STREAM SUCCESSION:

CHANNEL CHANGES AFTER WILDFIRE DISTURBANCE

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AUTHORIZATION TO SUBMIT

THESIS

This thesis of Nicholas E. Scheidt, submitted for the degree of Master of Science with a major in Civil Engineering and titled "STREAM SUCCESSION: CHANNEL CHANGES AFTER WILDFIRE DISTURBANCE," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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ABSTRACT

One concept in geomorphology is that vegetation is a fundamental control on sediment and water supplies to streams and, therefore, on downstream fluvial processes and channel morphology. Within this paradigm, wildfire has been implicated as a major driving force behind landscape erosion and changes to stream channels, periodically yielding pulses of sediment from uplands that may drive changes to stream channels. However, channel response to wildfire has not been well studied over long periods (>10 years), and the occurrence and nature of long-term changes in channel characteristics remain to be documented. The long-term effects of wildfire disturbance on channel characteristics were examined in moderate-gradient (2-4% slope), unconfined, mountain streams in the Idaho batholith. The study was designed using a space-for-time substitution, and three different times since wildfire were considered: recent (15-20 yrs.), mid (80-110 yrs.), and old (>150 yrs.). Characteristics of interest included measures of channel morphology (e.g., channel geometry, pool spacing, residual depth, substrate size) and wood (e.g., amount, location, function, size). Multi-response permutation procedures were used to measure between treatment variability. Results show that none of the 17 morphologic characteristics varied between treatments, and only 3 out of 25 wood characteristics varied between treatments ($\alpha = 0.10$). The lack of morphologic variability between treatments implies that wildfire disturbance does not have a long-term effect on channels of this stream type, suggesting that moderate-gradient, unconfined channels may act as relatively stable, potentially productive, refugia for aquatic organisms in areas prone to wildfire.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The primary question of this thesis is “How do stream channels change after fire?” In forest communities, fire disturbance initiates vegetative succession (temporal changes in species composition, age distribution, and ecosystem function), with responses lasting decades to hundreds of years (Agee, 1993). There are no analogous data for stream channels following wildfires, yet there is a common belief among watershed professionals that stream channels are impacted by wildfire and subsequently follow a post-fire trajectory of recovery. This process is herein referred to as “channel succession”, and is defined as a change in channel characteristics and stream habitat quality that coincides with terrestrial vegetative succession after fire disturbance. Limited data from the Oregon Coast Range suggest that streams attain optimal habitat condition at a mid-seral stage, on the order of 80-120 years after fire disturbance (Reeves et al., 1995). However, the generality of this response trajectory across different channel types and locations within a stream network is uncertain. For example, due to differences in process domains and susceptibility of channels to disturbance, we may expect fire-related response in high-gradient, confined streams that are dominated by debris flows to differ from that of low- or moderate-gradient, unconfined streams that are fluvially dominated (Montgomery and Buffington, 1998; Montgomery, 1999). There is a need to better understand channel succession across various stream types and regional settings. A comprehensive understanding of channel succession would help resource managers make better forest, fisheries, and fire management decisions related to stream channel condition. Here, channel response to wildfire is examined in moderate-gradient, high-elevation channels that are both prone to wildfire and provide important salmonid habitat in mountain basins.

Despite the common perception that post-fire channel succession occurs, the nature of the response trajectory and the relative roles of different physical drivers are largely unknown. Forest fires can cause short-term alteration of sediment supplies (Miller et al., 2003; Wondzell and King, 2003), the timing and size of peak flows (Moody and Martin, 2001) and spatial and temporal rates of wood recruitment (Benda et al., 2003). Alteration of these channel-forming processes may have a significant effect on channel morphology (Wolman and Miller, 1960; Wolman and Gerson, 1978; Harmon et al., 1986). Geomorphic significance of such alterations depends on 1) fire extent and severity; 2) physical setting (topography, geology, location within the stream network, and stream type); and 3) the frequency, magnitude, style, and timing of post-fire precipitation events (Swanson, 1981; Meyer et al., 1992; Meyer et al., 1995; Benda et al., 1998). Minshall et al. (1989) suggested that post-fire effects could be segregated into immediate, mid-term, and long-term categories. Immediate effects may include increases in stream temperature or potentially toxic substances (e.g., ammonia), or decreases in pH. Mid-term effects can be dramatic and typically peak within the first decade after fire; they are usually associated with fire-related changes in erosion and hydrologic regimes. Some previous research suggests that substantial channel recovery after floods can occur within a decade (Wolman and Gerson, 1978). Long-term effects are less dramatic and, potentially, coincide with in-stream wood dynamics associated with post-fire forest succession.

Several hypothetical response trajectories can be envisioned for how aquatic habitat quality might change over time due to wildfire disturbance. One hypothesis is that habitat quality is initially degraded, but slowly recovers over time (Figure 1, line A) (Minshall et al., 1989; Beechie et al., 2000). Here, the initial decrease in habitat quality is due to increased erosion and flooding, and the eventual increase in habitat quality is associated with increased abundance of in-stream wood due to forest maturation. Whether this occurs over a few years or a few hundred years is not clear. Some have suggested that response times are relatively long (Reeves et al., 1995; Benda and Dunne, 1997a,b; Minshall et al., 1989), while other research suggests that physical habitat could adjust to changes in hydrology within a few years (Wolman and Gerson, 1978). A more complex hypothesis is that habitat degrades temporarily from a long-term marginal condition, then achieves a state better than the initial condition for some period, followed by a gradual decline to the long-term (Figure 1, line B). This idea is prevalent where gravel availability is limiting (Reeves et al., 1995). In these sediment-starved channels, sufficient time is needed for post-fire sediment pulses to replenish alluvial substrate, and for forest regrowth and the incorporation of newly recruited wood into this sediment to cause a maximum in channel complexity (i.e., habitat quality). A third hypothesis is that there is no strong change in habitat quality with time (Figure 1, line C), which might be seen in low- to moderate-gradient, unconfined streams. Such streams are typically buffered from direct impacts of post-fire debris flows, decreasing the probability of a large disturbance. Furthermore, storage of wood and coarse sediment within the floodplain of these channels may mitigate post-fire effects of altered basin hydrology or altered supply of riparian wood that would otherwise lead to stronger channel response. As a stream incises or migrates laterally due to post-fire changes in basin hydrology and increased peak flows, or due to decreased supply of wood recruited from burned riparian zones, it may encounter buried wood or coarse sediment that mitigates further incision and lateral migration, helping to stabilize the channel.

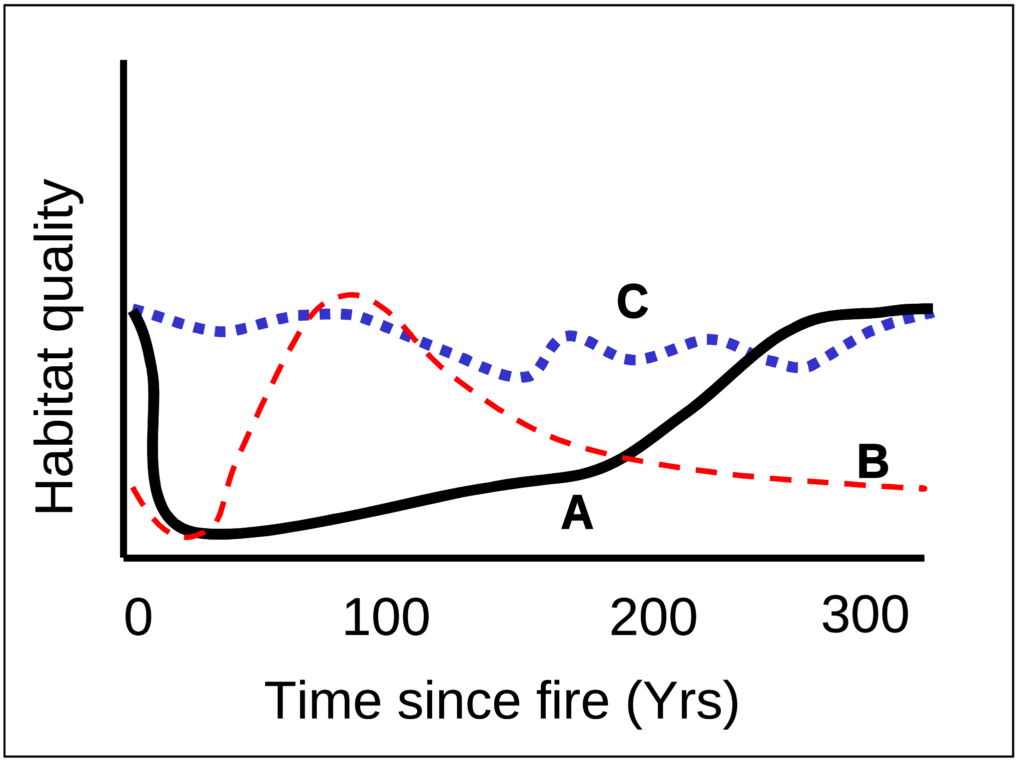

Figure 1. Hypothetical habitat quality response trajectories to wildfire.

This study investigates channel responses in moderate-gradient, unconfined, high-elevation basins that have experienced spatially extensive stand-replacing fires. The underlying hypothesis addressed is the idea that streams change systematically over time following wildfire disturbance. The focus on moderate-gradient, unconfined, high elevation streams is based on their importance for thermally sensitive salmonids. In these streams, direct impacts from debris flows and hyperconcentrated flows are excluded, and the focus is placed on post-fire changes in basin hydrology, upstream sediment supply (potentially influenced by debris flows and hyperconcentrated flows), and proximal riparian characteristics (supply of wood and bank strength from roots). Biologically, knowledge of recovery time scales is necessary to determine how likely simultaneous disturbance of several local populations might be, a key factor in local extinctions (Miller et al., 2003, Dunham et al., 2003, Rieman et al., 2003, Bisson et al., 2003).

STUDY DESIGN

A space-for-time substitution approach was used to examine the effects of wildfire on channel and wood characteristics (e.g., Welch, 1970). The analysis consisted of 3 treatments of time since fire: 15-20 years (recent), 80-110 years (mid), and >150 years (old). Several potentially confounding variables were identified, including geology, valley slope, valley confinement, elevation (which controls precipitation and vegetation), drainage area (a surrogate for discharge), glacial history, land use, and extent of burn. To control for these confounding variables, sites were selected that met the following criteria: 1) elevation between 1500-2000 meters; 2) watershed primarily located within the Idaho batholith (granite); 3) valley width greater than 4 bank-full channel widths; 4) valley slopes between 2.0-4.0%; 5) drainage area between 500-1200 hectares; 6) > 50% of the basin experienced a stand replacing wildfire, including the riparian stand; and 7) minimal anthropogenic disturbance (streams not affected by grazing, logging, and roads). Reaches were selected at relatively high elevations because wildfires in these locations are typically spatially extensive and stand replacing. The study reaches were limited to the Idaho batholith to control for geology. Valley width, valley slope and drainage area ranges were selected because the focus is on sites that are disconnected from hillslopes and direct sediment inputs from debris flows and hyperconcentrated flows. The percent of stand replacing burn was selected to insure that a significant portion of the basin burned. It was not possible to control for fire severity or post-fire precipitation events.

Candidate reaches were selected using 10 m digital elevation models (DEM) based on the first 5 control variables in combination with GIS coverages of fire history, land use, roads, and geology. Approximately 260 candidate streams were identified and further reduced to 45 sites using aerial photographs (1:15,840) to evaluate the last two control variables. Each of these streams was field checked to validate characteristics estimated from the photos and DEM, and 30 streams were ultimately selected for sampling. After the field season, it was determined that bank-full discharge and valley slope were not sufficiently controlled at 7 of the 30 streams. This determination was made by graphically identifying outliers.

Unfortunately, it was not possible to directly control all of the potentially complicating variables in each case. It was especially difficult to find riparian stands of similar age to burned upland forests in the recent and mid treatments, suggesting longer fire return intervals for some riparian stands (e.g., Romme and Knight, 1981). Consequently, some study reaches in basins with recent and mid treatments have riparian stands older than the basin treatment. This complication allowed us to assess channel response to different combinations of altered hydrologic regime, sediment regime, and riparian stand characteristics by classifying the data according to three different burn definitions: time since basin burn, time since riparian burn, and time since synchronous burn (simultaneous basin and riparian burn) (Table 1). Appendices A1-3 show site characteristics stratified by burn classification.

A variety of channel, wood, and habitat characteristics were examined that might be responsive to post-fire changes in sediment supply, hydrology, and riparian conditions. Measured channel characteristics included grain size, bank-full channel geometry, slope, and residual pool depth. Measured wood characteristics included piece dimensions, embedment, orientation and location, function, spacing, and decay stage. Riparian stand characteristics (tree diameter, species, life stage, and burn class) were measured to help determine or confirm the fire history of each site.

Table 1. Burn classifications and sample sizes.

Basin burn

Treatment	Time since riparian burn (Years)	Time since basin burn (Years)	% basin burned	*n*
Recent	unspecified	15-20	>50	6
Mid	unspecified	80-110	>50	9
Old	unspecified	>150	>50	8
				total=23

Riparian burn

Treatment	Time since riparian burn (Years)	Time since basin burn (Years)	% riparian burned	*n*
Recent	15-20	unspecified	>50	4
Mid	80-110	unspecified	>40	7
Old	>150	unspecified	>47	12
				total=23

Synchronous burn

Treatment	Time since riparian & basin burn (Years)	% riparian burned	% basin burned	*n*
Recent	15-20	>47	>50	4
Mid	80-110	>40	>50	6
Old	>150	>47	>50	8
				total=18

STUDY SITES AND METHODS

Site characteristics

The study reaches were located at high elevations (1500-2000 m) in the Idaho batholith, which has a predominantly granitic geology (Figure 2). The average annual precipitation in the study area is between 1000 and 1500 millimeters and falls predominantly as snow at these elevations. Regional hydrology is snowmelt dominated, with peak flows typically occurring in late spring or early summer, although occasional intense summer thunderstorms can produce peak flows in small basins during the summer.

Native fish species potentially present in these streams include bull trout *(Salvelinus confluentus),* chinook salmon *(Onchorhynchus tshawytscha),* steelhead and rainbow trout (*O. mykiss),* and sculpin (*Cottus* spp.). Brook trout *(Salvelinus fontinalis)* is the most prevalent non-native species. The forest communities are dominated by subalpine fir (*Abies lasiocarpa*), white fir (*Abies concolor*), grand fir (*Abies grandis*), Engelmann spruce (*Picea engelmannii*), and lodgepole pine (*Pinus contorta*). Forest types at the study sites were predominantly spruce–fir in the riparian zones and valley bottoms, with some inter-mixed lodgepole pine; lodgepole pine was more prevalent where severe fire occurred in the uplands. The predominant shrub found along the streams was mountain alder (*Alnus tenuifolia*). The historic (pre-European) fire regime is characterized by spatially extensive fires, typically stand replacing, with a return interval of 250 years (Morgan et al., 1996).

Study reaches were mainly third order streams (Horton, 1945), located away from major tributary junctions. Channel-reach morphologies were mostly pool-riffle and wood-forced pool-riffle, however one reach (Frank Brown Creek) had a plane-bed morphology (morphologic definitions of Montgomery and Buffington, 1997).

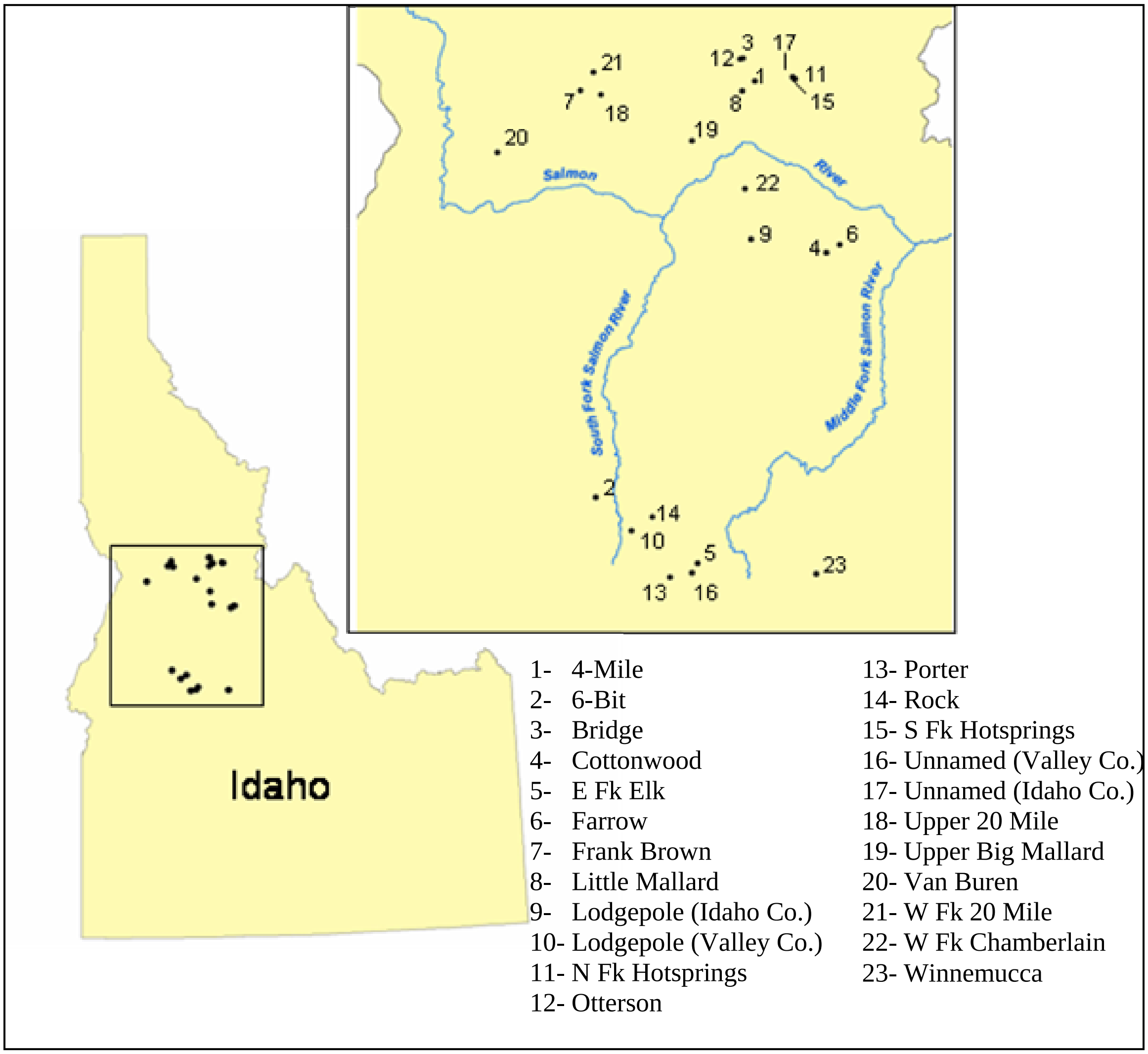

Figure 2. Location of study sites.

Channel morphology

A pilot study was conducted during the summer of 2002 to determine the sampling interval required to accurately represent reach-scale variation of channel width, depth, and surface grain size in mountain gravel-bed streams of central Idaho (C. H. Luce, unpublished data). No serial correlation was found beyond eight channel widths in that study; so each of our streams was characterized by 10 cross sections spaced 8 channel widths apart for a total reach length of 80 channel widths.

Cross sections, stream slope, and valley slope were measured with an engineer's level, measuring tape and stadia rod. Bank-full depth was measured relative to the bank-full elevation, defined as the point where stream flow spills onto the floodplain. In addition, the active channel depth was measured relative to the active channel elevation, defined by a convex break in the bank slope and a change to finer-grained sediments or, in the absence of those indicators, by the extent of riparian vegetation. The active channel depth was examined because it is affected by smaller, more frequent flows and, therefore, may be a more responsive indicator of fire-related disturbance than the bank-full depth.

The maximum residual depth was measured between each cross section, and was defined as the deepest point between two cross sections minus the associated downstream riffle-crest depth (a variant of Lisle's (1987) method for residual pool depths). Pools were inventoried, and the location of the center of each pool was recorded to determine exact spacing between pools. Pools were defined as topographic depressions either as long or as wide as the local active channel width. The residual depth of each pool was measured and the dominant sediment size was estimated within a 10 cm radius at the points of maximum pool depth and riffle-crest depth according to the substrate classes in Appendix A4. Wood was also used as a substrate class (organic substrate) at riffle crests, because it is resistant to erosion and often forms the riffle crest in these forest streams.

Sediment

A stratified random sampling technique was used to measure reach-average surface grain size. Two hundred grains were systematically sampled at equal intervals along the stream length (about every 0.4 channel widths). At each sample location, the bed width was divided into 9 evenly spaced sections and one section was randomly selected for sampling. A single grain was randomly obtained from the selected section using the Wolman (1954) pebble count technique and measured with a ruler to the nearest millimeter.

Riparian stand characteristics

Variable plot basal area cruises were conducted in the riparian zone of each reach using a 10 basal area factor prism (Dilworth and Bell, 1981). The plot dimensions in variable plot cruises depend on tree diameter, with greater diameter trees having larger plot areas. This technique ensures adequate sampling of all tree sizes, which is not ensured with small fixed area plots. Variable plot cruises enable small subsamples to accurately represent stand densities for various different diameter classes. Ten plots were established at cross-section intervals (8 channel widths) and measurements were conduced at the bank-full elevation; one half of the plot on each side of the stream. Data collected included diameter at breast height, tree species, life stage (Table 2), burn class (Table 3), and determination of whether the tree was dominant or subdominant with respect to the surrounding stand. Tree diameters were estimated, and one tree was randomly selected for true diameter measurement and coring. Paired observations of measured and estimated diameters were used to create a regression for predicting actual diameters of unmeasured trees.

Table 2. Tree age classification

	Alive*	Recently deceased	Young snag	Snag	Old snag
Needles	green	red/orange	none	none	none
Fine Branches	all	all	some	none	none
Bark	solid	solid	>50%	<50%	none
Wood	hard	hard	hard	mostly hard	mostly soft

*Life stage is assigned according to which particular column a tree most accurately fits.

Table 3. Burn categories

1	No evidence of burn
2	Scarred, but not dead
3	Dead, limbs/needles present
4	Dead, limbs not present

Wood

Several wood characteristics were analyzed that might be responsive to post-fire changes in sediment supply, hydrology, and riparian conditions. These included piece distribution, diameter, length, species, embedment, anchoring, orientation to flow, vertical location, function, cross-sectional extent, and decay/wearing class. Wood was classified as pieces longer than 1 m and greater than 10 cm in diameter (Swanson et al., 1976), and was measured over the entire reach length of 80 channel widths. The distance between the centers of each piece of wood was measured to determine the spatial distribution of wood within each study reach. Regressions between observed and estimated log diameters were developed, as was done for standing wood in the riparian zone. The length was measured to the nearest meter, and tree species was identified when possible. Embedment of each piece was classified as follows: bank embedded, bed embedded, both, or neither. Pieces were considered embedded if more than 50% of the bole diameter was buried. Anchoring was defined as still attached to the ground by roots in the place of growth. The orientation to flow was assigned as 0, 45, or 90 degrees to the centerline of the bank-full channel. The vertical position of each piece of wood was classified as either above or below the bank-full elevation. Each piece of wood was divided into quarters by length, and each quarter was assigned a function, multiple functions, or no function according to the following categories: 1) no function–does not meet any of the following classes; 2) forming a pool; 3) associated with a pool–within a pool at or below bank-full stage, but not the dominant cause for pool scour; 4) deflecting flow into the bank; 5) armoring the bank from fluvial erosion; 6) armoring the bed–partially buried in the bed, with sediment surrounding it on both the upstream and downstream sides; and 7) damming sediment–physical barrier to downstream sediment movement, causing upstream aggradation.

The extent to which each piece of wood spanned the channel was measured as a percentage of the bank-full width (0-200%, measured in increments of 25%). A piece more than 100% across the channel was one that was over/in the channel more than once. For example, a piece that completely crossed the channel twice by spanning a river bend was classified as 200% across the channel. Decay/wearing classes were assigned to each piece of wood according to the categories shown in Appendix A5.

DATA ANALYSIS

Statistical tests

Multi-response permutation procedures (MRPP) were used to test between-treatment variability and conduct pair-wise comparisons ($\alpha = 0.10$) (Mielke et al., 1984). MRPP was selected because it is a nonparametric test that compares the distribution of data sets. MRPP can be thought of as a comparison between medians and interquartile ranges, and is similar to an analysis of variance. However, it does not actually compare medians and interquartile ranges, just the cumulative distance between observations. Calculations were done with an Excel macro created by Rudy King of the USDA Forest Service, Rocky Mountain Research Station Statistics Unit (version, 4/2004). The exponent v in this macro is set equal to one, after recommendations of Mielke and Berry (1983) and Zimmerman et al. (1985). The Pearson type III approximation was used to reduce computation time (Mielke et al., 1981; Berry and Mielke, 1983; Iyer et al., 1983), which is an excellent approximation to exact MRPP analyses (Mielke and Berry, 1982; Mielke et al., 1982).

Quantile-Quantile (*Q*-*Q*) plots were created for spatially distributed and length-scaled characteristics (wood lengths and distribution, pool depths and spacing, etc.). *Q*-*Q* plots graphically show whether two data sets have similar cumulative distributions relative to a one-to-one reference line, thereby providing a means to visualize differences between treatments. Here, constructed *Q*-*Q* plots aggregate all data from each treatment and treat each sample independently, ignoring pseudoreplication. For example, while approximately 300 pieces of wood may have been sampled in each stream, statisticians would not consider these independent samples because they come from the same stream.

Percent burn

The percentage of the stand burned in each treatment (recent, mid, or old fire) was evaluated both for the entire basin and for the riparian stand alone. The percent of the basin burned since 1910 was determined from aerial photographs. Burned areas were evaluated by tree crown size and stand density.

The percent of the riparian stand burned in the recent treatment was calculated with the burn categories (Table 3) by dividing the number of fire-killed trees by the number of living trees multiplied by 100. This technique is an underestimate of how many trees were actually fire-killed, because fire-toppling may have caused approximately 70% of the fire-killed trees to fall (visual observation).

Calculating the percent of the riparian stand burned in the mid and old treatments was more complex due to longer times since disturbance. Lodgepole pine and spruce were assessed as pioneer species, assuming that an age cohort of this species was indicative of forest response to fire. Age cohorts of pioneer species were graphically identified and used to help determine or confirm the time since fire. For example, at Frank Brown Creek the greatest number of trees was recruited in the period of 1913-1903 (Figure 3). This peak is predominantly composed of two cohorts, spruce and lodgepole pine. The age of these cohorts agrees with fire history data (provided by Pat Green, Nez Perce National Forest) and, therefore, it was concluded that these cohorts were recruited in response to wildfire. The fraction of the riparian stand that was burned was then determined by dividing the number of pioneer individuals by the total number of individuals. However, the values estimated from this approach were lower than those found with the recent riparian burn technique. Consequently, these techniques may not be directly comparable. The actual percentages of riparian trees burned in the mid and old treatments lie somewhere between the percent of pioneer species younger than the time since fire and the total number of species younger than the time since fire, as true fir can sometimes regenerate after fire (Anne Black, personal communication). This was the case for Otterson Creek, where 98% of the trees were fire regenerated, of which 78% were true fir. Appendix A7 shows the time of fire and percent of the riparian and basin stands burned for each study site.

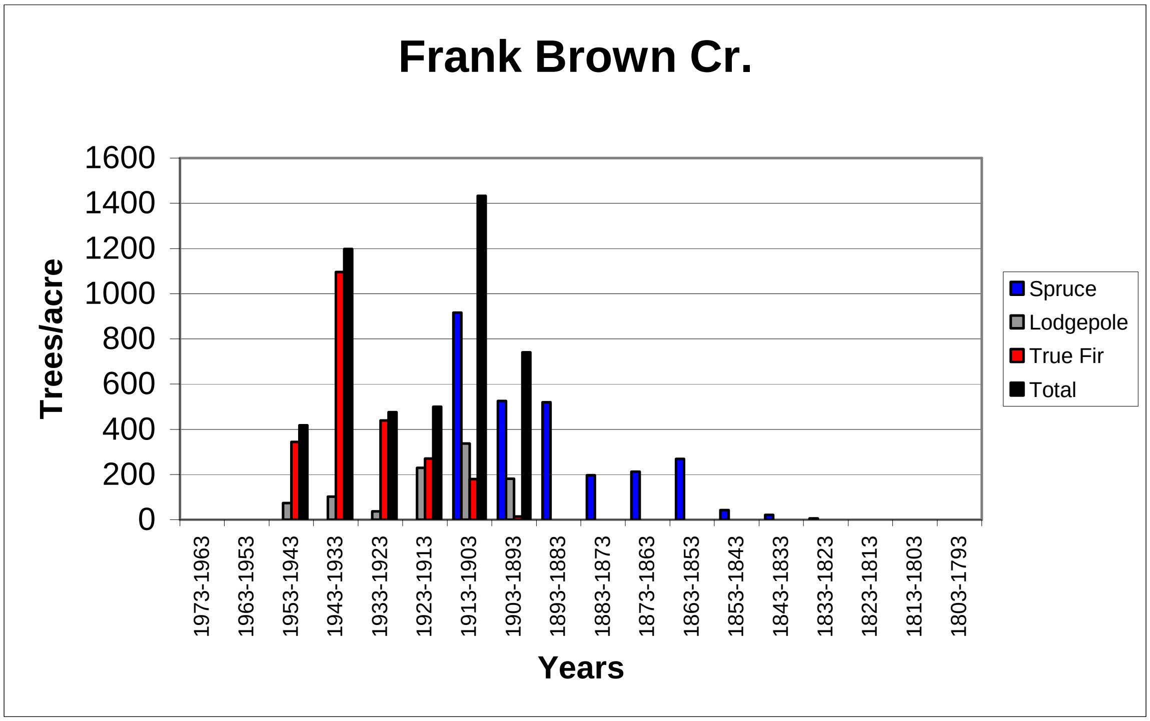

Figure 3. Tree density and age of recruitment by species.

Burn categories

Three burn classifications were used to isolate different potential drivers of post-fire change: time since basin burn; time since riparian burn; and time since synchronous basin and riparian burn. The basin burn category captures changes in channel morphology due to altered upstream hydrologic and sediment regimes for conditions where more than 50% of the contributing area experienced a stand-replacing burn. In contrast, the riparian burn category describes local changes in wood recruitment (size, amount, and frequency of wood input) that may, in turn, alter channel hydraulics and morphology (e.g., Montgomery et al., 1995; Buffington and Montgomery, 1999); the low rates of fluvial transport of wood into and out of these sites (due to relatively low channel slopes and narrow bank-full widths) ensures a focus on local wood recruitment for this burn category. Finally, the synchronous burn category evaluates the combined effects of these factors (changes in upstream hydrologic and sediment regimes, and changes in local wood recruitment).

The MRPP analysis was conducted for each of the above burn classifications to systematically examine the different scales and types of disturbance that could influence channel characteristics. Only the riparian and synchronous burn classifications were used in the wood analysis in order to focus on the succession of wood characteristics and consequent channel impacts initiated by fire disturbance.

RESULTS

Overview

Results show that only 3 of 25 wood characteristics (Table 4) and 0 of 18 channel characteristics differ statistically across the study reaches (Table 5). All *P*-values presented herein are for MRPP results, unless otherwise specified. Appendix 6 reports site characteristics for each stream.

Table 4a. Results of MRRP tests on wood characteristics for data stratified by time since riparian burn.

Wood characteristics	Riparian Burn Recent [+]		Mid		Old		*P*
Pieces/100m	84.7	14.3	58.8	26.8	73.4	13.9	0.112
Functional pieces/100m	46.0	14.3	39.4	13.7	46.8	13.9	0.921
Non-functional pieces/100m	46.8	12.5	19.4	10.5	24.0	11.1	0.032*
Piece diameter (cm)	19.4	2.4	18.2	1.7	19.4	2.3	0.354
Variance in diameter	83.0	42.1	54.7	4.2	66.9	35.3	0.302
Length (m)	2.6	0.6	2.7	0.4	2.9	0.9	0.628
Variance in length	3.5	1.6	3.6	1.5	5.1	4.9	0.101
Piece spacing (m)	1.2	0.2	1.5	0.8	1.2	0.3	0.169
Functional piece spacing (m)	2.1	0.9	2.3	0.8	2.0	0.7	0.869
Volume/100m	43.5	11.4	26.9	12.4	34.3	25.1	0.104
Proportion of pools formed by LWD	0.3	0.1	0.4	0.1	0.3	0.4	0.554
0 degree orientation (pieces/total # of pieces)	24.2	5.0	27.9	7.0	27.6	8.0	0.380
45 degree orientation (pieces/total # of pieces)	45.8	4.0	38.8	13.0	41.2	9.0	0.238
90 degree orientation (pieces/total # of pieces)	29.4	4.0	33.3	13.0	32.5	10.0	0.715
Only above bankfull (pieces/100m)	16.3	10.3	4.0	2.0	6.5	3.1	0.006*
Only below bankfull (pieces/100m)	48.1	11.1	43.8	17.1	46.9	19.5	0.652
Above and below bankfull (pieces/100m)	21.3	13.4	18.3	9.6	16.2	12.5	0.372
Bank embedded (pieces/100m)	22.6	17.2	25.0	12.8	23.4	12.1	0.977
Bed embedded (pieces/100m)	8.9	9.6	10.7	9.0	9.3	12.1	0.962
Not embedded (pieces/100m)	55.2	19.3	25.9	6.4	36.6	17.0	0.063*
Pieces anchored/100m	7.8	3.4	9.0	3.1	5.9	3.1	0.320
0% across channel (pieces/total # of pieces)	1.0	3.0	2.0	4.0	4.0	6.0	0.234
25% across channel (pieces/total # of pieces)	52.0	30.0	51.0	15.0	55.0	23.0	0.901
50% across channel (pieces/total # of pieces)	15.0	5.0	13.0	2.0	15.0	2.0	0.777
75% across channel (pieces/total # of pieces)	9.0	4.0	9.0	3.0	7.0	5.0	0.900
100% across channel (pieces/total # of pieces)	17.0	17.0	20.0	11.0	18.0	14.0	0.833
Function: Forming a pool (Quarters/100m)	5.7	2.1	7.9	6.2	2.8	4.6	0.282
Function: Associated with a pool (Quarters/100m)	37.0	47.4	39.0	16.7	29.9	42.1	0.910
Function: Deflecting flow into bank (Quarters/100m)	1.5	0.7	1.3	2.5	1.7	3.1	0.579
Function: Armoring the bank (Quarters/100m)	57.7	16.3	38.7	15.8	43.9	9.8	0.467
Function: Armoring the bed (Quarters/100m)	13.6	10.7	16.1	17.9	17.5	16.6	0.576
Function: Damming sediment (Quarters/100m)	19.7	9.3	24.4	6.9	26.5	10.5	0.577

[+] Median values of stream means are on the left of each treatment column, and interquartile ranges on the right (underlined). Significant differences (P<0.10) are marked with an asterisk *.

Table 4b. Results of MRRP tests on wood characteristics for data stratified by time since synchronous riparian and basin burn.

Wood characteristics	Synchronous Burn						
	Recent+		Mid		Old		*P*
Pieces/100m	84.7	14.3	64.3	24.8	77.4	10.2	0.190
Functional pieces/100m	46.0	14.3	43.2	16.2	51.1	12.3	0.748
Non-functional pieces/100m	46.8	12.5	21.1	8.7	24.0	7.3	0.042*
Piece diameter (cm)	19.4	2.4	18.3	1.3	19.3	2.3	0.607
Variance in diameter	83.0	42.1	54.9	3.2	59.5	26.2	0.314
Length (m)	2.6	0.6	2.8	0.4	2.9	0.8	0.819
Variance in length	3.5	1.6	3.9	1.2	5.1	4.5	0.103
Piece spacing (m)	1.2	0.2	1.5	0.6	1.2	0.2	0.310
Functional piece spacing (m)	2.1	0.9	2.1	0.8	1.8	0.5	0.822
Volume/100m	43.5	11.4	27.1	7.5	34.3	18.4	0.115
Proportion of pools formed by LWD	0.2	0.2	0.4	0.2	0.4	0.3	0.670
0 degree orientation (pieces/total # of pieces)	24.2	2.3	27.6	6.6	29.2	5.7	0.321
45 degree orientation (pieces/total # of pieces)	45.8	3.4	35.4	12.0	38.3	7.1	0.152
90 degree orientation (pieces/total # of pieces)	29.4	4.4	35.1	11.6	29.9	10.1	0.666
Only above bankfull (pieces/100m)	16.3	10.3	4.0	2.1	6.5	3.1	0.009*
Only below bankfull (pieces/100m)	48.1	11.1	45.0	10.5	55.0	12.9	0.468
Above and below bankfull (pieces/100m)	21.3	13.4	15.2	10.1	15.0	11.6	0.397
Bank embedded (pieces/100m)	22.6	17.2	19.8	13.2	24.9	10.1	0.869
Bed embedded (pieces/100m)	8.9	9.9	11.8	10.3	9.3	13.0	0.942
Not embedded (pieces/100m)	55.2	19.3	25.9	3.7	36.6	17.0	0.137
Pieces anchored/100m	7.8	3.4	9.0	0.7	5.9	2.2	0.370
0% across channel (pieces/total # of pieces)	1.3	2.7	3.2	3.3	5.0	6.6	0.128
25% across channel (pieces/total # of pieces)	51.1	31.0	48.0	13.9	56.6	16.6	0.773
50% across channel (pieces/total # of pieces)	14.7	5.4	12.5	2.3	15.2	1.9	0.760
75% across channel (pieces/total # of pieces)	8.6	3.8	8.7	1.6	6.6	1.9	0.545
100% across channel (pieces/total # of pieces)	16.8	15.9	23.2	12.2	13.0	12.8	0.626
Function: Forming a pool (Quarters/100m)	5.7	2.1	7.5	6.7	3.2	6.3	0.403
Function: Associated with a pool (Quarters/100m)	37.0	47.4	39.1	15.7	29.9	60.2	0.874
Function: Deflecting flow into bank (Quarters/100m)	1.5	0.7	1.6	2.8	1.7	2.6	0.639
Function: Armoring the bank (Quarters/100m)	57.7	16.3	34.7	10.9	43.4	6.3	0.109
Function: Armoring the bed (Quarters/100m)	13.6	10.7	19.7	20.5	17.5	9.1	0.608
Function: Damming sediment (Quarters/100m)	19.7	9.3	24.2	3.9	30.0	9.3	0.371

+ Median values of stream means are on the left of each treatment column, and interquartile ranges on the right (underlined). Significant differences (P<0.10) are marked with an asterisk *.

Table 5a. Results of MRRP tests on channel characteristics for data stratified by time since basin burn.

Channel characteristic	Basin Burn Recent+		Mid		Old		*P*
Max. residual depth between cross-sections (m)	0.29	0.08	0.27	0.10	0.29	0.08	0.909
Variance max. residual depth	0.007	0.003	0.011	0.005	0.011	0.006	0.597
Residual pool depth (m)	0.27	0.04	0.28	0.02	0.31	0.07	0.706
Var. in residual pool depth	0.01	0.003	0.01	0.015	0.01	0.008	0.803
Pool spacing (active channel widths)	4.91	2.69	3.71	1.30	5.71	4.18	0.702
D_{50} (mm)	29.75	47.13	17.00	21.50	28.25	19.50	0.741
Sinuosity (m/m)	1.26	0.13	1.21	0.26	1.23	0.08	0.889
Cross section area (m^2)	1.59	0.94	1.99	0.46	2.10	0.42	0.514
Hydraulic radius (m)	0.39	0.07	0.39	0.04	0.36	0.03	0.546
Channel width (m)	2.93	0.81	3.47	0.92	3.93	1.28	0.185
Var. channel width	0.40	0.593	0.65	0.689	0.97	0.521	0.311
Channel depth (m)	0.23	0.04	0.26	0.06	0.27	0.09	0.361
Var. channel depth	0.004	0.004	0.005	0.002	0.004	0.003	0.666
Bankfull depth (m)	0.42	0.14	0.43	0.02	0.40	0.05	0.335
Var. bankfull depth	0.006	0.006	0.007	0.003	0.005	0.002	0.507
Width-depth ratio# (m/m)	15.28	2.32	13.26	2.22	14.70	5.96	0.569

+ Median values of stream means are on the left of each treatment column, and interquartile ranges on the right (underlined). No characteristics are significantly different (P<0.10).
# Values for the active channel.

Table 5b. Results of MRRP tests on channel characteristics for data stratified by time since riparian burn.

Channel characteristic	Riparian Burn Recent[+]		Mid		Old		*P*
Max. residual depth between cross-sections (m)	0.30	0.02	0.29	0.11	0.25	0.10	0.327
Variance max. residual depth	0.008	0.006	0.011	0.005	0.009	0.006	0.270
Residual pool depth (m)	0.28	0.03	0.28	0.05	0.30	0.09	0.841
Var. in residual pool depth	0.08	0.07	0.10	0.07	0.08	0.07	0.786
Pool spacing (active channel widths)	4.41	2.12	3.87	2.40	5.01	4.03	0.376
D_{50} (mm)	21.50	20.75	34.00	37.50	27.00	24.75	0.732
Sinuosity (m/m)	1.31	0.17	1.25	0.14	1.20	0.13	0.122
Cross section area (m^2)	1.98	1.05	1.69	0.36	2.10	0.56	0.635
Hydraulic radius (m)	0.42	0.07	0.39	0.03	0.36	0.03	0.121
Channel width (m)	3.22	1.04	3.12	0.47	3.89	1.14	0.799
Var. channel width	0.71	0.51	0.62	1.09	0.89	0.71	0.858
Channel depth (m)	0.24	0.02	0.24	0.05	0.26	0.11	0.515
Var. channel depth	0.005	0.002	0.004	0.003	0.004	0.002	0.929
Bankfull depth (m)	0.47	0.11	0.43	0.03	0.40	0.08	0.217
Var. bankfull depth	0.008	0.004	0.007	0.003	0.005	0.002	0.656
Width-depth ratio[#] (m/m)	14.02	2.78	13.12	4.22	14.83	3.10	0.878

[+] Median values of stream means are on the left of each treatment column, and interquartile ranges on the right (underlined). No characteristics are significantly different (P<0.10).

[#] Values for the active channel.

Table 5c. Results of MRRP tests on channel characteristics for data stratified by time since synchronous burn.

Channel characteristic	Synchronous Burn						
	Recent[+]		Mid		Old		*P*
Max. residual depth between cross-sections (m)	0.30	0.02	0.28	0.09	0.29	0.08	0.565
Variance max. residual depth	0.008	0.006	0.012	0.002	0.011	0.006	0.833
Residual pool depth (m)	0.28	0.03	0.29	0.06	0.31	0.07	0.904
Var. in residual pool depth	0.08	0.07	0.13	0.08	0.11	0.08	0.819
Pool spacing (active channel widths)	4.41	2.12	3.69	0.52	5.71	4.18	0.521
D_{50} (mm)	21.50	20.75	15.00	17.13	28.25	19.50	0.842
Sinuosity (m/m)	1.31	0.17	1.34	0.21	1.23	0.08	0.518
Cross section area (m^2)	1.98	1.05	2.02	0.43	2.10	0.42	0.677
Hydraulic radius (m)	0.42	0.07	0.41	0.04	0.36	0.03	0.266
Channel width (m)	3.22	1.04	3.50	0.83	3.93	1.28	0.569
Var. channel width	0.71	0.51	1.23	0.86	0.97	0.52	0.708
Channel depth (m)	0.24	0.02	0.26	0.05	0.27	0.09	0.484
Var. channel depth	0.005	0.002	0.005	0.002	0.004	0.003	0.956
Bankfull depth (m)	0.47	0.11	0.44	0.03	0.40	0.05	0.232
Var. bankfull depth	0.008	0.004	0.007	0.003	0.005	0.002	0.498
Width-depth ratio[#] (m/m)	14.02	2.78	14.02	3.09	14.70	5.96	0.752

[+] Median values of stream means are on the left of each treatment column, and interquartile ranges on the right (underlined). No characteristics are significantly different (P<0.10).
[#] Values for the active channel.

Wood characteristics

Two wood characteristics varied in both the riparian and synchronous burn classifications: 1) the number of pieces only above bank-full and 2) the number of non-functional pieces. The riparian burn classification had one additional significant difference: the number of pieces not embedded in the bank or bed.

Comprehensive identification of wood species was not possible with the techniques employed, and therefore it was not possible to run a statistical analysis on wood species type. The sample size of pieces that crossed the channel more than once (>100%) was also too small for statistical analysis.

Location of wood within cross sections

The vertical position of wood within cross sections was classified as below bank-full, above, or both above and below. Wood classified as only above bank-full either bridged the bank-full channel or had greater than 1 m of length cantilevered above bank-full. Results show a significant difference in the amount of wood that is only above bank-full for both the riparian and synchronous burn classifications (P=0.006 and 0.009, Tables 4a-b, respectively). The results for the riparian burn classification are presented as an example (Figure 4), and are typical of the synchronous burn. The amount of wood above bank-full in the recent treatment is significantly greater than both mid and old treatments (P=0.006 and 0.040, respectively), while the amount of wood above bank-full in the old treatment is also significantly greater than the mid treatment (P=0.057). However, there is no significant difference across treatments in terms of the number of pieces below bank-full or both above and below bank-full (Figure 4).

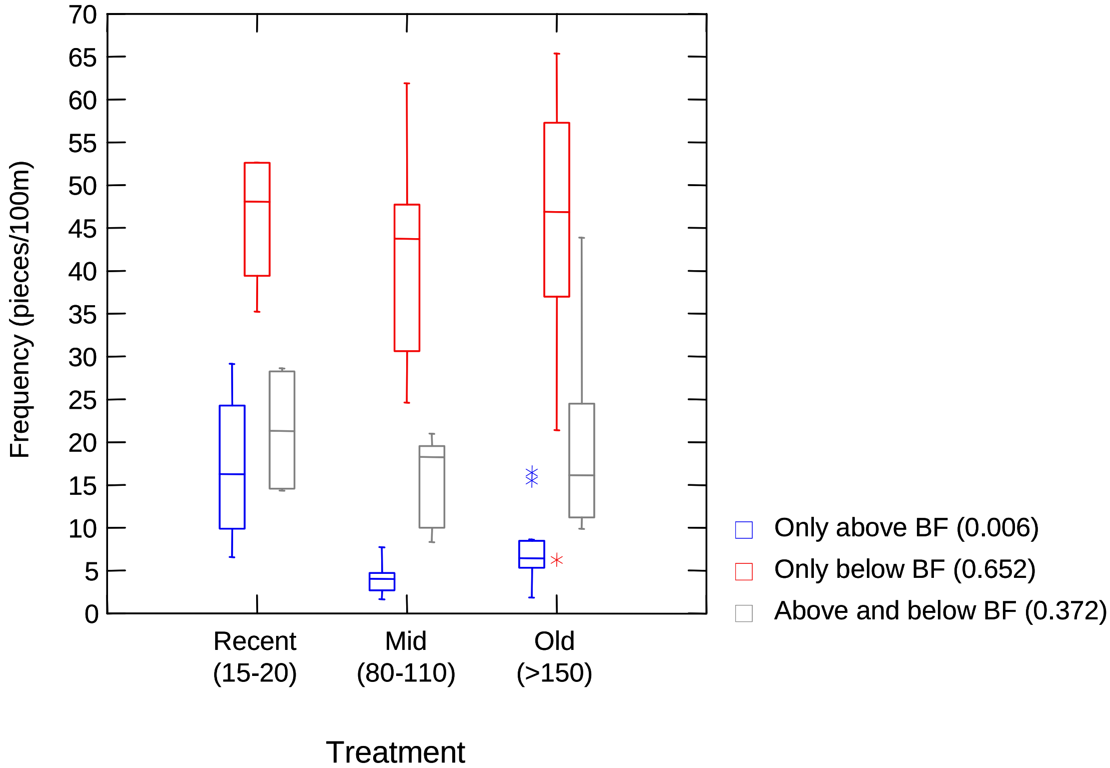

Figure 4. Box plots of the vertical position of wood within cross sections for data classified by time since riparian burn. *P*-values are shown in the legend. Values in parentheses on the *x*-axis represent the time since fire in years. Box plot features are: hinges- 1st and 3rd quartiles; whiskers- inner fences (top or bottom hinge plus/minus 1.5 times the interquartile range, or the extent of the data, whichever comes first); asterisk- data between inner and outer fences (hinge plus/minus 3 times the interquartile range); empty circle- data outside outer fence. BF indicates bank-full.

Embedment of wood

There is no significant difference between treatments in the amount of wood embedded in the bank or bed (Figure 5). There is, however, a significant difference in the amount of non-embedded wood. Recent and old treatments both have significantly more non-embedded wood than the mid treatment (*P*=0.052 and 0.072, respectively), while the former two are not statistically different from one another. The observed difference in the number of non-embedded pieces probably reflects the amount of wood suspended above the bank-full channel (Figure 4), which by definition is not embedded. Consequently, the Figure 5 results are not an independent difference.

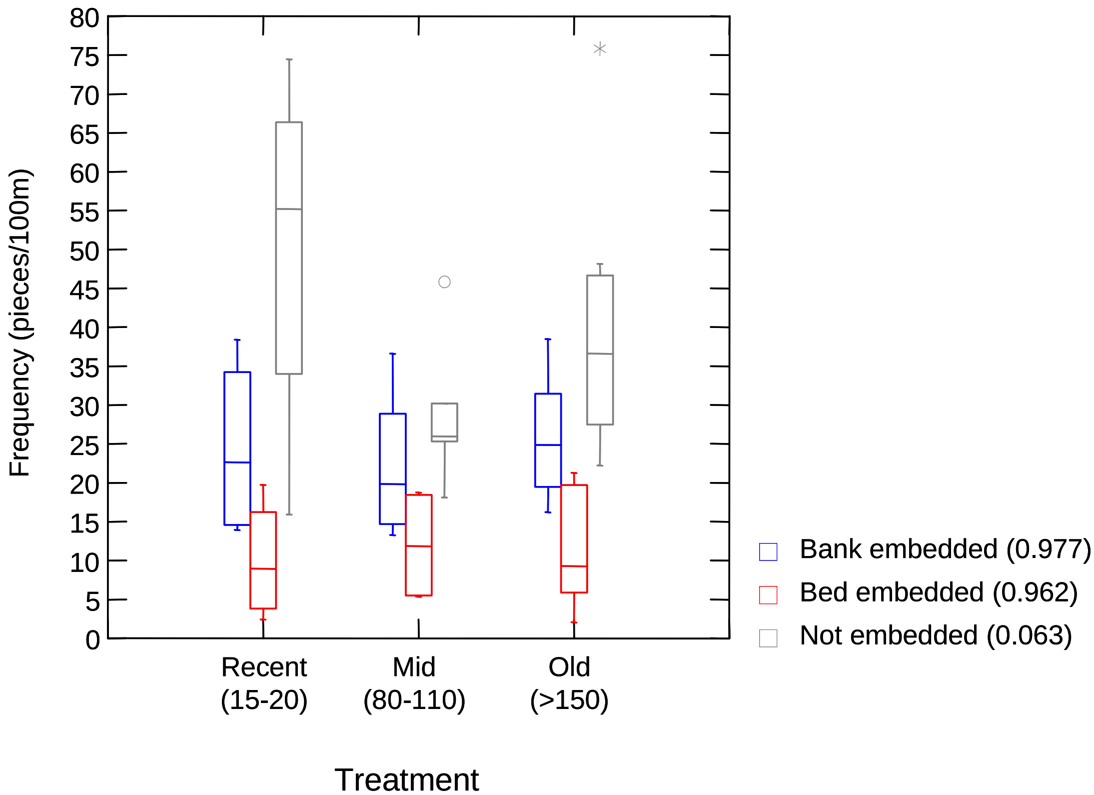

Figure 5. Box plots of wood embedment for data classified by time since riparian burn. *P*-values are shown in the legend. See Figure 4 caption for definition of box-plot symbols.

Wood frequency

The observed pattern in total wood frequency across treatments is similar to results of recent wood recruitment models (e.g., Benda and Sias, 2003), with the greatest frequency of wood occurring after fire (recent), the least during forest recovery (mid), and a moderate amount during old seral stages (old) (Figure 6). However, the observed differences in total wood frequency are not significant (*P*=0.112), nor are the differences in the frequency of functional wood (*P*=0.921). The only significant difference is the frequency of non-functional wood, with more non-functional wood in the recent treatment than in the mid and old treatments (*P*=0.015 and 0.095, respectively). Consequently, the pattern of changes in total wood across treatments is largely driven by changes in non-functional wood at the study sites.

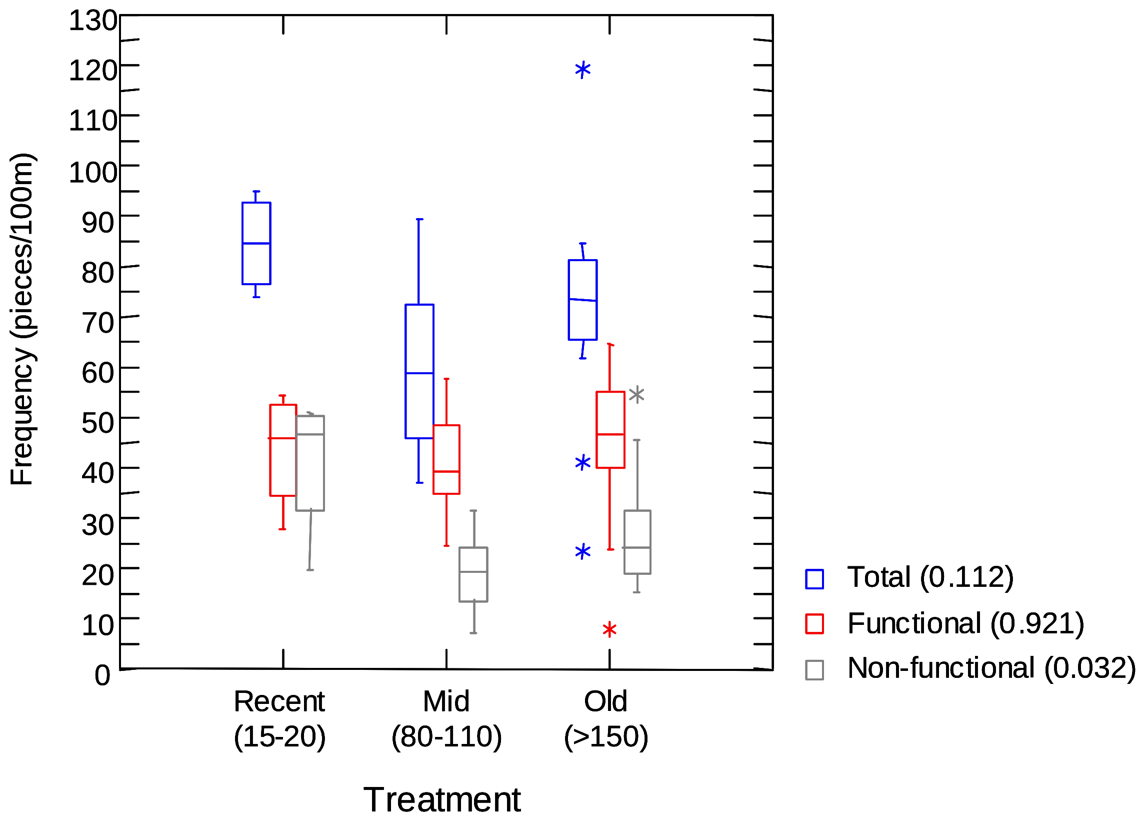

Figure 6. Box plots of wood frequency for the data classified by time since riparian burn. *P*-values are shown in the legend. See Figure 4 caption for definition of box-plot symbols.

Wood diameter

Wood diameter is not significantly different across treatments (*P*=0.354, Table 4); however, the observed variability was large enough to have physical or biological importance. *Q-Q* plots are a non-statistical approach for examining these differences. Figure 7 shows that the mid treatment has a smaller range of diameters than the recent and old treatments, which tend to be similar to one another. The mid treatment has a smaller range of wood diameters, with pieces typically less than about 50 cm in diameter. In contrast, the recent and old treatments both have maximum diameters near 100 cm and several observations greater than 50 cm. However, these differences in wood diameter do not cause any significant differences in channel characteristics (Table 5). Differences in diameter of this magnitude might be important in larger channels, where larger pieces of wood are required to affect channel form (Bilby and Ward, 1989; Montgomery et al., 2003).

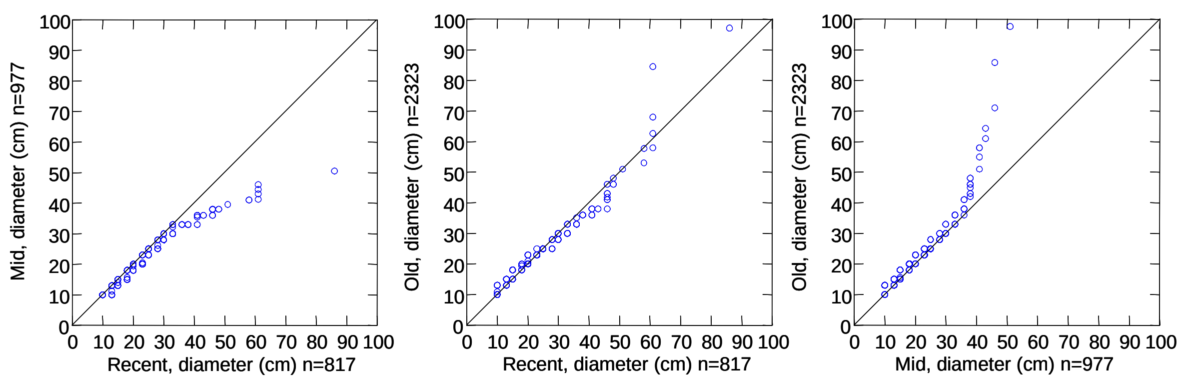

Figure 7. *Q-Q* plots of wood diameters (cm) for the data classified by time since riparian burn. The number of observations (*n*) is included on each axis label, with observations pooled per treatment.

Wood distribution

Recent studies show that riparian trees tend to fall towards streams (Sobota, 2003). However, less is know about the spatial distribution of wood within the channel, which may have relevance for processes bringing trees into channels, particularly where fluvial transport of wood is minor. Random events are based on Poisson processes, and the spacing between Poisson distributed events or objects is given by an exponential distribution (Haan, 1977). Therefore, trees that randomly fall into a stream should have spacings represented by an exponential distribution. A chi-squared test was used to compare observed wood spacing to that of an exponential distribution.

Twenty of the 23 reaches studied had wood distributions significantly different from an exponential distribution (P<0.05, χ^2 test). Reaches with exponential wood distribution (Figure 8) had fewer pieces in the smallest spacing class (0-1.0 m), or less clumping, than reaches with non-exponential wood spacing (Figure 9). The non-exponential data show a greater number of pieces closer to one another (0-1 m), fewer pieces with moderate spacing (1-4 m), and more pieces with large spacing (> 4 m) than would be predicted by an exponential distribution (Figure 9). This may indicate a separation of scales with some process yielding clumping at scales less than 1 m and others at greater than 4 m. Clumping of wood may be due to multiple trees falling in the same location, with one tree knocking over others, by a localized wind burst, localized disease, localized undercut banks, or other spatially coherent process. The formation of periodic wood jams via fluvial transport is likely precluded at these study sites due to their low stream slopes and relatively narrow channel widths, allowing transport of only very small wood. Therefore, the observed spatial clumping of wood suggests that wood was not recruited to the stream based on individual random tree falls. These results agree with those of Robison and

Beschta (1990), who found non-systematic (or discontinuous) spacing of wood in undisturbed southeast Alaska streams of similar size to these sites. At the Idaho sites, all non-exponential distributions appeared to be better fit by a negative binomial distribution. Results herein show that wood spacing is not random and suggest that models based on or derived from consideration of individual tree fall need to consider interaction between individual trees when estimating total wood loading (Gregory et al., 2003).

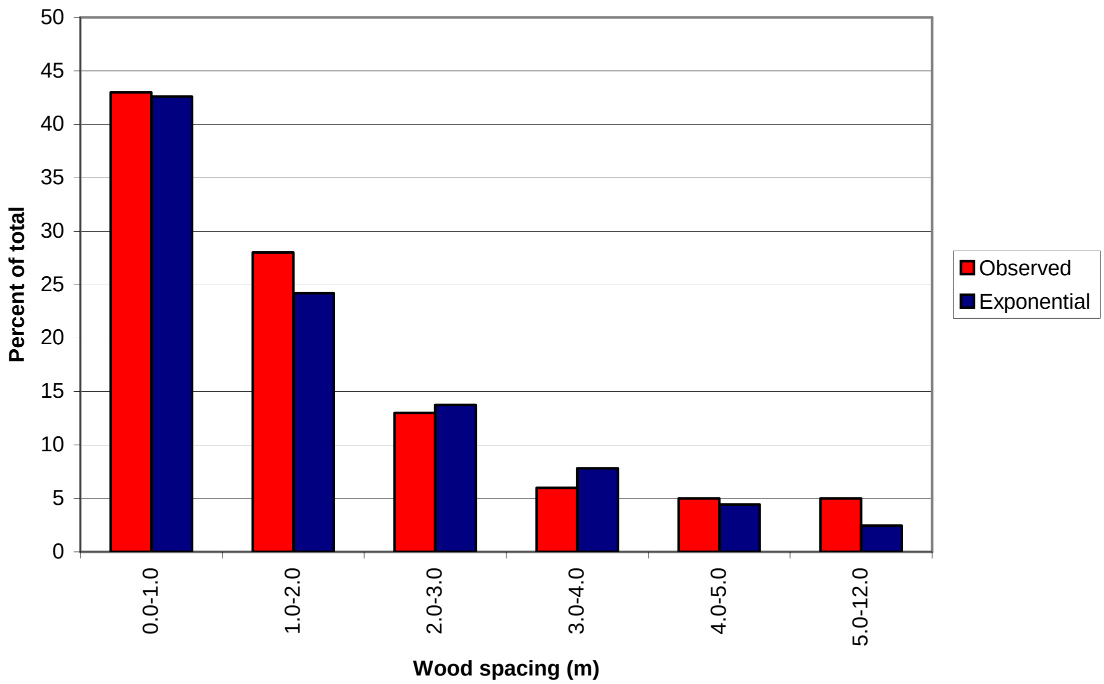

Figure 8. Example of a stream with an exponential distribution of wood spacing, Van Buren Creek.

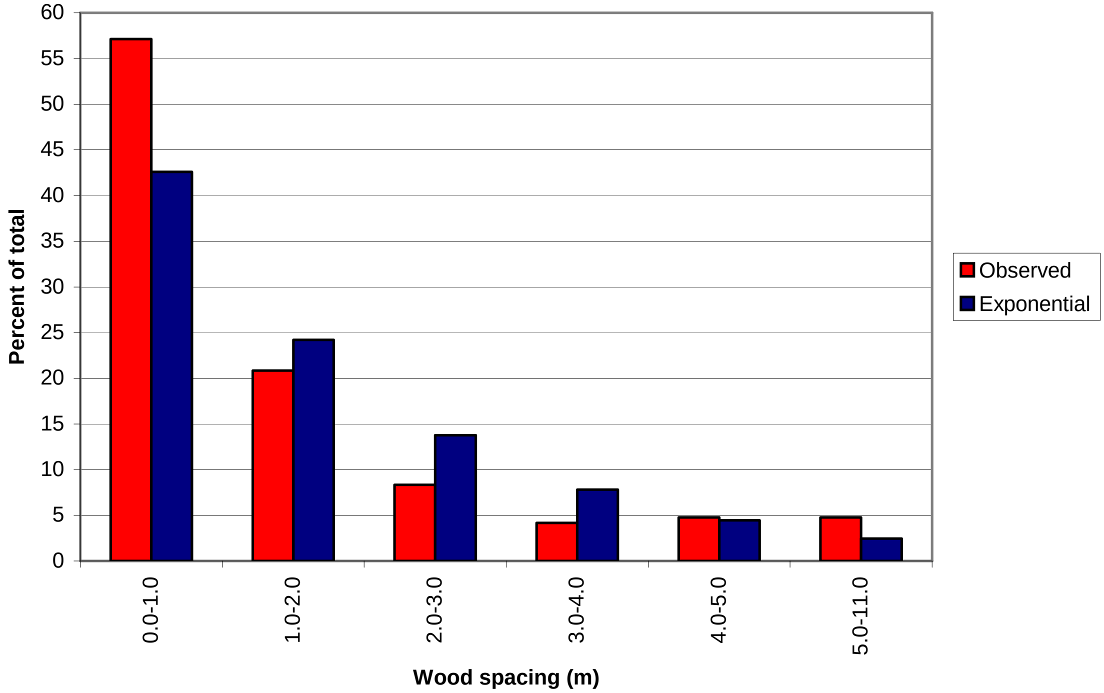

Figure 9. Example of a stream with non-exponential distribution of wood spacing and some clumping of wood, Otterson Creek.

Wood decay and timing of recruitment

There are no significant differences in wood decay classes for riparian and synchronous burn classifications of the data (*P*>0.261, MRPP, not shown in Table 4). To better understand the effects of fire on riparian recruitment of wood, we can define the following four sources of input: 1) carry over (wood that was in the stream or on the floodplain prior to fire), 2) fire mortality (wood that toppled into the stream after being burned), 3) remnant stand (recruitment from the unburned portion of the riparian forest), or 4) new stand (input from the fire-regenerated stand) (Spies et al., 1988). As discussed in previous sections, fluvial transport of wood is unlikely at the study sites and, therefore, upstream input is not considered as a source of wood.

Wood decay classes (Appendix A5) and degree of burial were used to estimate sources of wood input in each treatment (Figure 10). The base (white segment) of each bar represents decay classes 3 and 4 (Appendix A5), or “old wood”. The top of each bar (gray segment) represents unburied wood having decay classes 1 or 2 (Appendix A5), or “new wood”. At recently burned sites, fire mortality and the remnant stand were the two primary sources of new wood (decay classes 1 and 2), while decay classes 3 and 4 better represent carry-over wood. In the mid treatment, new and remnant stands can provide new wood (decay classes 1 and 2), and old wood is derived from fire mortality, carry-over wood, or the remnant stand. The remnant stand may provide new or old wood to the mid and old treatments because it may have a wide range of tree ages. In the old treatment, it is less likely that fire mortality and carry over contribute to the amount of old wood present in the stream.

Although decay classes are not uniquely related to specific wood sources over time and across treatments, the amount of new wood in the recent treatment is relatively small compared to the amount of old wood, or carry over (Figure 10). This suggests that carry-over wood may play an important role in supplying the mid-treatment channels with wood during the post-fire lag in recruitment while the riparian forest is regrowing. However, as will be discussed in later sections, fire-related wood stored in suspension is another important source of future functional wood that may buffer fire-related disruption of riparian recruitment. The wood stored in suspension may have been derived, in part, from carry-over, fire mortality or the remnant stand. Hence, all of these sources of wood may also be important for supplying wood to mid-treatment channels.

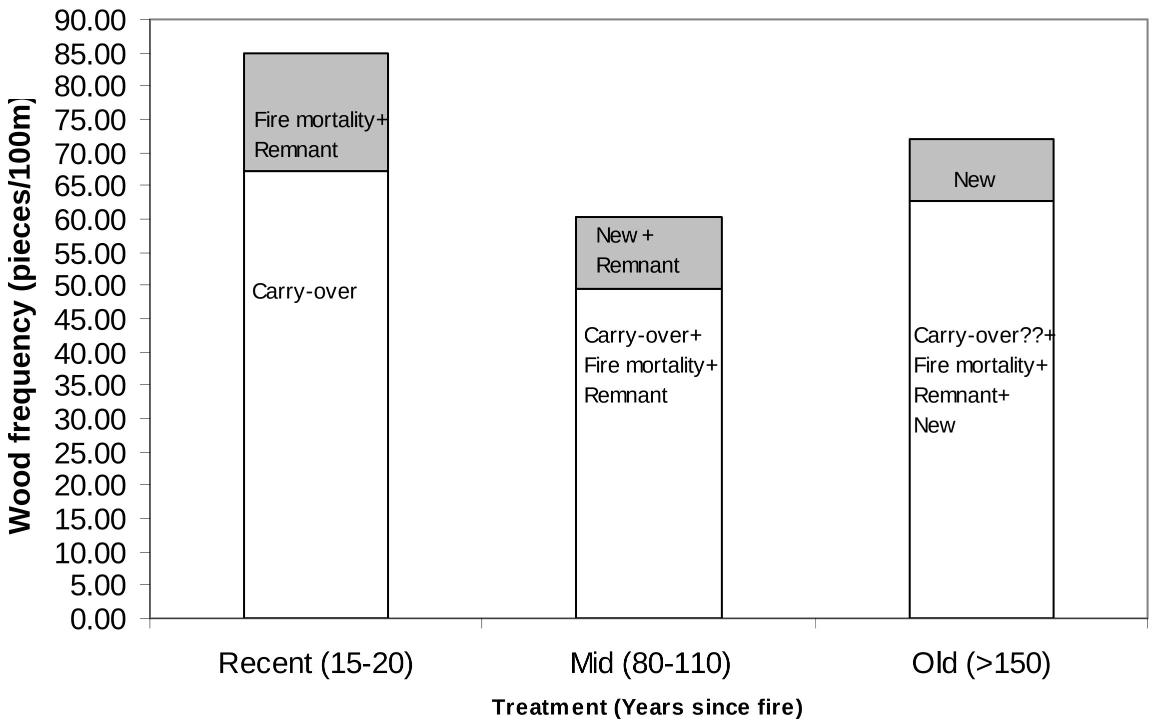

Figure 10. Mean values of wood sources over time for data classified by time since riparian burn. The base of each bar represents decay classes 3 and 4 (Appendix 5), or "old wood". The gray portions represent decay classes 1 and 2 (Appendix 5), or "new wood". The likely wood source(s) are indicated within each box.

Channel characteristics

Sediment

Median surface grain size (D_{50}) was not significantly different between treatments (P=0.741, Table 5). However, the treatment means show substantial differences on the order of 43 % (Table 5a), which may have biological importance in terms of the availability of suitable spawning gravels for salmonids (e.g., Kondolf and Wolman, 1993; Buffington et al., 2004). *Q-Q* plots are used to further examine characteristics of the full grain-size distributions (rather than just the median size) for each treatment. The basin burn classification of the data is presented here to analyze potential grain-size response to post-fire alterations of sediment supply and hydrology. In this analysis, grain sizes were limited to those smaller than 256 mm (boulders) because larger grain sizes at the study sites are less mobile, and therefore less responsive to changes in hydrology. Larger grain sizes are also less responsive to changes in sediment supply, as it would require a greater amount of fine sediment to bury these large grains. *Q-Q* analysis shows that the mid treatment has a slightly finer distribution than the recent and old treatments (Figure 11). In particular, the shift in treatment means is primarily due to a greater abundance of particles less than 15 mm in the mid treatment. These results also may have biological importance, in that increases in the abundance of fine material can be detrimental to aquatic species (e.g., Bjornn and Reiser, 1991).

In addition, the proportion of dominant substrate (Appendix A4) at the points of maximum pool depth and riffle crest were not significantly different between treatments for all burn classifications ($P>0.05$, χ^2 test of equality of proportions) (Figures 12 and 13). The point of maximum pool depth is expected to be the location of maximum scour in high flows, and a likely place for fine sedimentation at low flows. Riffle crests can be a local point of aggradation that is related to scour characteristics of the pool immediately upstream. The lack of difference in the substrate found at these locations suggests that high and low flow sedimentation is similar between treatments. These results are of particular importance to salmonid spawning, as salmon and trout often prefer to spawn near the riffle crest (i.e., pool tail-outs) and require clean gravels (<20% of the grain-size distribution finer than 6 mm) (Bjornn and Reiser, 1991; Baxter and Hauer, 2000).

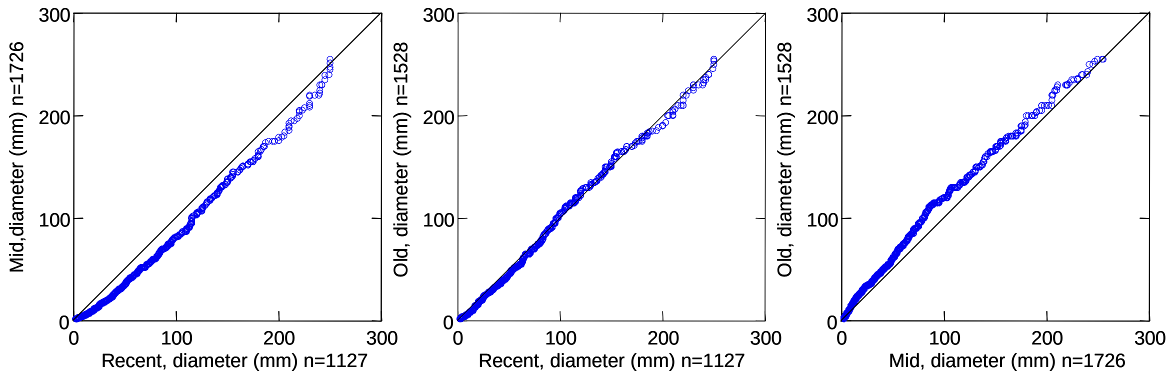

Figure 11. *Q-Q* plots of surface grain sizes smaller than 256 mm for data classified by time since basin burn. The number of observations (*n*) is reported on each axis label, with observations pooled per treatment.

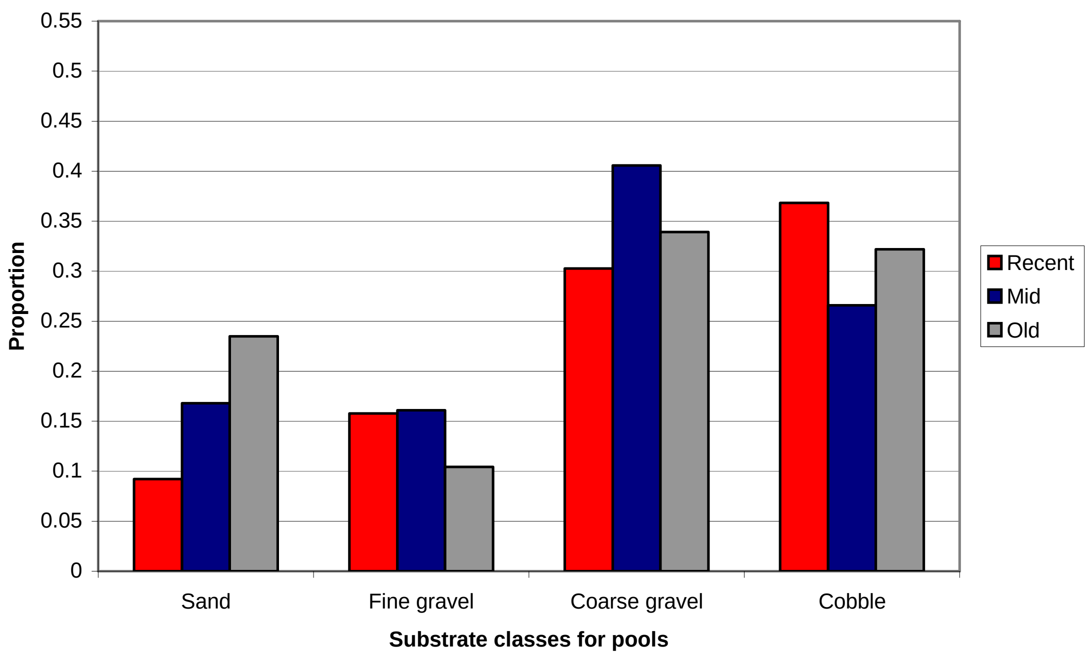

Figure 12. Dominant substrate at pool bottoms for data classified by time since basin burn. A χ^2 test of equality of proportions finds no significant difference between treatments (P>0.05). Where, sand is <2 mm, fine gravel is 2-8 mm, coarse gravel is 8-64 mm, and cobble is 64-256 mm.

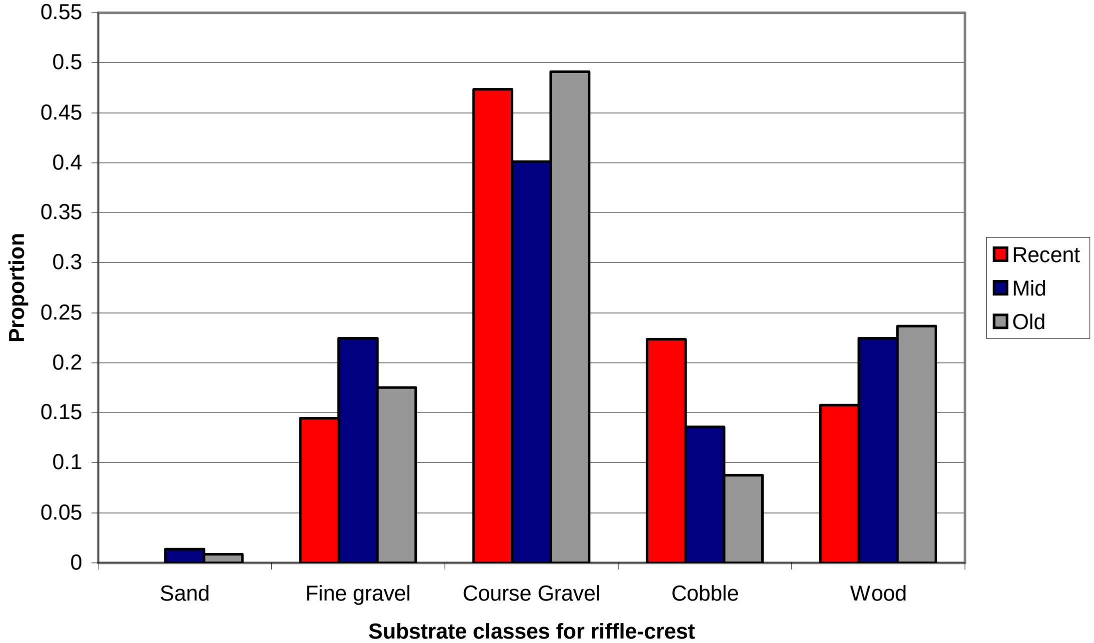

Figure 13. Dominant substrate at riffle crests for data classified by time since basin burn. A χ^2 test of equality of proportions finds no significant difference between treatments (P>0.05). Where, sand is <2 mm, fine gravel is 2-8 mm, coarse gravel is 8-64 mm, and cobble is 64-256 mm.

Pool spacing & pool type

The riparian and synchronous burn classifications of the data are used here to examine the effects of locally-supplied wood in forming pools during riparian forest succession; as discussed earlier, it is hypothesized that little fluvial transport of wood occurs at the study sites and that most of the in-channel wood is supplied from the local riparian forest. No significant differences in pool spacing were observed across the different burn classifications (P=0.702, Table 5), but pool spacing is an important measure of habitat quality, and so is further examined here. Pool spacing was normalized by the average active channel width, as opposed to the bank-full width, because active channel widths could be measured with more confidence than bank-full widths.

Q-Q plots reveal that distributions of pool spacing are similar among treatments up to values of about 7 active channel widths, beyond which the recent and old treatments tend to have a greater number of more widely spaced pools than the mid treatment (Figure 14). Again showing that the mid treatment has different characteristics than the recent and old treatments. However, because these observations make up a small proportion of the entire data set this difference is not significant according to the MRPP analysis. The observed values of wood frequency and pool spacing for the Idaho study sites are within the range reported by Montgomery et al. (2003) for other western streams, but are most similar to their data for the southern Rockies and northern Cascade mountain ranges.

Results also show that there is no significant difference in the total frequency of pools (P=0.568), the frequency of self-formed and boulder-forced pools (P=0.748), or the frequency of wood-forced pools (P=0.598) across the riparian and synchronous burn classifications (Figure 15). Self-formed and boulder-forced pools are combined in this analysis because we did not differentiate between the two in the field.

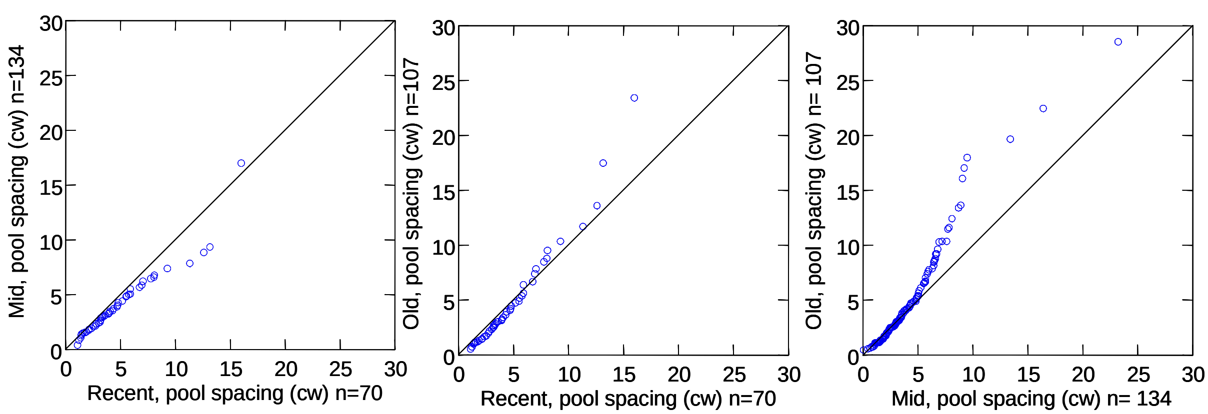

Figure 14. *Q-Q* plots of pool spacing (expressed in active channel widths, cw) for data classified by time since riparian burn. Results shown here are typical of the other burn classifications. The number of observations (n) is indicated on each axis label, with data pooled per treatment.

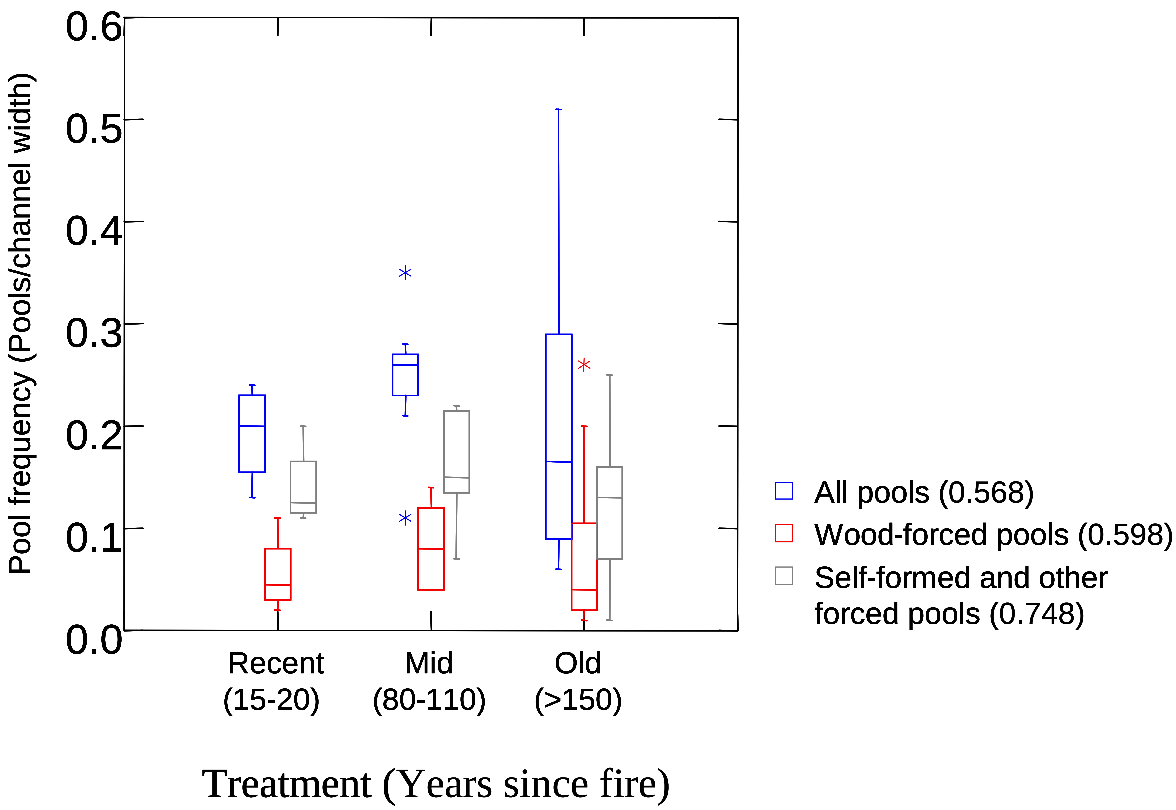

Figure 15. Box plots of pool frequency for data classified by time since riparian burn. *P*-values are shown in the legend. See Figure 4 caption for definition of box-plot symbols.

Maximum residual depth between cross sections

There is no significant difference in maximum residual depth between cross sections for data classified by time since basin burn (*P*=0.909), riparian burn (*P*=0.327), or synchronous burn (*P*=0.565) (Table 5). Nevertheless, maximum residual depth is an important measure of habitat cover and, therefore, is further examined. Figure 16 shows results for maximum residual depths for data classified by time since basin burn. Again, the basin burn classification of the data is presented, as it is typical of the other burn classifications. These data show that maximum residual depths are most similar in the old and mid treatments, while the recent treatment tends to have relatively shallow residual depths. Consequently, channels recently impacted by wildfire may have somewhat less habitat cover (smaller residual depths), but the differences between treatments are not statistically significant according to the MRRP analysis.

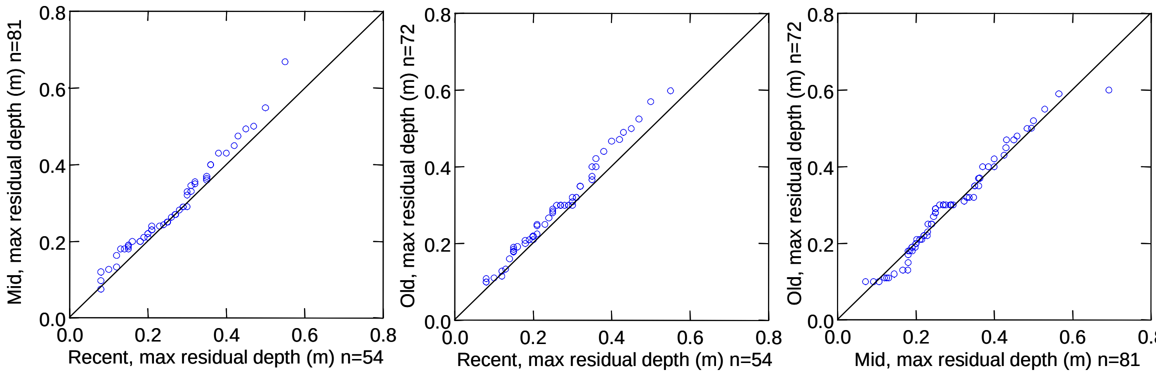

Figure 16. *Q-Q* plots of maximum residual depth between cross sections for data classified by time since basin burn. The number of observations (*n*) is included on each axis label, with data pooled per treatment.

DISCUSSION

Channel characteristics

The lack of significant differences in channel characteristics for the basin and synchronous burn classifications of the data suggests that fire-related alterations of hydrologic and sediment regimes did not have long-term (> 20 year) effects on the channel morphology of these reaches. Consequently, any changes in these regimes were either geomorphically insignificant or were short-lived, with the channel form recovering within 15-20 years (i.e., over time scales shorter than the smallest sampling period used in this study). For example, Potyondy and Hardy (1994) found that fine sediment introduced by wildfire was quickly winnowed from the streambed by flood flows, and that surface material recovered to pre-disturbance conditions within 2-3 years.

The lack of significant differences in channel characteristics for time since basin burn (reaches where only the upland forest burned) is the least surprising, given the notion that fire-related effects on hydrologic and sediment regimes tend to be more short-lived than effects on the riparian forest and consequent wood recruitment to these channels (Minshall et al., 1989; Minshall and Brock, 1991). The lack of significant differences in channel characteristics for time since synchronous burn and time since riparian burn is more surprising, given that numerous studies have hypothesized that channel characteristics will change in concert with forest succession and altered characteristics of wood recruitment (e.g., Minshall, 1989; Beechie et al., 2000).

Wood characteristics

Significant differences in wood characteristics did not drive significant differences in channel characteristics for time since riparian burn or time since synchronous burn because there was little change in wood that affected channel hydraulics. Most of the wood input after fire is suspended above the channel because of small channel widths relative to wood lengths. The majority of riparian trees at the study sites are tall/long enough to easily bridge the channel for many fall directions, even if they break upon fall. Furthermore, the probability of fall breakage is likely to be low given the relatively short height of riparian trees (mean height = 21 m) (Sobota, 2003). Hence, we would expect to see a large percentage of recently recruited wood to be suspended above the channel (Van Sickle and Gregory, 1990; Robison and Beschta, 1990) and geomorphically ineffective for most flows.

When wood initially falls over an unconfined stream, the potential for it to fall below bank-full where it can interact with the stream may be related to the ratio of stream width (*w*) to length of input wood (*L*), termed here the functional recruitment ratio (*FR*=*w*/*L*). Figure 17 is a cartoon that compares a high *FR* ratio to a low *FR* ratio, where the wood length is constant for each case, but the stream width is varied. Wood that is suspended over the channel may eventually enter the channel due to decay and breakage, or due to fluvial undercutting of the supporting bank. However, Murphy and Koski (1989) found that some wood in southeast Alaskan streams may remain suspended over the channel as long as 100 years after recruitment from the riparian forest. Consequently, low *FR* values and, subsequent, suspension of wood over the channel could significantly slow the recruitment of wood to geomorphically effective locations, buffering the effects of post-fire increases in riparian input of wood (Swanson and Lienkaemper, 1978).

Figure 3 supports this expectation, showing that the recent treatment has significantly more wood pieces above bank-full than both the mid and old treatments, and that there is no difference between treatments in the number of pieces below bank-full and both above and below bank-full. Hence, suspension appears to buffer the effects of greater post-fire input of wood from the riparian zone. In similar streams, Robinson et al. (2005) found 5 times more wood in streams recently burned, compared to unburned streams. They also found that a significant portion of recently recruited wood did not directly interact with the channel, and reported that 80 percent of the wood bridged these burned streams.

Within the context of this study, the FR ratio addresses the problem of wood entry into the channel. However, once wood enters the channel its geomorphic effectiveness depends on the size of the wood relative to the size of the channel (e.g., Montgomery et al., 2003).

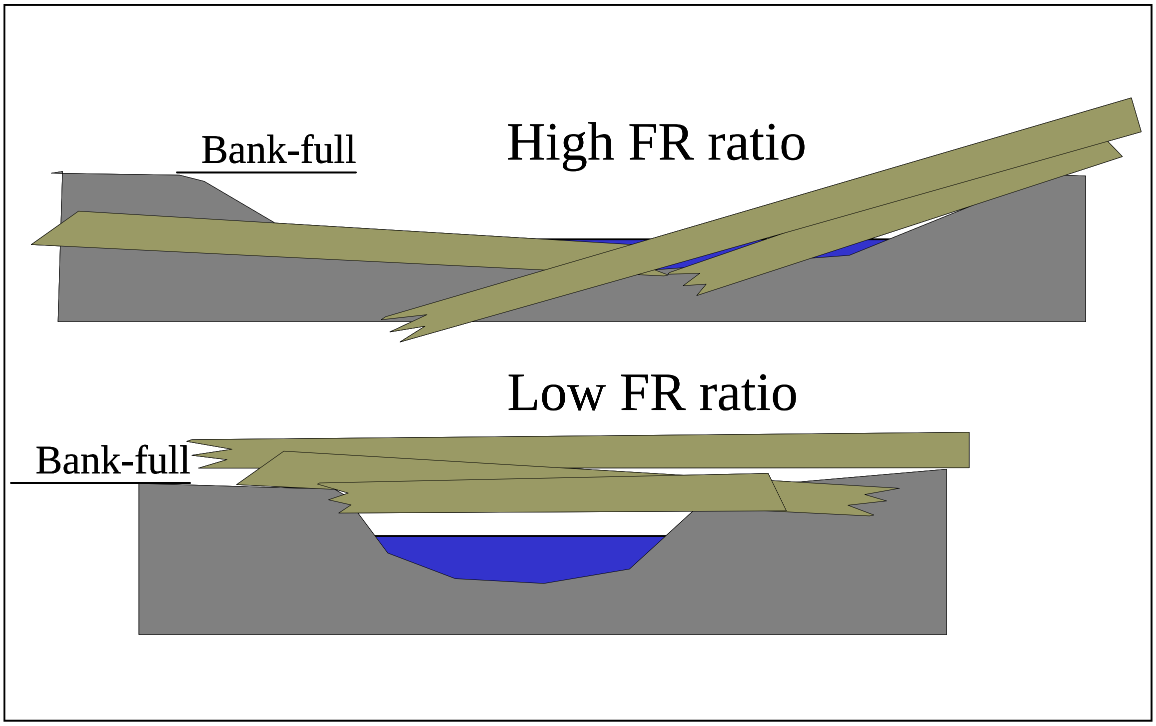

Figure 17. Cartoon depicting generalized *FR* ratios.

The greater number of pieces of wood above bank-full from fire-toppling in the recent treatment likely explains the higher numbers of non-functional wood in that treatment (Figure 6) and the greater abundance of wood not embedded in the channel bed and banks (Figure 5). To examine this issue, the MRPP analysis was re-run after removing the recently recruited pieces of wood (unsubmerged pieces in decay classes 1 and 2, Appendix 5) that were located above bank-full in the recent treatment. This reanalysis removes the differences in non-functional wood and non-embedded wood across the treatments ($P > 0.10$). Hence, there is really only one, independent, significant difference in the wood characteristics at these sites: the number of pieces only above bank-full. The numbers of non-embedded and non-functional pieces are not independent factors, but rather are functions of the number of pieces above bank-full.

It was also found that the frequency of functional wood does not vary statistically among reaches. This suggests a stable supply of functional wood over time despite wildfire disturbance. To better understand this finding we can consider wood sources and the mechanisms that supply wood from these sources to the stream. Potential stores of wood include pieces suspended above bank-full, wood on the floodplain, wood buried below the channel and wood buried in the banks (Hyatt and Naiman, 2001; Montgomery and Abbe, 2006). Wood suspended above the channel could be accessed through decay and breakage into the channel, through channel migration that undercuts a supporting bank and causes suspended wood to fall into the channel, or by the channel aggrading up to the wood. Branches hanging from a suspended piece of wood may slow the flow or trap other floating debris, causing the channel to locally aggrade and either erode one bank, undercutting the suspended piece of wood, or partially bury the wood, creating a stepped profile. Lateral migration or, in more extreme cases, channel avulsion may cause the stream to capture wood located on the floodplain or buried within the alluvial valley fill. Finally, should the channel begin to incise, it may interact with more buried wood (e.g., Lisle, 1986). Roughly half of the wood in the mid and old treatments was embedded, implying origins in buried wood (Table 4), and suggesting active movement of the channel that both buries and exhumes wood. Frequent over-bank sedimentation may also be important to burial. Rapid burial by channel movement and floodplain sedimentation is important to creating large stores of wood because preservation of wood requires it to be buried or submerged soon after it falls. The abundance of functional wood within the channel may also be modulated by low rates of wood decay and mechanical wearing due to low channel slopes and low water and air temperatures (Bilby, 2003).

It was found that the majority of wood in the recent treatments was carry-over wood from the antecedent stand (Figure 10). This suggests that carry-over wood from the recent treatment may play a significant role in supplying wood to these streams during forest reestablishment. Carry-over wood may result from a low mechanical wearing/decay rate of in-channel wood or come from one of the stores discussed above. Studies have shown that buried wood decays extremely slowly and may persist for hundreds, or even thousands, of years (Nanson et al., 1995; Hyatt and Naiman, 2001; Abbe and Montgomery, 2006). Wood submerged or buried in the floodplain maintains structural integrity over time. If such wood is exposed to surface discharge, as the channel migrates laterally or incises, it can be relatively resistant to stress and abrasion. These pieces may act as a rigid structure maintaining channel form and moderating wood abundance (e.g., Montgomery and Abbe, 2006) by buffering the overall decrease in wood amount during times of net sediment transport and incision as a stream exposes buried wood.

Although, one might expect to see more pieces of wood associated with streams after fire-toppling and less during times of forest reestablishment, it is hypothesized that the study sites are characterized by buffering mechanisms (wood stored in suspension and buried wood) that maintain a relatively constant amount of geomorphically effective wood over time scales of forest succession. In early seral stages (recent treatment) wood may be trapped above bank-full due to low *FR* ratios, modulating the impact of post-fire pulses of wood input to the stream. As for mid-seral stages (mid treatment), buffering mechanisms may be exhumation of wood or the incorporation of suspended wood into the stream, thereby supplying wood during the lag time in riparian recruitment. Moreover, the lack of significant geomorphic differences between treatments for all burn classifications indicates that the dotted blue line in Figure 1 best represents the response trajectory of habitat quality for these reaches.

Management implications

The stability of small, low- to moderate-gradient streams with wide valleys may have implications for population dynamics of fishes in dynamic landscapes. Ensuring connectivity between these stream types and ones more prone to disturbance may be of critical importance to persistence of fishes by providing potential refugia from disturbance, or creating population sources for recolonization of catastrophically disturbed areas.

The identification of stable stream habitats may also help to prioritize fuel treatment locations at the watershed scale. For example, fuels reduction treatments meant to "protect" this stream type may not be needed given its lack of response to fire disturbance. Furthermore, periodic input of fire-toppled wood that is stored in suspension and slowly input to the channel over time may be an important part of maintaining functional wood and channel stability in this stream type. Consequently, fire management that disrupts this process may have a negative impact on channel stability and aquatic habitat quality.

Reaches similar to those studied here, but that were subject to anthropogenic disturbance, such as “stream cleaning” or riparian logging, may be good locations for channel restoration efforts, as habitat improvement structures should be stable over long time periods. Structures placed in such sites would likely be stable and persistent because they are decoupled from hillslope disturbances, have low potential for fluvial transport due to low channel slopes, and may have low decay/mechanical wearing rates. However, if the buffering mechanisms (wood trapped above bank-full and floodplain storage of wood) are no longer present due to the anthropogenic disturbance, the channel may be less stable than the sites examined in this study.

CONCLUSIONS

The lack of morphologic variability over time since major fires implies that wildfire disturbance does not have a major long-term effect on channels of this stream type, suggesting that low- to moderate-gradient, unconfined channels can act as relatively stable, potentially productive, refugia relative to larger-scale disturbances occurring in a basin. Response to post-fire disturbances depends on channel type and position in the river network (connection to hillslopes and sequence of upstream channels and their ability to transmit disturbances (Montgomery and Buffington, 1998; Rice, 1994). The channels examined in this study were buffered from direct post-fire debris-flow impacts because of low stream gradients and wide alluvial valleys (decoupling the channel from direct hillslope inputs and allowing debris flows to spread out and deposit upstream from the study sites). These channels exhibit characteristics of response reaches (unconfined, alluvial valley fill, low slopes) (Montgomery and Buffington, 1998), yet results indicate that the study sites are relatively stable and morphologically unresponsive to wildfire disturbance. However, response may have occurred over shorter time-scales than those examined in this study (i.e., less than 15 years after fire). Given that this study focuses on a single stream type, additional studies are needed in other stream types and geomorphic settings to examine variability in channel changes after wildfire disturbance. Compilation of such studies would greatly assist in development of risk-assessment models for stream and riparian ecosystem response to wildfire and forest management. Future studies of this nature should focus on *FR* ratios, decay/mechanical wearing rates, and wood sources and budgets (including buried wood) to gain a better understanding of mechanisms that influence functional wood supply.

Although this study focused on statistical differences between treatments, it is also important to consider physical and biological relevance of observed differences. While some differences were not statistically significant, it is possible that the absolute magnitudes of the difference are great enough to have physical or biological relevance. For example, if we consider D_{50} values observed in the recent and mid treatments for time since basin burn, we see that D_{50} values for the mid treatment are 43% smaller than the recent treatment. Despite a lack of statistical significance, differences such as this may be important biologically in terms of the availability of spawning gravel or rearing habitat for specific species (Kondolf and Wolman, 1993; Buffington et al., 2004), and may be an important factor when evaluating the effect of fire-related response on aquatic organisms.

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APPENDIX

Appendix A1. Sites classified by time since basin burn.

Basin Burn Classification		Controls					Characteristics	
Stream	Treatment	Elevation (m)	Valley width (channel widths)	Valley Slope (m/m)	Drainage Area (ha)	Average Basin Slope (m/m)	Discharge (m^3/s)	Stream Order
Cottonwood	Recent	2053	4	0.039	1178	0.33	1.85	4
E. Fk. Elk	Recent	2103	9	0.038	1175	0.28	3.82	3
Farrow	Recent	1980	5	0.033	894	0.37	2.93	3
Lodgepole (Idaho Co.)	Recent	1932	4	0.023	1180	0.43	2.07	3
No name (trib to N. Fk Elk)	Recent	1997	4	0.024	968	0.27	4.24	3
W. Fk. Chamberlain	Recent	1850	8	0.024	813	0.40	3.54	3
Bridge	Mid	1488	4	0.03	815	0.20	3.62	3
Frank Brown	Mid	1727	5	0.028	902	0.21	3.43	3
L. Mallard	Mid	1793	8	0.029	665	0.21	2.63	3
Otterson	Mid	1471	3	0.025	920	0.23	3.82	3
Porter	Mid	2076	3	0.028	709	0.25	3.60	3
Rock	Mid	2078	3	0.037	699	0.33	3.32	3
U.20 Mile	Mid	1846	4	0.029	699	0.28	3.61	3
VanBuren	Mid	1634	5	0.035	557	0.39	3.76	3
W. Fk. 20 Mile	Mid	1328	4	0.028	1106	0.15	2.06	3
4-Mile	Old	1782	6	0.034	645	0.13	3.54	3
6-Bit	Old	1852	3	0.031	911	0.35	3.40	3
Lodgepole (Valley Co.)	Old	1776	7	0.039	876	0.39	3.19	3
N. Fk. Hotsprings	Old	1557	4	0.036	686	0.33	3.12	2
No name (trib to Bargaman cr.)	Old	1549	5	0.027	658	0.29	3.02	2
S. Fk. Hotsprings	Old	1564	4	0.037	443	0.33	2.27	2
Upper Big Mallard	Old	1950	3	0.024	412	0.09	3.13	3
Winnemucca	Old	2215	4	0.028	793	0.27	3.21	3

Recent Mean		1986	5.67	0.030	1035	0.347	3.07
Mid Mean		1716	4.33	0.030	786	0.251	3.32
Old Mean		1781	4.50	0.032	678	0.273	3.11
Group Mean		1809	4.74	0.031	813	0.284	3.18

Appendix A2. Sites classified by time since riparian burn.

Riparian Burn Classification		Controls					Characteristics	
Stream	Treatment	Elevation (m)	Valley width (channel widths)	Valley Slope (m/m)	Drainage Area (ha)	Average Basin Slope (m/m)	Discharge (m^3/s)	Stream Order
E. Fk. Elk	Recent	2103	9	0.038	1175	0.28	3.82	3
Farrow	Recent	1980	5	0.033	894	0.37	2.93	3
Lodgepole (Idaho Co.)	Recent	1932	4	0.023	1180	0.43	2.07	3
No name (trib to N. Fk Elk)	Recent	1997	4	0.024	968	0.27	4.24	3
Bridge	Mid	1488	4	0.03	815	0.20	3.62	3
Frank Brown	Mid	1727	5	0.028	902	0.21	3.43	3
L. Mallard	Mid	1793	8	0.029	665	0.21	2.63	3
Otterson	Mid	1471	3	0.025	920	0.23	3.82	3
Porter	Mid	2076	3	0.028	709	0.25	3.60	3
U.20 Mile	Mid	1846	4	0.029	699	0.28	3.61	3
W. Fk. Chamberlain	Mid	1850	8	0.024	813	0.40	3.54	3
4-Mile	Old	1782	6	0.034	645	0.13	3.54	3
6-Bit	Old	1852	3	0.031	911	0.35	3.40	3
Cottonwood	Old	2053	4	0.039	1178	0.33	1.85	4
Lodgepole (Valley Co.)	Old	1776	7	0.039	876	0.39	3.19	3
N. Fk. Hotsprings	Old	1557	4	0.036	686	0.33	3.12	2
No name (trib to Bargaman cr.)	Old	1549	5	0.027	658	0.29	3.02	2
Rock	Old	2078	3	0.037	699	0.33	3.32	3
S. Fk. Hotsprings	Old	1564	4	0.037	443	0.33	2.27	2
Upper Big Mallard	Old	1950	3	0.024	412	0.09	3.13	3
VanBuren	Old	1634	5	0.035	557	0.39	3.76	3
W. Fk. 20 Mile	Old	1328	4	0.028	1106	0.15	2.06	3
Winnemucca	Old	2215	4	0.028	793	0.27	3.21	3

Recent Mean		2003	5.50	0.030	1054	0.337	3.26
Mid Mean		1750	5.00	0.028	789	0.256	3.46
Old Mean		1778	4.33	0.033	747	0.282	2.99
Group Mean		1809	4.74	0.031	813	0.284	3.18

Appendix A3. Sites classified by time since synchronous basin and riparian burn.

Synchronous Burn Classification		Controls					Characteristics	
Stream	Treatment	Elevation (m)	Valley width (channel widths)	Valley Slope (m/m)	Drainage Area (ha)	Average Basin Slope (m/m)	Discharge (m^3/s)	Stream Order
E. Fk. Elk	Recent	2103	9	0.038	1175	0.28	3.82	3
Farrow	Recent	1980	5	0.033	894	0.37	2.93	3
Lodgepole (Idaho Co.)	Recent	1932	4	0.023	1180	0.43	2.07	3
No name (trib to N. Fk Elk)	Recent	1997	4	0.024	968	0.27	4.24	3
Bridge	Mid	1488	4	0.03	815	0.20	3.62	3
Frank Brown	Mid	1727	5	0.028	902	0.21	3.43	3
L. Mallard	Mid	1793	8	0.029	665	0.21	2.63	3
Otterson	Mid	1471	3	0.025	920	0.23	3.82	3
Porter	Mid	2076	3	0.028	709	0.25	3.60	3
U.20 Mile	Mid	1846	4	0.029	699	0.28	3.61	3
4-Mile	Old	1782	6	0.034	645	0.13	3.54	3
6-Bit	Old	1852	3	0.031	911	0.35	3.40	3
Lodgepole (Valley Co.)	Old	1776	7	0.039	876	0.39	3.19	3
N. Fk. Hotsprings	Old	1557	4	0.036	686	0.33	3.12	2
S. Fk. Hotsprings	Old	1564	4	0.037	443	0.33	2.27	2
No name (trib to Bargaman cr.)	Old	1549	5	0.027	658	0.29	3.02	2
Upper Big Mallard	Old	1950	3	0.024	412	0.09	3.13	3
Winnemucca	Old	2215	4	0.028	793	0.27	3.21	3
Recent Mean		2003	5.50	0.030	1054	0.337	3.26	
Mid Mean		1734	4.50	0.028	785	0.232	3.45	
Old Mean		1781	4.50	0.032	678	0.273	3.11	
Group Mean		1814	4.72	0.030	797	0.273	3.26	

Appendix A4. Pool and riffle-crest substrate classifications:

1. Wood (used only for riffle crest depth)
2. Sand, < 2mm
3. Fine gravel, 2-8 mm
4. Coarse, gravel >8-64 mm
5. Cobble, >64-256 mm
6. Boulder, >256 mm

Appendix A5. Wood decay classifications stratified by submergence and burn combinations:

	Decay Class			
Wood Type	1 (young)	2	3	4 (old)
Submerged (not burned)	Needles present on any part of tree (including outside of the channel/submerged volume)	No bark and the surface is smooth, or bark and no branches	Bole surface rough and soft	Gnarled bole and very hard (generally black)
Not submerged (not burned)	Needles present on any part of the tree	Some loose bark, but most is firmly attached, or no bark and bole is smooth	Bark is easily pulled off bole, wood losing integrity	Very soft, crumbly
Submerged (burned)	Burnt bark and limbs, or no bark and limbs due to fire	Bole is smooth	Bole surface rough and soft	Gnarled bole and very hard (generally black)
Not submerged (burned)	Burnt bark and limbs, or no bark and limbs due to fire	No bark, some surface cracks, wood sound	Extensive cracks, wood losing integrity	Very soft, crumbly

Appendix A6. Site characteristics.

Stream	Average residual pool depth (m)	Average pool spacing (acw)+	Average cross section area (m^2)*	Average hydraulic radius (m^2/m)*	Average active channel width (m)	Average active channel depth (m)	Average bank-full depth (m)	Sinuosity	Valley Slope (m/m)	Wood amount (pieces/100 m)
Cottonwood	0.15	10.71	0.87	0.26	2.50	0.15	0.28	1.12	0.039	23.44
E. Fk. Elk	0.3067	2.47	2.48	0.44	4.45	0.28	0.51	1.37	0.038	90.80
Farrow	0.2956	5.01	1.48	0.35	2.88	0.22	0.33	1.25	0.033	78.70
Lodgepole (Idaho Co.)	0.3189	3.80	1.30	0.39	2.29	0.24	0.43	1.51	0.023	74.01
No name (trib to N. Fk Elk)	0.2867	7.31	2.50	0.48	3.55	0.24	0.54	1.20	0.024	94.84
W. Fk. Chamberlain	0.2056	4.80	1.69	0.39	2.97	0.19	0.40	1.27	0.024	45.63
Bridge	0.2011	3.20	2.04	0.37	3.47	0.27	0.46	1.43	0.03	69.80
Frank Brown	0.2922	3.87	1.51	0.32	3.53	0.22	0.36	1.21	0.028	46.00
L. Mallard	0.3589	2.96	1.67	0.40	3.12	0.30	0.42	1.42	0.029	89.29
Otterson	0.2711	3.71	1.99	0.42	3.10	0.24	0.45	1.25	0.025	75.45
Porter	0.4011	8.61	2.22	0.41	4.20	0.22	0.43	1.20	0.028	36.92
Rock	0.3367	6.90	1.64	0.39	2.90	0.26	0.43	1.15	0.037	73.00
U.20 Mile	0.2456	3.66	2.22	0.42	4.21	0.28	0.44	1.89	0.029	58.75
VanBuren	0.2125	3.53	2.10	0.37	4.02	0.30	0.44	1.11	0.035	61.73
W. Fk. 20 Mile	0.2333	4.83	1.30	0.32	3.02	0.20	0.36	1.16	0.028	84.48
4-Mile	0.2511	7.01	2.10	0.35	4.78	0.19	0.33	1.08	0.034	81.48
6-Bit	0.4167	6.23	2.50	0.44	4.10	0.29	0.46	1.11	0.031	119.03
Lodgepole (Valley Co.)	0.3056	9.09	2.19	0.36	4.55	0.24	0.36	1.22	0.039	71.66
N. Fk. Hotsprings	0.2778	1.85	2.15	0.36	4.73	0.31	0.41	1.23	0.036	81.11
No name (trib to Bargaman cr.)	0.3311	3.12	1.70	0.35	3.20	0.23	0.37	1.28	0.027	73.75
S. Fk. Hotsprings	0.2122	3.43	1.21	0.33	2.57	0.32	0.39	1.18	0.037	81.25
Upper Big Mallard	0.3211	5.19	2.10	0.40	3.75	0.37	0.45	1.68	0.024	69.31
Winnemucca	0.2	12.39	1.75	0.37	3.36	0.17	0.40	1.23	0.028	41.15

Appendix A7. Percent of stand burned in the basin versus within the riparian zone. Percent burn values correspond with times of fire, respectively. For old stands, it was not possible to determine the percent of the basin burned with aerial photography, nor was it possible to use stand cruise data to determine the percent of the riparian stand that burned, due to the extensive time since fire. Hence, old basin and riparian stands were ones where less than 50 percent of the forest had burned within 150 years of the study.

	Basin burn treatments	Time of fire(s)	% basin burned	% riparian burned
Cottonwood	Recent	1988	75	20
E. Fk. Elk	Recent	1987	70	66
Farrow	Recent	1987	95	60
Lodgepole (Idaho Co.)	Recent	1986, 2000	90, 10	60, 0
No name (trib to N. Fk Elk)	Recent	1987	70	47
W. Fk. Chamberlain	Recent	1966, 2000	75,25	10, 0
Bridge	Mid	1919	50	36
Frank Brown	Mid	1919	70	55
L. Mallard	Mid	1870, 1910	30, 60	0,42
Otterson	Mid	1919	80	98
Porter	Mid	1910	80	64
Rock	Mid	1900	70	0
U.20 Mile	Mid	1919	85	52
VanBuren	Mid	1910	60	0
W. Fk. 20 Mile	Mid	1919	75	0
4-Mile	Old	1773, 1910	?, 35	?, 0
6-Bit	Old	1843, 1910	?, 30	?, 0
Lodgepole (Valley Co.)	Old	1773, 1910	?, 20	?, 0
N. Fk. Hotsprings	Old	1833, 1910	?, 30	?, 18
No name (trib to Bargaman cr.)	Old	1833, 1911	?, 30	?, 0
S. Fk. Hotsprings	Old	1803, 1910	?, 40	?, 31
Upper Big Mallard	Old	1853, 1919	?, 35	?, 0
Winnemucca	Old	1843, 1910	?, 30	?, 0