodplain disturbance, and vegetation development: Ain River, France. Geomorphology 13 (1), 121–131.

Mellina, E., Hinch, S.G., 2009. Influences of riparian logging and instream large wood removal on pool habitat and salmonid density and biomass: a meta-analysis. Can. J. For. Res. 39, 1280–1301. http://dx.doi.org/10.1139/X09-037.

Miller, R.R., 2010. Is the past present? Historical splash-dam mapping and stream disturbance detection in the Oregon coastal province(Thesis) Oregon State Univeristy.

Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geol. Soc. Am. Bull. 109 (5), 596–611.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., Pess, G., 1995. Pool spacing in forest channels. Water Resour. Res. 31 (4), 1097–1105.

Montgomery, D.R., Massong, T.M., Hawley, S.C.S., 2003. Influence of debris flows and log jams on the location of pools and alluvial channel reaches, Oregon Coast Range. Geol. Soc. Am. Bull. 115, 78–88.

Murphy, M.L., Koski, K.V., 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. N. Am. J. Fish Manag. 9, 427–436.

Nilsson, C., Lepori, F., Malmqvist, B., Tornlund, E., Hjerdt, N., Helfield, J.M., Palm, D., Ostergen, J., Jansson, R., Brannas, E., Lundqvist, H., 2005. Forecasting environmental response to restoration of rivers used as log floatways: an interdisciplinary challenge. Ecosystems 8 (7), 779–800.

Nowakowski, A.L., Wohl, E., 2008. Influences on wood load in mountain streams of the Bighorn National Forest, Wyoming, USA Environmental Management. 42, 557–571.

Palmer, M.A., 2009. Reforming watershed restoration: science in need of application and applications in need of science. Estuar. Coasts 32 (1), 1–17.

Philips, J.D., Park, L., 2009. Forest blowdown impacts of Hurricane Rita on fluvial systems. Earth Surf. Process. Landf. 34, 1069–1081. http://dx.doi.org/10.1002/esp.1793.

Piégay, H., Gregory, K.J., Bondarev, V., Chin, A., Dahlstrom, N., Elosegi, A., Gregory, S.V., Joshi, V., Mutz, M., Rinaldi, M., Wyzga, B., Zawiejska, J., 2005. Public perception as a barrier to introducing wood in rivers for restoration purposes. Environ. Manag. 36 (5), 665–674.

PRISM Climate Group, Oregon State Universityhttp://prism.oregonstate.edu created 9 Sept 2013.

Raffa, K.F., Aukema, B.H., Bentz, B.J., Carroll, A.L., Hicke, J.A., Turner, M.G., Romme, W.H., 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. Bioscience 58 (6), 501–517.

Richmond, A.D., Fausch, K.D., 1995. Characteristics and function of large woody debris in mountain streams of northern Colorado. Can. J. Fish. Aquat. Sci. 52, 1789–1802.

Rosgen, D.L., 1994. A classification of natural rivers. Catena 22 (3), 169–199.

Ryan, S.E., Bishop, E.L., Daniels, J.M., 2014. Influence of large wood on channel morphology and sediment storage in headwater mountain streams, Fraser Experimental Forest, Colorado. Geomorphology 217, 73–88.

Sedell, R., Leone, F.N., Duval, W.S., 1991. Water transportation and storage of logs. Am. Fish. Soc. Spec. Publ. 19, 325–368.

Segura, C., Booth, D.B., 2010. Effects of geomorphic setting and urbanization on wood, pools, sediment storage, and bank erosion in Puget Sound streams. J. Am. Water Resour. Assoc. 46 (5), 972–986.

Simon, A., Castro, J., 2003. Measurement and analysis of alluvial channel form. In: Kondolf, G.M., Piégay, H. (Eds.), Tools in Fluvial Geomorphology.

Swanson, F.J., Lienkaemper, G.W., Sedell, J.R., 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. U.S. For. Serv. Gen. Tech. Rep. PNW-56.

Thompson, D.M., 1995. The effects of large organic debris on sediment processes and stream morphology in Vermont. Geomorphology 11 (3), 235–244.

Vaz, P.G., Merten, E.C., Warren, D.R., Robinson, C.T., Pinto, P., Rego, F.C., 2013. Which stream wood becomes functional following wildfires? Ecol. Eng. 54, 82–89.

Wallace, J.B., Webster, J.R., Eggert, S.L., Meyer, J.L., 2001. Small wood dynamics in a headwater stream. Int. Ver. Theor. Angew. Limnol. Verh. 27 (3), 1361–1365.

Walter, R.C., Merritts, D.J., 2008. Natural streams and the legacy of water-powered mills. Science 319 (5861), 299–304.

Webb, A.A., Erskine, W.D., 2003. A practical scientific approach to riparian vegetation rehabilitation in Australia. J. Environ. Manag. 68 (4), 329–341.

Wohl, E., 2001. Virtual Rivers: Lessons from the Mountain Rivers of the Colorado Front Range. Yale University Press.

Wohl, E., 2006. Human impacts to mountain streams. Geomorphology 79 (3–4), 217–248.

Wohl, E., Cadol, D., 2011. Neighborhood matters: patterns and controls on wood distribution in old-growth forest streams of the Colorado Front Range, USA. Geomorphology 125 (1), 132–146.

Wohl, E., Cenderelli, D.A., 2000. Sediment deposition and transport patterns following a reservoir sediment release. Water Resour. Res. 36 (1), 319–333.

Wohl, E., Goode, J.R., 2008. Wood dynamics in headwater streams of the Colorado Rocky Mountains. Water Resour. Res. 44 (W09429), 1–14.

Wohl, E., Jaeger, K., 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. Earth Surf. Process. Landf. 34 (3), 329–344.

Wohl, E., Merritt, D., 2008. Reach-scale channel geometry of mountain streams. Geomorphology 93 (3–4), 168–185.

Wohl, E., Ogden, F.L., Goode, J.R., 2009. Episodic wood loading in a mountainous neotropical watershed. Geomorphology 111, 149–159.

Wohl, E., Cenderelli, D.A., Dwire, K.A., Ryan-Burkett, S.E., Young, M.K., Fausch, K.D., 2010. Large in-stream wood studies: a call for common metrics. Earth Surf. Process. Landf. 35 (5), 618–625.

Young, M.K., Haire, D., Bozek, M.A., 1994. The effect and extent of railroad tie drives in streams of southeastern Wyoming. West. J. Appl. For. 9 (4), 125–130.

Zelt, R.B., Wohl, E., 2004. Channel and woody debris characteristics in adjacent burned and unburned watersheds a decade after wildfire, Park County, Wyoming. 57 (3–4), 217–233.