WILDFIRE SEVERITY EFFECTS ON IN-STREAM LARGE WOOD IN THE FRANK CHURCH-RIVER OF NO RETURN WILDERNESS, IDAHO

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On my Honor, I have neither given, nor received, unauthorized aid on this thesis.

Honor Code Upheld.

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Abstract

Large wood (LW) provides habitat to aquatic organisms and can significantly alter stream geomorphology. Sources of LW to stream ecosystem originate in riparian forests and are influenced by wildfire regimes. To quantify the relationship between burn severities and in-stream LW, we surveyed 15 low order streams effected by varying wildfire burn severities in a near-pristine watershed of the Frank Church River of No-Return Wilderness in Central Idaho. In the field and using remotely sensed imagery, burn severity was divided into four categories: "unburned," "low," "moderate," and "high". We hypothesized that burn severity would be positively correlated with in-stream LW. Alternatively, in areas with the highest burn severities, LW might be limited due to combustion. To test this hypothesis we used principal components analysis that indicated fire severity, recruitable LW, and pre-fire vegetation are the most important predictors of in-stream LW in landscapes with a natural wildfire regime. In particular, high category severity burns had significantly more LW than the other categories. An increase in burn severity is also correlated with increased average piece size. The comparison of fire severity maps to field data found a significant correlation locally but no correlation with fire severity of upstream reaches. Few studies have compared the interaction of in-stream LW and fire severity in a near-pristine stream ecosystem. The results of this study improve our understanding of LW dynamics in Intermountain West watersheds with a natural wildfire regime, and could inform post-fire salvage logging management practices.

Introduction

Large wood (LW) is an important allochtonous input into forest streams. LW can influence stream erosion rate, determine streambed pebble size, and create critical habitat for fish and aquatic invertebrates (Benda 2003, Reeves 2006, Swanson 1978). LW is especially important for salmonids, because it controls gravel size for spawning and provides habitat for juvenile fish (Buffington 2004). LW abundance and distribution are controlled by multiple local and watershed scale factors, including forest mortality, forest growth, bank erosion, mass wasting, transport capacity of streams, fragmentation and decay rate, and disturbance (Benda and Sias 2003). In particular, natural disturbances to riparian vegetation, such as wind, normal mortality, or fire that kills vegetation, significantly influences the recruitment rate of LW into the stream channel (Benda 2003). For many stream ecosystems, these disturbances are critical for maintaining LW inputs and the subsequent impacts on stream geomorphology and ecology (Bisson 2003). LW is especially important during post-fire recovery and restoration, as it creates habitat structures, slows water velocities, and provides nutrients to the stream. (Minshall *et al*., 1989).

In Northwest forests wildfires are a natural and important disturbance to aquatic ecosystems (Beschta 2004). However, the fire regime in the Rockies, and much of western North America, is changing. Fire suppression, logging, and climate change are altering the frequency and magnitude of wildfires, and managed forests are more likely to have stand replacing fires of great severity (Benda 2003, Rose 2001, Westerling 2006). Such changes to the natural fire regime have been less pronounced in forests managed as Wilderness. According to the US Forest Service (Forest Service Manual 2324.21), wilderness fire management permits lightning caused fires to play “their natural ecological role” while still reducing the “risks and consequences" of wildfire. On the contrary, fires near people or managed timber forests have been typically suppressed, which has had large and significant ecosystem level consequences.

We can more effectively manage human impacted forest streams by better understanding the natural dynamics of habitat structure. Many current management approaches use impacted watersheds as a baseline for post-fire restoration actions. Managing this way may "relegate aquatic systems to a permanently degraded condition" (Beschta 2004). There are few large areas that have not been changed by humans after wildfire that could be used as controls in ecological research (Beschta 2004). The Frank Church River of No Return Wilderness is the largest contiguous wilderness area in the lower 48 states, which makes it one of the best places to study a near anthropomorphically unaltered ecological and geomorphic baseline.

Studies have shown that in-stream LW decreases immediately after a fire. Berg (2002) showed that a fire in the Sierra Nevada Mountains decreased the number of debris aggregations in a burned stream up to one year after the fire. On a longer timescale, however, models have shown that in-stream LW increases over a period of several decades after a fire, then decreases below pre-disturbance levels (Bragg 2000). Burton (2005) also describes a similar sequence of events, with the pre-fire stream containing high levels of LW and after just the fire this LW being flushed out by floods. Afterwards, as the burned trees fell, the amount of in-stream LW increased. However, this pattern might differ among rivers of varying sizes.

Smaller streams begin to recover to pre-fire levels of woody debris sooner than larger streams, and the frequency of debris dams decreases with increasing stream size (Likens and Bilby 1982). In addition, a recent study in the Frank Church Wilderness suggests that streams within burned riparian forests have greater annual variation in LW rather than perennially higher or lower LW levels (Arkle 2010). In a comparison of burned and unburned catchments in the

Frank Church Wilderness, Robinson (2005) found that wood volume was similar between burned and unburned in 2nd and 5th order streams, but 5 times greater in burned 3rd order streams than unburned. Benda and Sias (2003) predict that the largest LW recruitment in a 150-year fire cycle forest occurs when burnt snags fall within a few decades of forest death, and half of LW inputs come from fire-killed trees. In the North Fork Boise River, post-fire erosion and floods transported such large volumes of wood into stream channels that managers removed the wood to protect downstream bridges (Benda 2003).

Although it has been shown that fire affects LW, it is possible that the severity of the fire might alter the response of LW. Severity has been shown to have an effect on aquatic ecosystems (Malison 2010), but geomorphic studies incorporating severity are few, and no studies have examined LW in the context of fire severity. Wildfires have heterogeneous burn severities that could affect LW in different ways. In this paper, we hypothesize that 1) the highest fire severity will produce the highest total wood volume and increased average piece size, and 2) local fire severity is a more effective predictor than upstream fire severity. In the discussion we review some of the management implications of wildfires of different severities in headwater streams.

Methods

Site Description

Study reaches were located on tributaries of Big Creek, which flows into the Middle Fork of the Salmon River in the Frank Church Wilderness of central Idaho. The elevation ranged from 5200 feet to 3900 feet. The hydrologic regime is snowmelt driven, with peak flows in May and June; base flows occur in late summer through winter. The dominant tree species that create LW are Ponderosa Pine (*Pinus ponderosa*), Douglas Fir (*Pseudotsuga menziesii*), and Water Birch (*Betula occidentalis*). Drier slopes are dominated by sagebrush (*Artemesia sp*.) and grasses, and other riparian plants include willows (*Salix sp*.), Red Osier Dogwood (*Cornus sericea*), Rocky Mountain Maple (*Acer glabrum*), and alders (*Alnus sp*.).

The Frank Church Wilderness around Big Creek has been mostly unaffected by anthropogenic land cover changes such as logging, although there are small local disturbances around historically occupied areas. The US Forest Service does not suppress wildfires in the area unless they threaten property (Forest Service Manual 2324.21). There were fires within our study reach watersheds in 1988, 2000, 2006, and 2007 (Monitoring Trends in Burn Severity http://mtbs.gov). The Diamond Peak fire in 2000 was the largest, burning 606.1 km^2 of central Idaho (Pilliod et al 2008).

In June and July of 2010, we selected 21 reaches on 15 tributaries of Big Creek. (Fig 1). The Diamond Peak fire was intended as our treatment, following Malison (2010), due to the varying intensities of the burn. Our study reaches comprised four categories of burn severity:

High Severity	Moderate Severity	Low Severity	Unburned
Burn marks on tree trunks; complete lack of canopy	Burn marks on tree trunks; some canopy present	Burn marks on tree trunks; canopy intact	No burn marks on tree trunks; canopy intact
N=8	N=5	N=5	N=3

The study design was unbalanced due to the extent of the fire; more unburned areas were impractically far away, as hiking was the only access. To select an adequate reach, we identified a several-hundred meter section of stream that contained no abrupt changes in valley slope or hill slope, had characteristic riparian vegetation, and seemed representative of the entire stream. The reach length was defined as 20 times the width; if there were less than 10 pieces of LW, the reach was extended until we counted 10 pieces to ensure more accurate averages. Streams ranged from 2nd order to 4th order (Strahler 1952), and all reaches were located in alluviated canyons.

Sampling

At each reach, we recorded the GPS coordinates (Garmin eTrex, Olather, Kansas) and determined aspect using a compass. A clinometer was used to determine average valley slope within the reach. If vegetation made viewing the entire reach impossible, we averaged the slope of several shorter sections. The predominant geologic type was also noted. In each reach we surveyed the LW, defined as in-stream wood greater than 10 cm in diameter and over 1 m in length (Peterson 1992). Only LW within bankfull width (estimated by bank slope change and vegetation) was counted. Starting at the downstream edge of the reach, we walked upstream and counted every piece of LW. Each piece of LW was classified based on three distribution categories:

Jammed	Alone	Touching
Part of a cluster of LW that significantly alters stream flow	Isolate within a stream	In contact with other pieces of LW; pieces are not as tightly clustered or flow altering as “Jammed”

Length, diameter, and presence/absence of burn marks were measured on the first ten pieces of LW and then on every fifth piece. We also measured basal area of recruitable wood next to each reach. Wood that could potentially fall in the bankfull area of the reach was defined as recruitable, counted, and diameter at breast height (DBH) and presence of burn marks were recorded for five random trees.

Remote Sensing Analysis

We determined burn severity and prefire vegetation using remote sensing data from Landsat 7 Enhanced Thematic Mapper Satellite imagery (U. S. Geological Survey, Sioux Falls, SD, USA). Normalized burn ratio (NBR) and delta NBR were calculated from satellite images taken pre-fire on July 18 1999 and post-fire on September 9 2001, as described by Key and Benson (2006). This map of the Diamond Peak fire burn severities was compared to the Monitoring Trends in Burn Severity (MTBS) maps and found to be accurate (http://mtbs.gov); all further analyses were done using MTBS maps for the Diamond Peak, Golden, Dunce, Cabin Creek, Westy, Rush Creek, and Cottonwood fires. Using ArcGIS (ESRI Version 9.3.1 2009), the riparian NBR and dNBR were calculated by measuring 20m on each side of the stream and upstream to the top of every stream as determined by ArcHydro. Local NBR and dNBR were measured 100m upstream from the bottom of the study reach. When a reach had burned multiple times, we averaged all relevant fire severity maps together to determine local and riparian fire intensity over the period from 1988-2010. Local and riparian NDVI were sampled from pre-fire

Landsat images.

Statistical Analysis

We compared the burn severity categories using a univariate ANOVA (SPSS Statistics for Windows, Rel. 17.0. 2008. Chicago: SPSS Inc.). Tukey's HSD was used to compare means and P-P plots were used to test for normality. Some data were log transformed to meet Levene's test for homogeneity of variance assumed for ANOVA. Scale variables were analyzed using linear and curve estimation regression functions.

We used PC-ORD multivariate statistics software (PC-ORD, McCune and Mefford 2006) to examine the structure of the data. Principle components analysis (PCA), canonical correspondence analysis (CCA), and nonmetric multidimensional scaling (NMS) analyses were conducted. These multivariate statistics are useful due to the difficulty of seeing patters in data sets with many dimensions (Smith 2002). PCA had the best combination of rigor and significance out of the three multivariate tests tried. Unlike other statistical tests, PCA requires no formal assumptions; however, it is sensitive to outliers (James 1990), which were present in our data set. An ordination of predictor variables was used to collapse cross-correlated variables without losing important parts of the data. The collapsed predictor variables were then compared to the response variables.

Results

A PCA ordination of predictor variables reveals a fairly well distributed data structure, with many data points in small, burned sites and few in large, unburned sites (Fig 2). The axes Figure 2 represent percentages of variables, compressed together, instead of one variable. The ordination of predictor variables shows that width, drainage, length, and slope are correlated. Collapsed for simplicity of analysis, drainage is used as a proxy for all four variables in future ordinations. Fire as measured in the field (hereafter "fire severity (field)") and fire intensity sampled from GIS fire severity maps (hereafter "fire intensity (GIS)") are correlated, so fire severity (field) is used in future ordinations. When fire severity (field) and fire severity (GIS) are directly compared, "high" severity is almost significantly different than "unburned" (p=0.054) and "low" severity (p=0.054). As fire severity (field) increases, fire severity (GIS) appears to increase, justifying future use of the fire severity (field) metric (Fig 4).

In Figure 3, the collapsed predictor variables as determined by Figure 2 are compared to the response variables measured in the field. Predictor and response variables that are aligned along similar axes are considered to be correlated. When the data were tested using PCA, fire severity (field), basal area, and pre-fire NDVI were the only significant predictor variables above an r-squared cutoff of .15 (Fig 3). A CCA ordination of predictor variables and response variables finds the same predictor variables above an r^2 cutoff of .3.

The fire severity (field) had significant effects on the total volume, percentage with burn marks, and average piece size of LW. For log transformed total wood volume, "high" severity was significantly different than "unburned" (p=0.005), "low" severity (p=0.007), and "moderate" severity (p=0.01). The other burn severity categories were not significantly different from each other. As fire severity increases to the "high" threshold, the total wood volume increases (Fig 5).

Fire severity (field) is also correlated with average large wood piece size. Using log transformed piece size, “high” severity is significantly different than “low” severity ($p=0.034$) and is possibly different than “unburned” ($p=0.084$) and “moderate” severity ($p=0.170$). As fire severity (field) increases, average LW piece size increases (Fig 6). Finally, fire severity (field) is correlated with the percentage of large wood with burn marks. “High” severity is significantly different than “unburned” ($p=0.002$) and “low” severity ($p=0.022$), and “low” severity might be different than “moderate” severity ($p =.064$). Unsurprisingly, as fire severity (field) increases, the percentage of large wood with burn marks increases (Fig 4).

Basal area, a measure of recruitable LW, is another significant predictor variable. As basal area decreases, total wood volume increases (Fig 8). This regression is significant when total wood volume is log transformed ($p=0.037$ and $r^2=0.209$). Drainage area is correlated with average piece size. This regression is significant when drainage area is log transformed ($p=0.028$ and $r^2=0.23$), but significance seemed to be driven by a few outliers (Rush Creek was by far the largest stream). As drainage area increases, the average size of a LW piece increases.

Pre-fire NDVI is correlated with total wood volume. The regression is significant when total wood volume is log transformed ($p=0.050$, $r^2=0.188$). As the prefire NDVI in 1988 and 2000 increases, the total wood volume decreases (Fig 9).

Some response variables were cross-correlated but not collapsed: Total wood volume increases significantly as fraction of LW with burn marks increases ($p=0.001$, $r^2=0.431$). Total wood volume also increases significantly as average piece size increases ($p<0.0005$ and $r^2= 0.823$).

There were some notable absences of significance in the dataset. There was no significant relationship between the riparian burn severity and any of the response variables. The distribution response variables (alone, touching, jammed) yielded no apparent correlations with predictor variables.

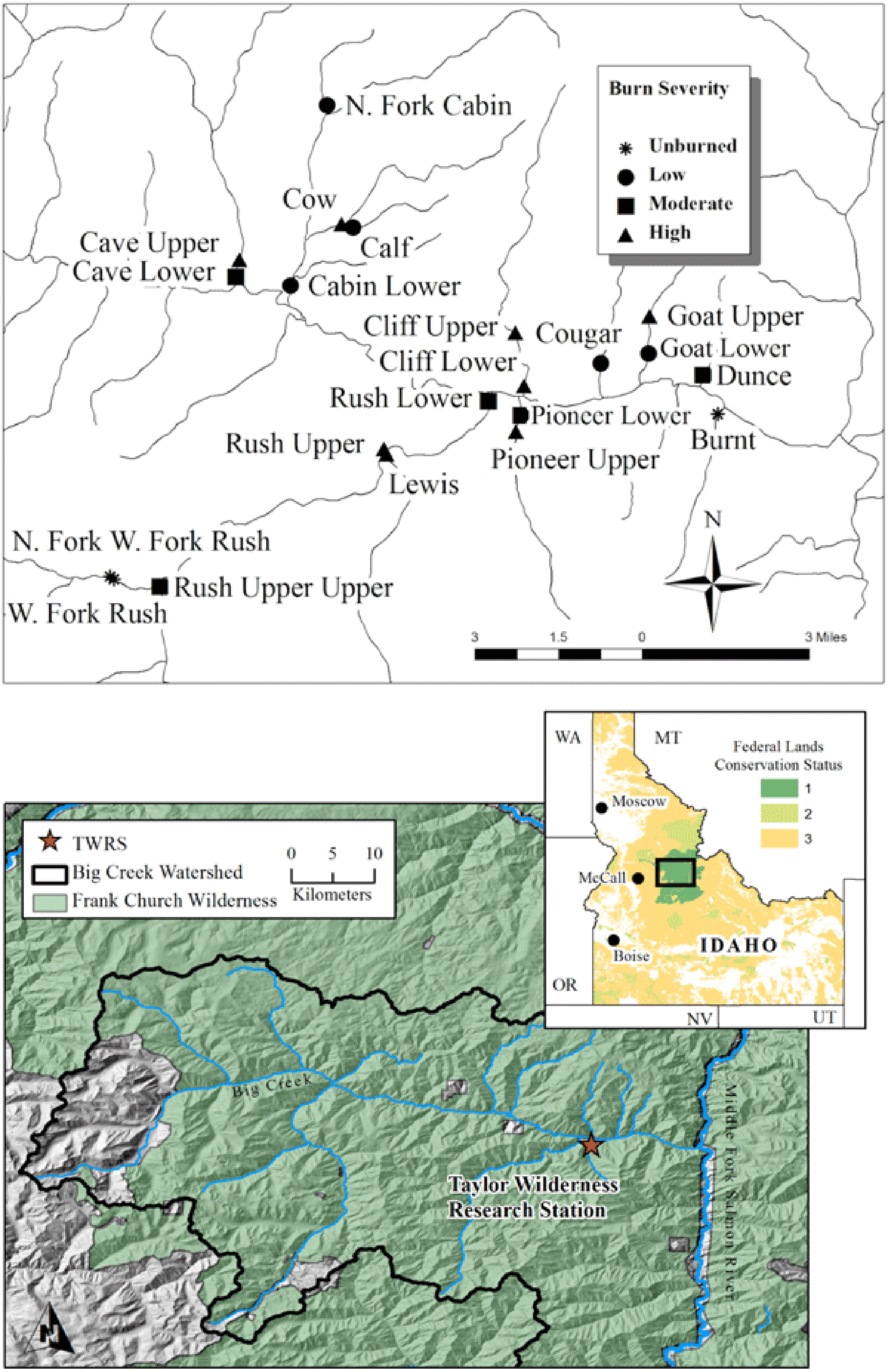

Fig 1. Map of study sites in the Frank Church-River of No Return Wilderness, Idaho.

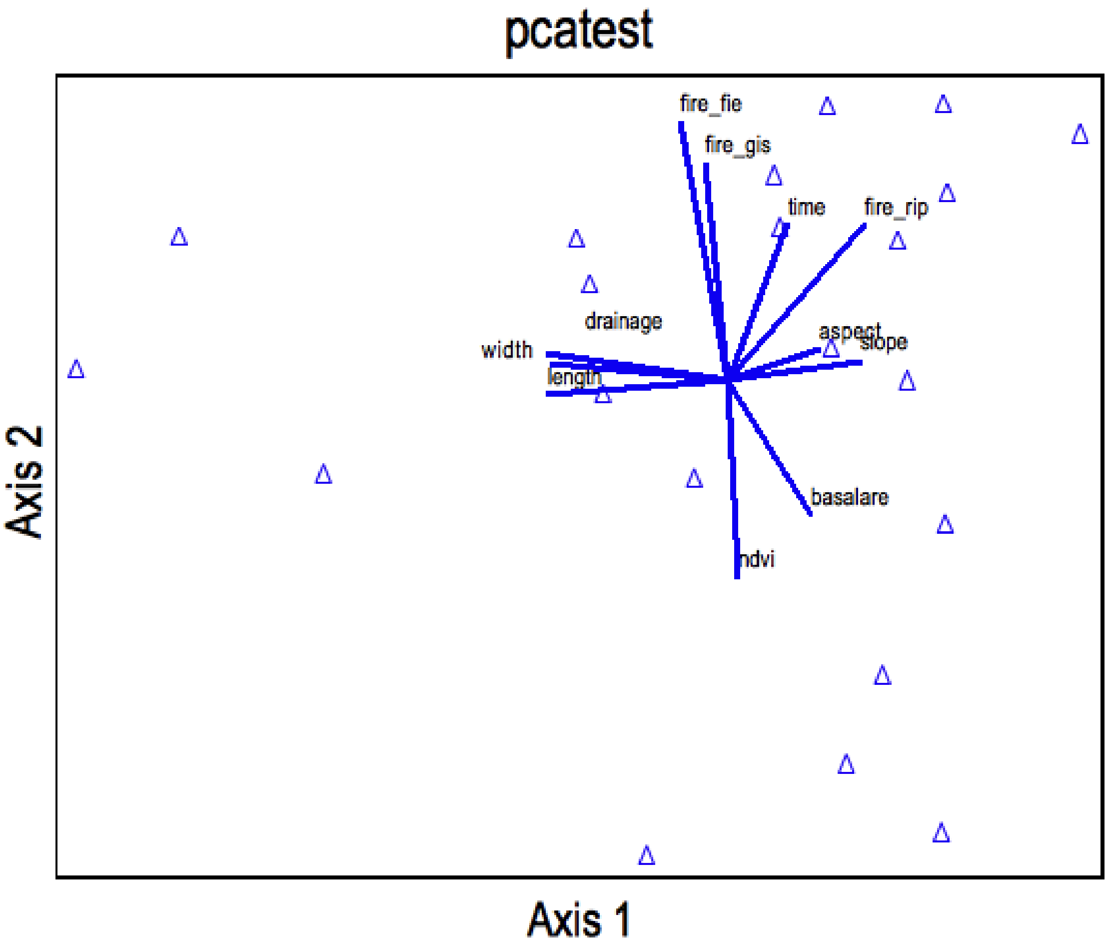

Fig 2. PCA ordination of predictor variables (lines) and field sites (triangles). Axis 1 could be interpreted as stream size, while Axis 2 could be interpreted as fire severity.

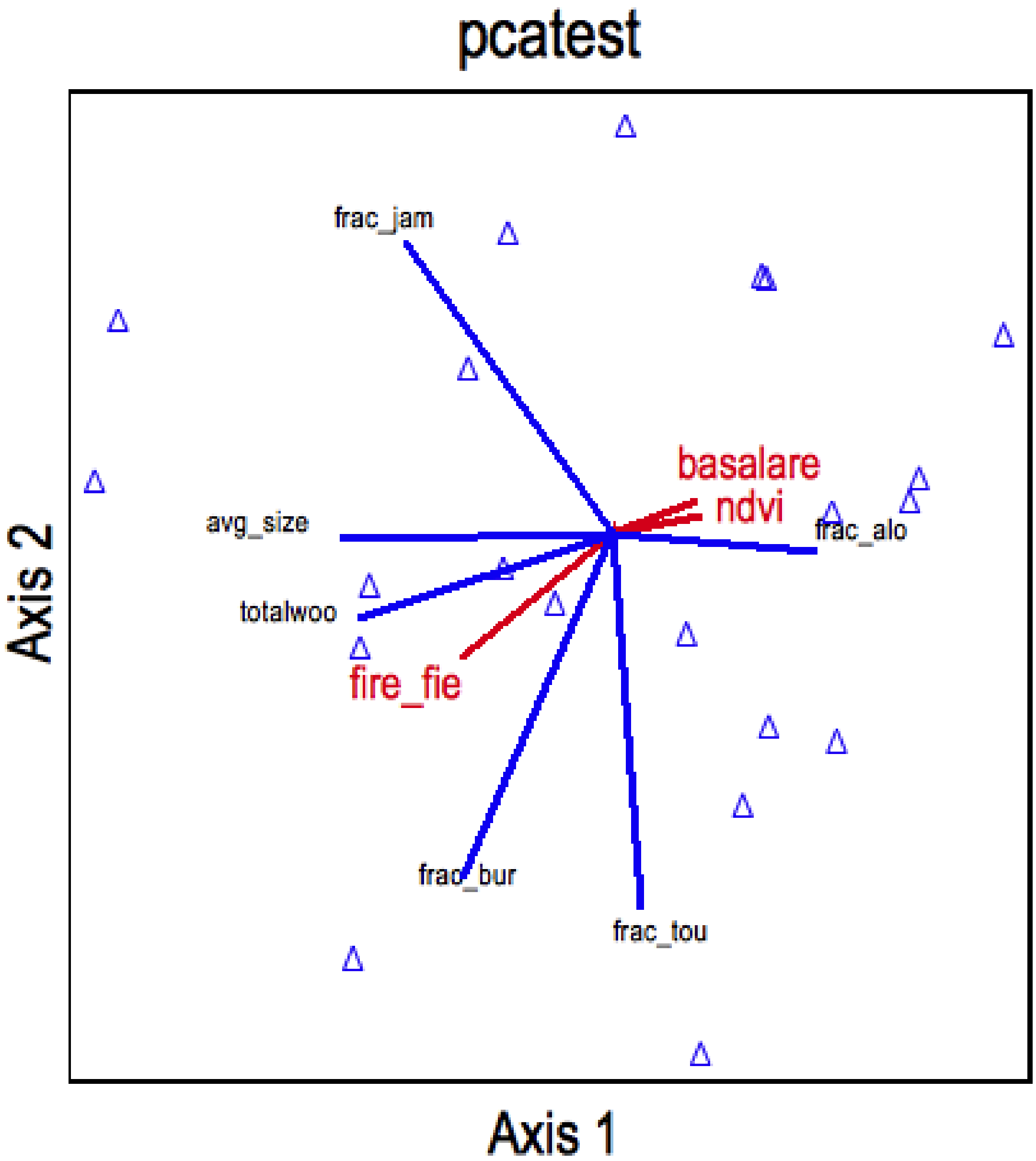

Fig 3. PCA ordination of predictor variables (blue lines) and response variables (red lines).

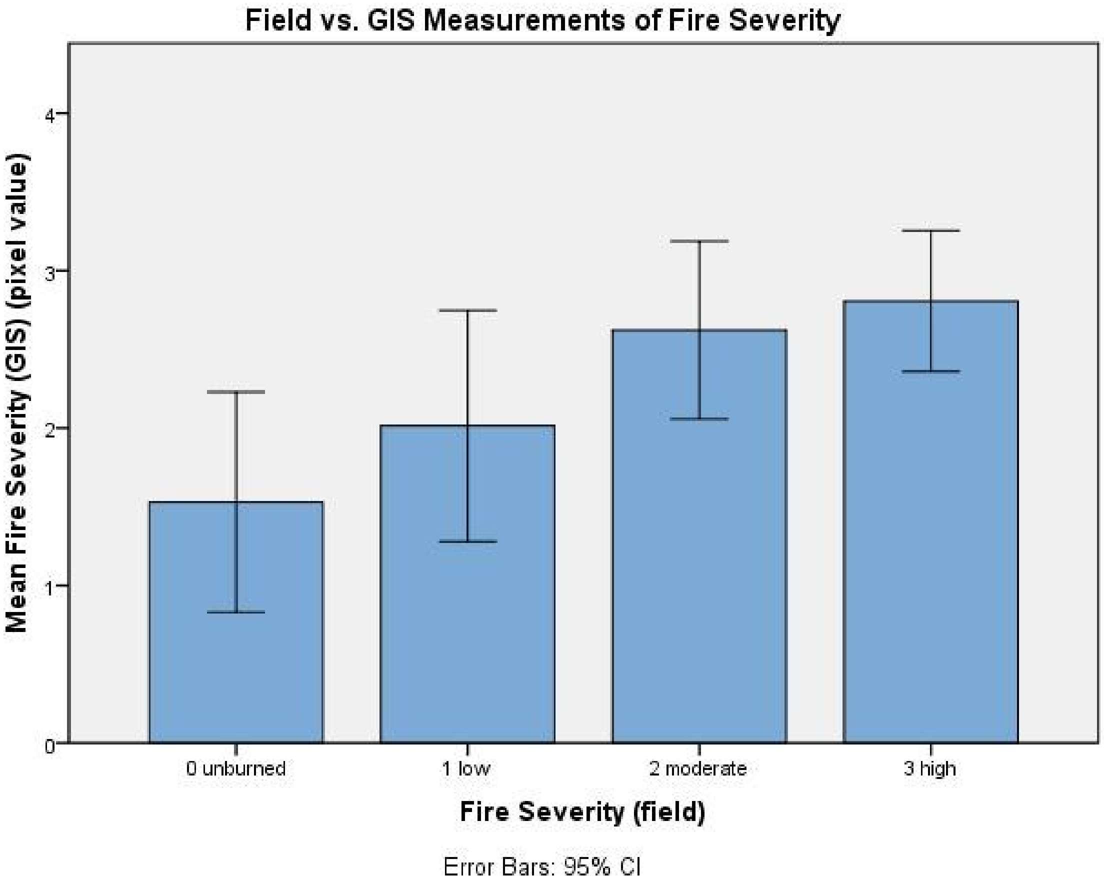

Fig 4. The fire intensity as observed in the field correlates weakly with fire intensity determined from USFS fire severity maps. Error bars represent the 95% confidence interval.

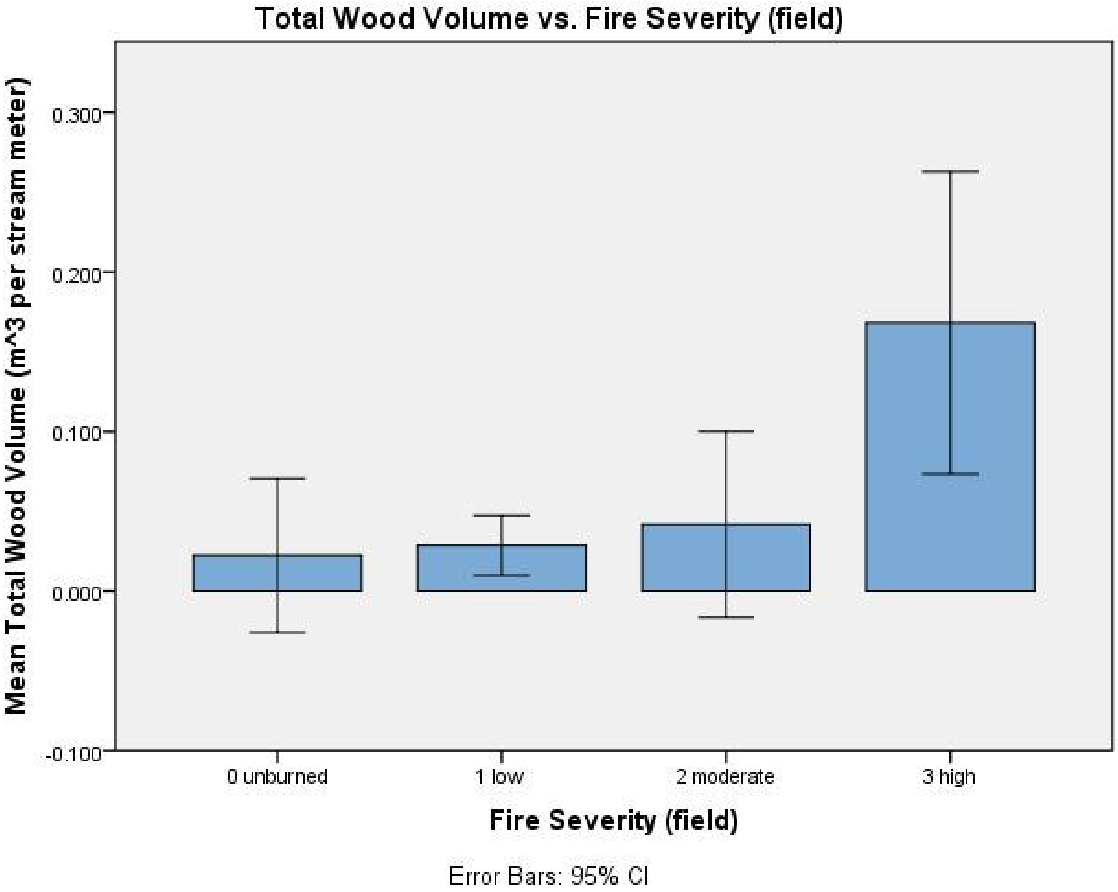

Fig 5. The total wood volume at "High" fire severity is significantly different than "Unburned," "Low," and "Moderate" severities. Error bars represent the 95% confidence interval.

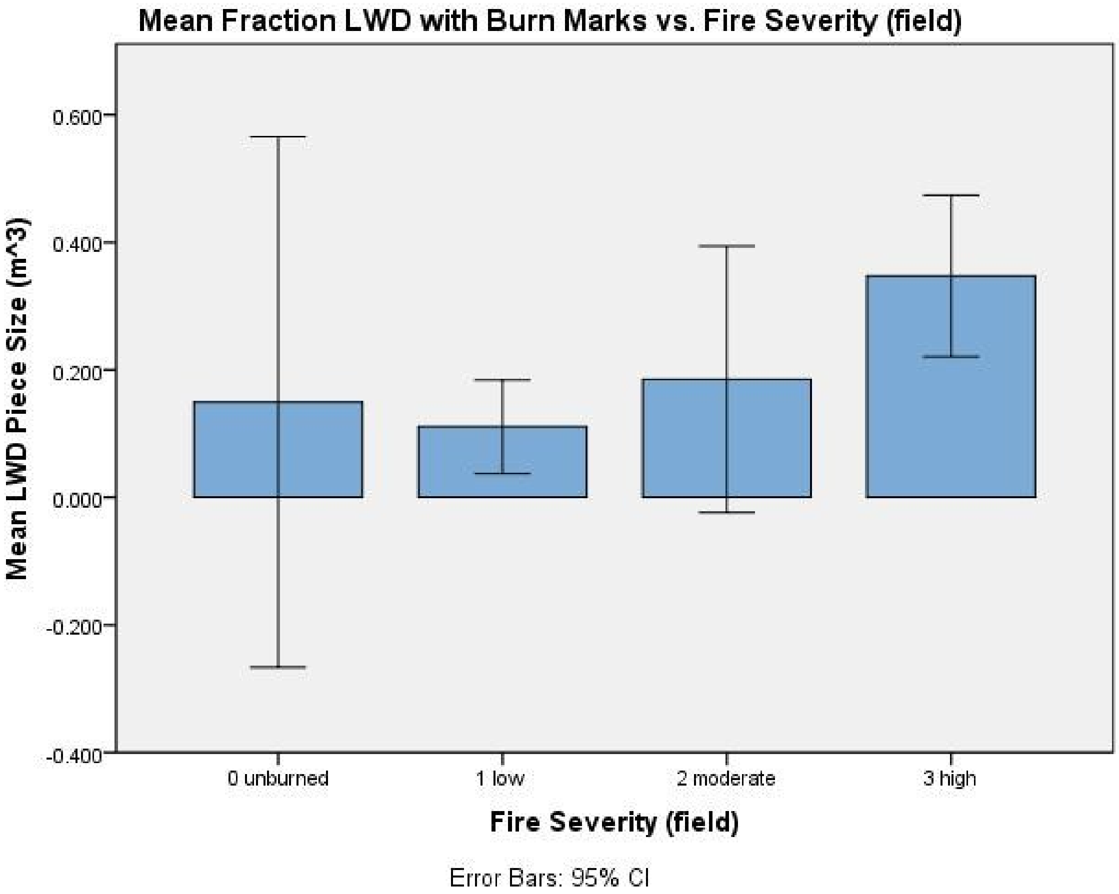

Fig 6. As fire intensity increases, the average size of a piece of LW increases.

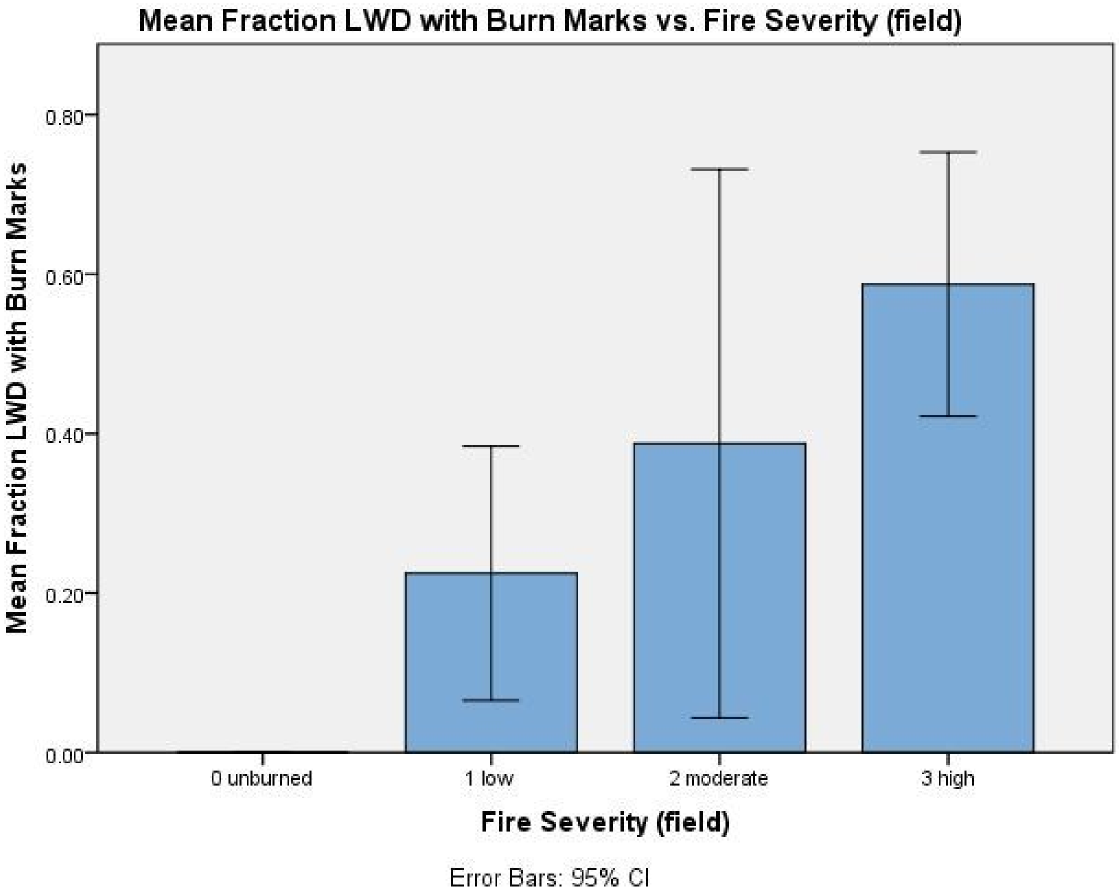

Fig 7. As fire intensity increases, the percentage of LW with burn marks increases.

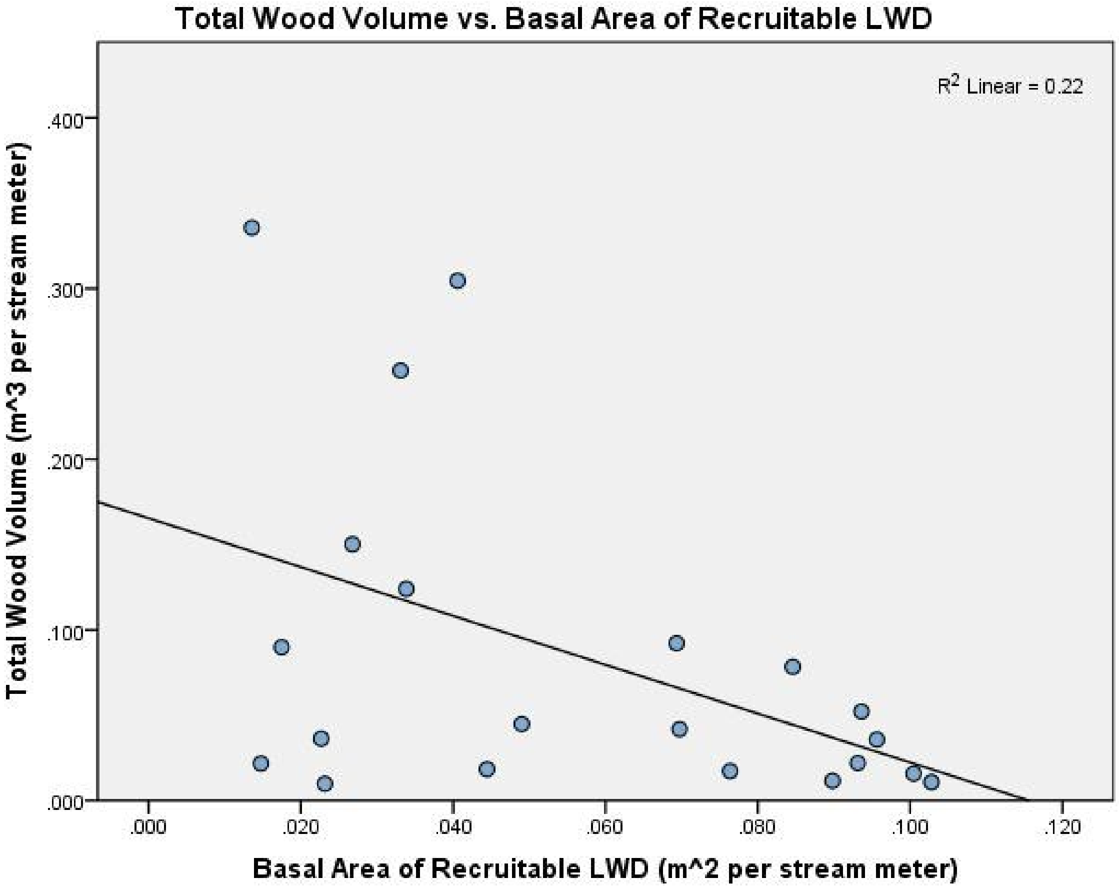

Fig 8. An increase in total wood volume is significantly but weakly correlated with a decrease in basal area.

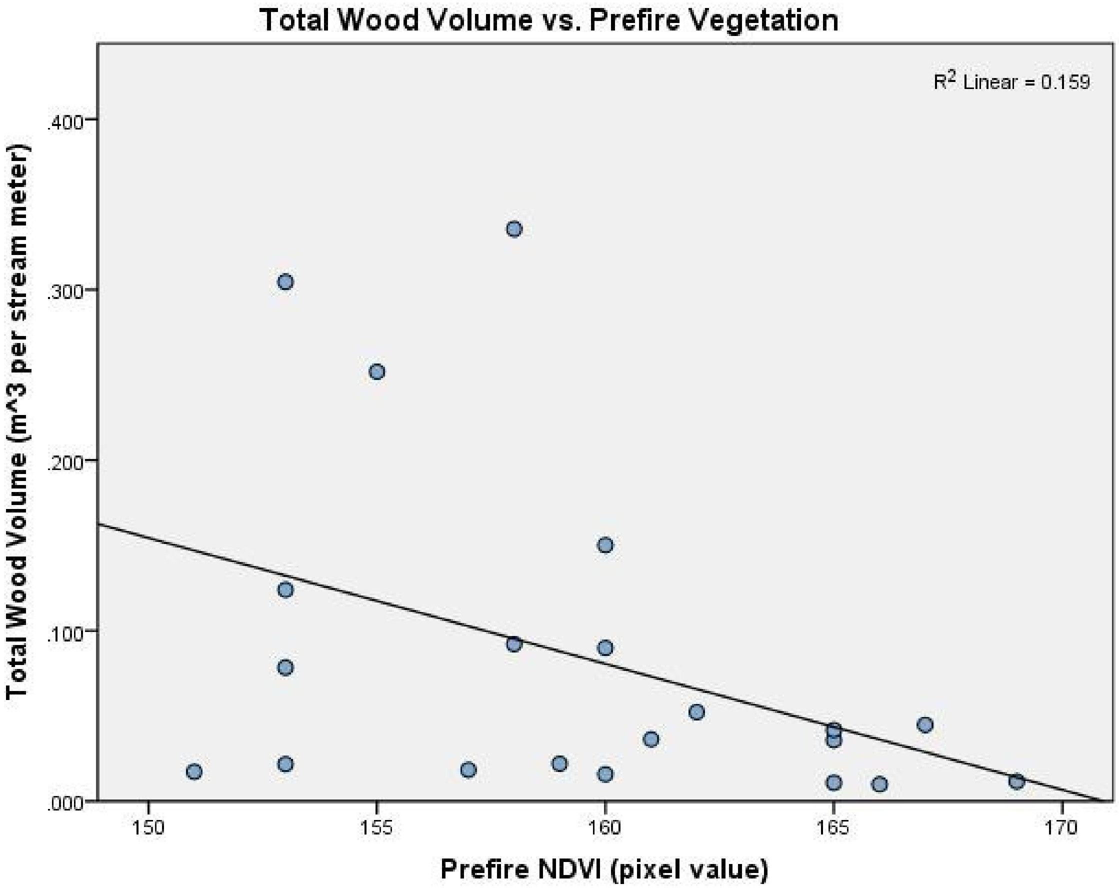

Fig 9.

As the pre-fire NDVI in 1988 and 2000 increases, the total wood volume decreases significantly.

Discussion

This study indicates that local, high severity fires have a significant effect on LW volume and average size. Benda and Sias (2003) present an equation that partially explain the theoretical importance of fire severity:

$$I_m=(B_L M H P_m)N$$

Where I_m is annual flux of LW; B_L is volume of standing live biomass per unit area; M is rate of mortality; H is the average stand height; P is the average fraction of stem length that becomes in-channel LW when a riparian tree falls; and N is 1 or 2 depending on whether one or both sides of the channel are forested (Benda and Sias 2003).

In our study, we assume that we have sampled a great enough diversity of sites that H, P, and N are not correlated with fire severity, as shown in the data structure in Figure 2. Although B_L was significantly correlated, rate of mortality (M) is the critical variable. Only the most severe fires lead to an increased rate of mortality, which will increase flux of LW and therefore the total wood volume (Figure 5). By definition of our categorization, the other fire severity categories (with half or greater canopy intact) did not encompass as much tree mortality.

In Figure 5, “high” fire severity leads to a much greater wood volume than the other severities, and is the only severity that is significantly different from the other categories. This “high” severity could be a mortality threshold that produces more LW than lower severities. Percentage of LW with burn marks could also be a proxy of fire severity, and an increase in LW with burn marks is correlated with an increase in total wood volume. Fire intensity also increases piece size (Figure 6), which could be even more important than total wood volume.

Larger pieces of LW have a significant effect on channel morphology, as the jam structures they create are less likely to wash away than structures created from smaller pieces (Zelt 2004). However, we observed many of these fire-killed trees tend to bridge smaller streambeds rather than alter flows within the wetted perimeter; Robinson (2003) noted the same thing in 3rd order streams.

The effects of fire were only observed at a local scale, however. Basal area decreased as wood volume increased (Figure 8), indicating that snags directly adjacent to stream reaches were the primary LW input. This is due to the fact that our reaches were lower order and most lacked the capacity to transport larger pieces of wood (Minshall 1989). Also, burn marks were absent in unburned reaches, indicating that those streams were not transporting LW from upstream burns. Burn marks were correlated fairly well with local, not riparian, fire severity.

The final significant predictor variable was NDVI. The equation above predicts that as volume of biomass (B_L) increases, LW flux will increase. Assuming that NDVI is a good measure of recruitable LW, Figure 9 indicates the opposite; LW decreases as pre-fire NDVI increases. Although this is a statistically significant, it is probably not a good predictor variable. There could be a correlation between NDVI and fire severity (more fires in drier, low NDVI areas, for example). Also, NDVI might not be representative of recruitable LW, because it is a measure of greenness; it might show vegetation too small to become LW.

The riparian fire intensity upstream did not have a significant effect on LW in the stream reaches. This is probably due to a lack of stream transport power as well as the nature of the GIS analysis. The scale we used in the field (tens of meters of stream length) may not be compatible with GIS mapping ($30m^2$ pixels). This could also explain why the local fire severity measured in the field was not correlated better with local severity measured in GIS. GIS is a powerful tool for watershed-scale analyses and visually examining fire history, but for this study the field measurements of fire severity are probably more accurate.

None of the LW distribution response variables (alone, touching, jammed) were conclusively related to any predictor variables. This could be because LW distribution, unlike volume and size, is more related to local stream geomorphology than local burn severity. We observed that there were fewer jams on smaller streams, but the data did not reveal any obvious pattern.

Time is a critical variable in predicting LW, as models have shown (Bragg 2000, Benda and Sias 2003). Our "time" variable was inconclusive, however. This could be because our sites were sampled after different fires, some having burned multiple times, so the effects of time since fire covaried with other more apparent factors. It is also possible that our time scale was too short to see pronounced changes; Bragg (2000) predicts peak LW loads about 30 years after a disturbance; our average year since fire was only 9.1 years. Pilliod (2008) found no change from 2002-2006 in LW levels in nearby streams in the Frank Church Wilderness.

Management Implications

Any kind of tree removal is detrimental to LW levels in smaller streams; Murphy (1989) recommends no less than a 30m untouched riparian buffer zone to ensure that natural levels of LW are maintained. Harvesting fire-killed snags will be most detrimental in "high" severity burned riparian areas, because these high severity fires, unlike lower severities, are the kind of disturbance that is large enough to create LW structures. Post-fire salvage logging will also have effects for decades into the future, as models show (Bragg 2000). This type of logging usually targets the largest trees, which could reduce the efficacy of LW for biological habitat (Karr

2004). Salmonid populations have been observed to rebound quickly from fires, partially due to favorable habitat created from LW inputs (Reeves 2006). Removing the largest snags would also change the natural pattern we observed of fire increasing piece size. Stream channel width often increases after a fire, making LW more mobile (Zelt 2004), so the largest pieces of LW are especially important in anchoring wood structures.

Our research could enhance LW models and provide a more nuanced understanding of how heterogeneous fires affect aquatic habitat. A “more holistic practice” of management and ecosystem restoration is often more urgent than fire prevention or post-fire restoration (Minshall 2003), This type of management moves beyond superficial “solutions” to consider and be consistent with natural patterns of LW transport in aquatic ecosystems (Bisson 2003). Managers often remove “excess” wood from streams; Benda (2003) describes removal of large post-fire wood jams to protect a downstream bridge, and wood is often removed in larger streams for navigation or aesthetic purposes. In keeping with natural processes, managers should never remove LW from a stream unless there is a public safety hazard. Also, following a fire, enough burnt snags should be left in the riparian corridor to allow recruitment of LW (Murphy 1989). Ideally, managers should try to emulate the fire regimes of the 19th century and earlier (Karr 2004), which create the occasional high severity fires that are large enough disturbances to put LW in streams. If fire is suppressed, snags removed, or wood is taken directly out of the stream, the consequences could be grave for aquatic species that have evolved to thrive in a less impacted environment.

Limitations and Further Research

This study was only conducted over one season and in only 21 reaches; a better measure of wildfire disturbance would include more streams and a wider variety of "time since burn" sampled. This study was also conducted entirely in the wilderness; disturbance in managed forests could behave differently (Benda 2003). Trees are likely to be the same age and height in a forest managed for timber harvest, for example, which might change the dynamics of a high severity fire. There are often fewer large trees in logged forests; this may reduce the difference in total wood volume and average piece size between levels of fire severity.

Fires are not necessarily "good" or "bad;" they cause a variety of impacts that can be contradictory in managing for a particular goal (Rieman 2010, Benda 2003). Burton, for example, notes that salmonid populations decreased immediately following a severe fire/debris flow, but recovered several years later along with rejuvenated habitat (Burton 2005). The effects of fire severity on LW need to be considered along with myriad other effects of fire on terrestrial and aquatic ecosystems. We hope that the results of this research can be used to improve geomorphic models and aid managers in stream restoration by better understanding LW dynamics after a fire. Long term monitoring programs of salvage logging are necessary, because such programs are currently missing (Reeves 2006).

Conclusions

The data presented here can be used to both increase knowledge of geomorphic processes and inform management decisions on more impacted aquatic ecosystems. Bisson et al. (2003) describe priorities in aquatic conservation; some of the highest priorities are watersheds where "threat of large fire is high" and "local populations of sensitive aquatic species are at risk." Much of central Idaho is at risk for high severity fires, and there are many endangered species such as wild Chinook salmon populations. Climate change is predicted to increase the frequency and duration of severe wildfires as earlier spring runoff increases the fire season (Westerling 2006). By understanding LW dynamics, managers might be able to mitigate the effects of land-use change and better prepare stream ecosystems for a changing climate.

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