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Environmental Remediation Technologies, Regulations and Safety

Riparian Zones

Protection, Restoration and Ecological Benefits

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FIRE REGIMES, STAND STRUCTURE, FUEL LOADS, AND FIRE BEHAVIOR IN RIPARIAN AND UPLAND FORESTS, SIERRA NEVADA MOUNTAINS, USA

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ABSTRACT

Fire once played an important role in shaping many Sierran coniferous forests, but reduced fire frequency and extent have altered forest conditions. Productive, mesic riparian forests can accumulate high stem densities and fuel loads, making them susceptible to high-severity fire. Fuels treatments applied to upland forests, however, are often excluded from riparian areas due to concerns about degrading forest habitat and water quality. Objectives of this study were to compare fire frequency and seasonality, stand structure, fuel loads, and potential fire behavior between adjacent riparian and upland forests under current and reconstructed conditions. Dendrochronological fire records, current fuel loads, tree diameters, heights, and height to live crown were measured in 36 pairs of riparian and upland plots. Historic estimates of stand structure and fuel loads were reconstructed using equations derived from fuel accumulation rates, current tree data, and increment cores. Fire behavior variables were modeled using Forest Vegetation Simulator Fire/Fuels Extension.

Under a liberal filter, riparian fire return intervals (FRIs) ranged from 8.4 to 42.3 years (mean 16.6), while upland FRIs ranged from 6.1 to 58.0 years (mean 16.9). Riparian and upland FRIs were significantly different in only 1/4 of the sites sampled. Riparian and upland areas did not burn with different seasonalities, and fire events occurred primarily during the late summer-early fall dormant season. FRIs were shorter in forests with a higher proportion of fire-tolerant pine, sites east of the Sierra crest, lower

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elevation sites, and riparian zones bordering narrower, more incised streams. Upland areas exhibited a greater degree of fire-climate synchrony than riparian areas.

Riparian and upland forests were significantly more fire prone under current than reconstructed conditions, with greater basal area, stand density, snag volume, duff loads, total fuel loads, canopy bulk density, surface and crown flame lengths, probability of torching, predicted mortality, and lower torching and crowning indices. Under current conditions, riparian forests were significantly more fire prone than upland forests, with greater stand density, probability of torching, predicted mortality, and lower quadratic mean diameter, canopy base height, and frequency of fire tolerant species. Reconstruction methods found historic riparian and upland forest conditions were not significantly different. Our reconstruction results suggest that historic FRIs, fuels and forest structure may not have differed significantly between many riparian and upland forests. Under current conditions, however, modeled severity is much greater in riparian forests, suggesting habitat and ecosystem function may be more severely impacted by wildfire than in upland forests. Our results emphasize the need for managers to prioritize fuels reduction treatments in Sierra Nevada riparian forests.

1. INTRODUCTION

Fire plays an important role in shaping stand structure, species composition, and fuel loads in many Sierran coniferous forest types. However, longer fire return intervals and reductions in annual area burned caused by fire suppression and changes in climate and grazing practices have altered forest conditions (Anderson and Moratto, 1996; Douglass and Bilbao, 1975; Dwire and Kauffman, 2003; Pyne, 1982; Skinner and Chang, 1996; Stephens et al., 2007). High densities of small trees and increased fuel loads are now present in many productive forest types that were historically maintained by frequent low- to moderate-intensity fires, resulting in increased risk of high-intensity fire (McKelvey and Busse, 1996; Stephens and Moghaddas, 2005). Development in wildland-urban interface areas with high fuel loads continues at an increasing rate, spurring land managers to suppress most wildfires despite policies that encourage reintroduction of fire as an ecosystem process (Jensen and McPherson, 2008).

Although fuel reduction is accomplished in strategic areas using treatments such as mechanical thinning and prescribed burning, treatment has historically been limited or excluded from riparian areas (FEMAT, 1993; UDSA, 2004; McCaffery et al., 2008; Safford et al., 2009). While active management of fuels in riparian areas is becoming increasingly common (Stone et al., 2010), there is a lack of riparian stand structure and fuel load data that could support the perceived need for riparian fuels management. Riparian forests are often very productive due to greater moisture availability and have accumulated high stem densities and fuel loads, making them susceptible to high-severity fire and subsequent stream channel erosion, loss of wildlife habitat, and decreased ecosystem function (Camp et al., 1997; Olson and Agee, 2005; Segura and Snook, 1992; Skinner and Chang, 1996). High fuel loads and stem densities in riparian forests may allow them to act as a wick for high-intensity fire through a landscape of treated upland forest (e.g. the 2007 Angora Fire in the Tahoe Basin) under some conditions (Murphy et al., 2007; Pettit and Naiman, 2007). Although riparian areas are characterized by lower temperatures and higher humidity (Rambo and North 2008, 2009) than adjacent upland areas, which may slow fire spread through the landscape under non-drought conditions (Skinner and Chang, 1996), they often burn at similar frequencies and may even propagate fire through the upland matrix during extreme weather conditions (Agee, 1998; Dwire and Kauffman, 2003; Pettit and Naiman, 2007). Despite increasing recognition of the importance of fire in some riparian forests, few studies have attempted to reconstruct historic riparian stand structure and fuel loads in the context of an active fire regime (Poage, 1994). Assessing the relationship between current and historic fire regimes, stand structure and fuel loads in adjacent riparian and upland forests could be useful in guiding efforts to restore forest ecosystems altered by fire exclusion and past timber harvesting.

Objectives of this study were to determine whether adjacent coniferous riparian and upland forests historically burned with different frequencies and seasonalities, whether the relationship varied by forest, site and stream characteristics, whether fire synchrony with climate conditions differed between riparian and upland forests, whether current riparian and upland forests have different stand structure, fuel loads, and potential fire behavior than historic riparian and upland forests, and whether riparian forests currently or historically had different stand structure, fuel loads, and potential fire behavior than upland forests. Because few studies of the linkages between fire and riparian stand dynamics have been conducted, additional objectives were to explore the relationships between historic stand conditions and fire regimes, as well as between riparian and upland forests under current versus historic conditions.

We hypothesized that: (1) riparian areas would have longer fire return intervals than adjacent upland forests; (2) riparian areas would have a lower proportion of non-dormant season fires than adjacent upland areas; (3) riparian and upland fire return intervals would be shorter in sites with a greater percentage of the species composition comprised of fire-tolerant pine; (4) riparian and upland fire return intervals would be longer in higher-precipitation (west side) forests than in lower-precipitation (east side) forests; (5) riparian and upland fire return intervals would be shorter in sites with steeper slope, south-facing aspect, and lower elevation; (6) riparian fire return intervals would be longer in sites with a broad channel shape, a perennial flow regime, and greater stream channel width, depth, width to depth ratio, and lower gradient; (7) riparian forests would show greater synchrony between fire events and extreme drought conditions than upland forests; (8) both riparian and upland forests would show a reduction in fire return interval after Euro-American settlement; (9) current riparian and upland stands would have stand structure and fuel loads more conducive to high-intensity fire than reconstructed riparian and upland stands; (10) current riparian stands would have stand structure and fuel loads more conducive to high-intensity fire than current upland stands; and (11) reconstructed riparian stands would have stand structure, fuel loads and potential fire behavior similar to reconstructed upland stands. Attributes suggesting that a stand is conducive to high-intensity fire include high basal area, stand density, snag volume, fuel loads, flame length, probability of torching, canopy bulk density, and potential mortality, and low quadratic mean diameter, canopy base height, fire-tolerant species composition, torching index, and crowning index. Additionally, we investigated the correlation between: (a) fire return intervals and reconstructed stand structure, fuel loads, and predicted fire behavior in riparian and upland forests; and (b) riparian and upland stand structure, fuel loads, and predicted fire behavior under current and reconstructed conditions.

2. METHODS

2.1 Study area and Site Selection

Sampling occurred in four areas of the northern Sierra Nevada: the Almanor Ranger District of the Lassen National Forest (15 sites), the Onion Creek Experimental Forest (4 sites), and the east and west sides of Lake Tahoe Basin (6 and 11 sites, respectively) (Figure 1).

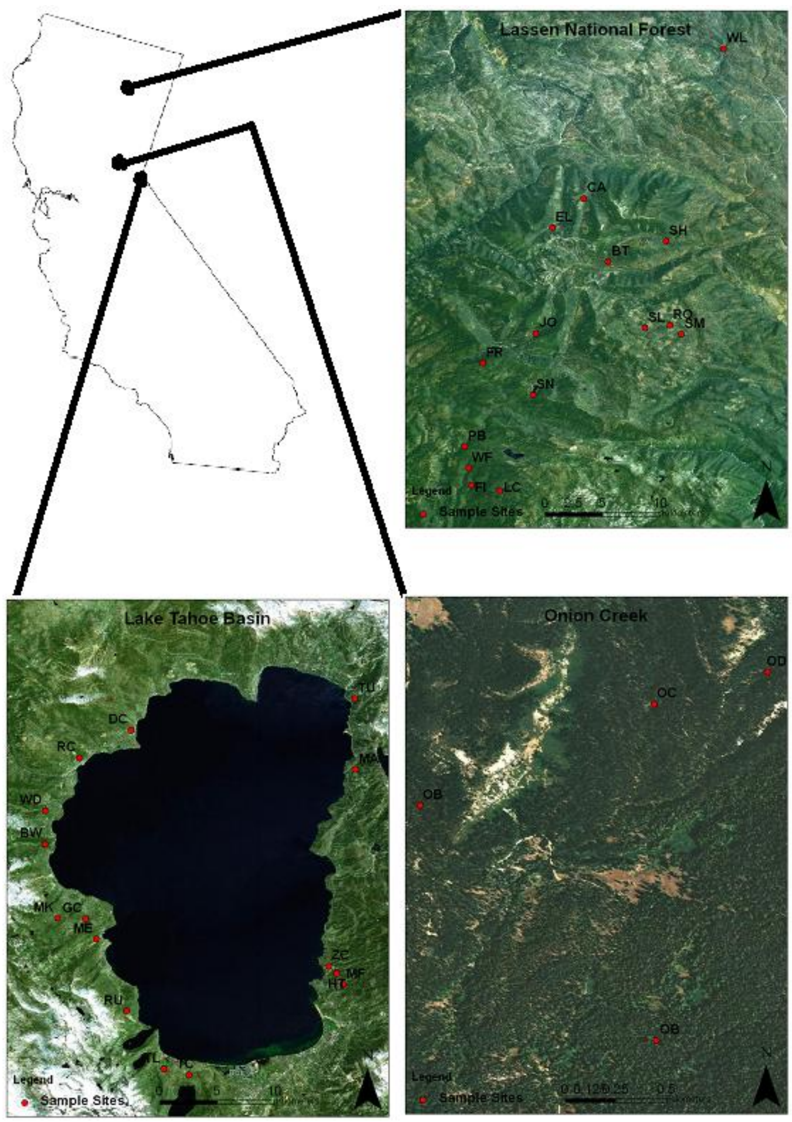

Figure 1. Location of the four sample areas in California (upper left), and of sample sites within each area.

Elevations ranged from 1519 m at Philbrook Creek on the Lassen National Forest to 2158 m at Tunnel Creek in the Lake Tahoe Basin. Longitudes ranged from 119º 55' W to 121º 30' W, and latitudes ranged from 38º 55' N to 40º 20' N. Most precipitation occurs during the winter as snow, and average annual totals (data from 1903 to 2009) varied from 460 mm on the east side of the Lake Tahoe Basin to 1340 mm on the Lassen National Forest (Beaty and Taylor, 2001; DRI, 2009). Forest composition varies widely with elevation, aspect and precipitation, and includes white fir (*Abies concolor*), red fir (*Abies magnifica*), Jeffrey pine (*Pinus jeffreyi*), ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), lodgepole pine (*Pinus contorta ssp. murrayana*), western white pine (*Pinus monticola*), incense-cedar (*Calocedrus decurrens*), Douglas-fir (*Pseudotsuga menziesii*), black oak (*Quercus kelloggii*), quaking aspen (*Populus tremuloides*), black cottonwood (*Populus balsamifera ssp. trichocarpa*), mountain alder (*Alnus incana ssp. tenuifolia*), and willow (*Salix spp.*) in varying proportions. Jeffrey pine or ponderosa pine typically dominate on drier sites and south-facing slopes, while white fir or red fir typically dominate on wetter sites and north-facing slopes. Sampling was confined to Sierra Nevada forest types that were historically characterized by frequent (<30 year), low- to mixed-severity fire regimes.

Anthropogenic influence in all sampling areas has likely had a profound effect on stand structure and fuel loads. The Washoe Indians and their ancestors have inhabited the Lake Tahoe Basin for the last 8000 to 9000 years, and may have used fire to improve accessibility, wildlife habitat, hunting, and plant material quality. Major Euro-American settlement of the Tahoe Basin began when the first pack trail into the basin was completed in the 1850s. Logging began on the south shore of Lake Tahoe in 1859, and numerous settlements were established in the 1860s. Much of the Lake Tahoe Basin was heavily logged from the 1860s to 1890s to support the mining of Nevada's Comstock Lode. Accumulation of logging slash and introduction of new ignition sources such as sawmills, railroads, and logging equipment likely influenced fire frequency, residual stand structure, and fuel loads during this era (Lindstrom et al., 2000).

The Almanor Ranger District of the Lassen National Forest is located in Plumas County, which was also extensively logged beginning with the opening of the first sawmill in 1851 (Lawson and Elliot, 2008). The Onion Creek Experimental Forest was subject to considerably less human influence than the Tahoe Basin and Lassen areas, with only 20% of the area logged in the early 1900's (Berg, 1990). Because logging likely removed many of the larger trees with the longest tree ring records, sampling was concentrated on remnant late successional forest patches that would facilitate the best reconstruction of historic stand conditions.

Potential sites were identified by first consulting US Forest Service maps of late successional forest patches likely to contain a long fire record. Potential sites were then scouted to determine the prevalence of numerous fire-scarred trees, stumps, and logs. Sample sites were non-randomly chosen to provide a long record of fire history and to represent the variability of forest types and riparian area characteristics present in Sierra Nevada forests influenced by fire exclusion. Sites in some forest types and riparian zone width classes were greatly limited by fire scar availability, and sites with east side precipitation regimes were only available in the Lake Tahoe Basin sampling area (with the exception of Warner Creek in the Lassen National Forest sampling area). We found fifteen sites with Jeffrey pine forest type, seventeen sites with mixed-conifer forest type, and four sites with white fir forest type;

twenty-nine sites with west side precipitation regimes, and seven sites with east side precipitation regimes.

Within these sample sites, plot locations were randomly selected for both the riparian and upland areas, with the stipulation that upland sites were located on the same side of the stream from which most historical fires likely approached, given local topography and regional wind patterns. This ensured that the effects of fire on stand structure and fuel loads measured in upland forests were not influenced by riparian microclimates. The riparian zone was determined by a combination of stream channel incision and understory plant community composition (i.e. riparian indicator species that were common throughout the study area, such as *Rubus parviflorus, Pteridium aquilinum, Alnus incana spp. tenuifolia, Salix spp.*). Riparian zone widths varied from 7 m on narrow ephemeral headwater streams to 420 m on wide alluvial flats of large perennial streams.

2.2 Plot-Level Data Collection

At each site, fire-scarred trees, stumps and logs were scouted and catalogued along both sides of an approximately 2 km length of stream with late-successional forest characteristics as identified on US Forest Service maps. During sampling, collection priority was given to specimens with a large number of fire events recorded (Swetnam and Baisan, 2003), large trees likely to have a long tree ring record, and dead material such as snags, stumps and logs with the least rotten wood. Full cross sections were obtained when possible from dead material, while partial cross sections were obtained from live trees in order to cause the least structural damage (Arno and Sneck, 1977). Eighteen to thirty-two specimens were collected at each site, taking roughly half from the upland area and half from the riparian area. For comparison, upland sample sites were selected ranging from 50 to 300 m from riparian sample sites, in the same forest community. Riparian and upland samples were collected over similar sized areas (within 20%). Forest, site and stream characteristics were recorded at each site, including forest type, percent species composition by basal area occupied by fire tolerant pine species (Jeffrey, ponderosa and sugar pine), precipitation regime (wet west side vs. dry east side), elevation, slope, aspect, stream order, riparian zone width, flow regime (perennial vs. intermittent), and channel bankfull width, depth, width to depth ratio, gradient, and approximate shape. We defined first order streams as the smallest streams visible on standard USGS 7.5 minute topographic maps, second order streams as those formed by the junction of two first order streams, etc. (Strahler, 1952).

Forest structure, species composition, and fuel loads were measured in each of the 36 adjacent riparian and upland sites (72 plots total). Paired riparian and upland plots were each randomly placed in the general locations where fire scar samples had been collected for analysis of fire history. Riparian plots were placed parallel to the channel with the streamside edge located at the bankfull stage, defined as the highest position on the stream bank reached by flows of a 1.5 year recurrence interval, and often identifiable by a change in bank steepness and vegetation composition (Dunne and Leopold 1978). Upland plots were generally located 50 to 300 m away in the same watershed and forest type to ensure adequate pairing with corresponding riparian plots. Plots were rectangular, with a 0.05 ha plot (25 m long by 20 m wide) nested inside a 0.1 ha plot (50 m long by 20 m wide). Where riparian zones were less than 20 m wide on each side of the channel, riparian plot dimensions were adjusted accordingly to ensure accommodation of the entire plot area within the riparian zone.

Species, structure type (live, snag, log, stump), diameter at breast height (DBH), total height, and height to the first live branch were measured for all structures larger than 5 cm DBH within a 0.05 ha rectangular plot, and for all trees larger than 50 cm DBH within a 0.1 ha rectangular plot. Snags were defined as any standing dead trees greater than 1.3 m in height that were not in full contact with the ground, logs were defined as any fallen trees in full contact with the ground and attached to a root wad originating within the plot, and stumps were defined to be less than 1.3 m in height. Additionally, between 7 and 22 trees of representative diameter classes and species were cored to the pith at soil height within each plot to aid in stand reconstruction. Representative diameter classes varied with the range of diameters present at each site, but generally consisted of trees 20-50 cm, 50-80 cm, and >80 cm DBH. Surface fuel loads (dead and down woody material, litter and duff) were measured along 3 transects at each plot using Brown's planar intercept method (Brown, 1974). Shrub cover by species and canopy cover were measured along two 50 m transects along the sides of each plot, and seedling species and height were recorded in ten 1 m^2 plots located at 10 m intervals along the same transects.

2.3 Reconstruction Methods

The reconstruction period for each plot was set at the year of the last fire at that site, which ranged from 1848 to 1990 as determined from site-specific fire scar records, with 64% of the periods before 1940. Mean (standard deviation) reconstruction periods for the Lassen, Onion Creek, east and west Tahoe sampling areas were 80 (41), 116 (13), 98 (39), and 78 (42) years before 2009 for riparian plots, and 72 (35), 104 (39), 92 (32), and 91 (40) years before 2009 for upland plots. Historical stand structure at the time of the last fire was reconstructed for each riparian and upland plot following methods commonly used in southwestern ponderosa pine forests, in which the DBH, total height, and height to the first live branch of live trees during the reconstruction period are estimated from measurements of current live trees, snags, logs, and stumps (Fulé et al., 1997; Mast et al., 1999; Moore et al., 2004).

These reconstruction methods were adapted to accommodate the presence of both shade-intolerant and shade-tolerant species in Sierra Nevada mixed-conifer forest types. Because the cores taken from each plot (761 total) provided a sample proportional to the current species composition, the most frequent shade-tolerant species such as white fir, incense-cedar, and red fir comprised the majority of the sample. This favored representation of the greater variability in annual radial increment commonly exhibited in shade-tolerant species (Oliver and Larson, 1996). The 761 cores were sanded with 400 grit sandpaper to allow accurate visual identification of tree ring boundaries, and were manually cross-dated using standard procedures (Stokes and Smiley, 1968).

For trees with stem rot or large diameter that could not be cored to the pith (26% of all cores taken), methods following Scholl and Taylor (2010) were used to determine the ages of trees with incomplete cores. Regressions between DBH and core length inside bark were developed for each species from complete cores. All regressions were significant (p values ranging from <0.001 to 0.016) with r^2 values ranging from 0.477 to 0.876. For incomplete cores, actual core length was subtracted from predicted core length to determine the missing length. For cores in which the predicted length was less than the actual length, the actual length was used as the closest approximation for the total core length (Scholl and Taylor, 2010). From the complete cores, the average number of rings per centimeter for each species was determined from the width of the first five years' growth. The number of rings per centimeter was multiplied by the missing length of incomplete cores to determine the number of missing years from the end of the core to the pith. Tree age was then estimated by adding the missing years to the incomplete core age.

2.3.1 Live Tree Reconstruction

To reconstruct the historic size of current live trees measured in each plot, species-specific equations were used to predict current DBH inside bark from current DBH outside bark (Dolph, 1981). Reconstructed DBH inside bark (at the time of the last fire in each site) was estimated using mean annual radial increment calculations for each species developed from regression equations predicting DBH inside bark from tree age using data from the cores. Regressions equations for each species were applied to trees of that species in all four sampling areas. All regressions were significant ($p<0.001$), with r^2 values ranging from 0.872 to 0.984. Reconstructed DBH outside bark was then estimated using the equations in Dolph (1981).

Reconstructed total tree height and height to the first live branch were estimated using regression equations (developed from current tree data) for each species predicting those variables from DBH. Although trees under historical conditions of low stand density likely had crown structure different from that observed under current conditions, historical crown structure data sufficient for developing regression equations was unavailable. All regressions were significant (p values <0.001 for height equations, and ranging from <0.001 to 0.050 for height to first live branch equations), with r^2 values ranging from 0.870 to 0.991 for height, and 0.501 to 0.861 for height to first live branch. Reconstructed stand-level characteristics were then calculated from the reconstructed DBH, total height, and height to the first live branch of live trees (Table 2).

2.3.2 Snag and Stump Reconstruction

Reconstructing the status and size of snags, logs, and stumps at the time of the last fire from increment cores is often not feasible because the extensive rot present in many structures makes determining the year of death impossible. Year of tree death for snags in each plot was estimated from a field rating of decay class and species-specific equations predicting decay class transition times (Morrison and Raphael, 1993; Raphael and Morrison, 1987). The live tree equations were then applied to reconstruct tree size at the time of the last fire for snags that died after the reconstruction year. Reconstructed snag volume was calculated from snag DBH using published species-specific volume equations (Table 2) (Wensel and Olson 1995). The year of stump death was determined from field observations of stump characteristics and known logging periods (Lawson and Elliot, 2008; Lindstrom et al., 2000), and the live-tree equations were applied to estimate tree size at the time of the last fire for trees that were cut after the reconstruction year.

Table 2. Reconstruction approaches for stand-level characteristics.

Stand Metric	Reconstruction Approach
BA (m²/ha)	Individual live tree BA calculated from DBH, expanded to hectare scale and summed
Stand Dens (stems/ha)	Individual live tree counts expanded to hectare scale and summed
QMD (cm)	Square root taken of the sum of live tree diameters squared divided by the number of live trees in the plot
Avg CBH (m)	Height to first live branch calculated for individual trees using species-specific regression equations, then averaged
% Comp (by BA)	BA summed for fire tolerant and intolerant species groups (Table 3), then divided by total BA
Snag Vol (snags/ha)	Individual snag volumes calculated from DBH using published equations, expanded to hectare scale and summed
Fuel Loads (Mg/ha)	Published fuel deposition rates applied to # yrs elapsed between last and second-to-last fires at each site

2.3.3 Log Reconstruction

The year of transition from snag to log for logs in each plot was estimated using species-specific equations predicting log age from field rating of decay class (Kimmey, 1955; Harmon et al., 1987). Year of tree death for snags that subsequently transitioned to logs was estimated as described above using snag decay class transition time equations. Tree size at the time of the last fire was then estimated for logs that originated from snags that died after the reconstruction year, using the live tree equations as described earlier. Tip-up mounds and consistent log orientation with prevailing winds were rare, indicating that most down trees were snags prior to becoming logs, a trend noted elsewhere in Sierran mixed-conifer forests (Innes et al., 2006; North et al., 2007). However, this method for reconstructing live-tree DBH from log diameter and decay class should be considered a conservative estimate for any trees that were blown down by wind events without first dying and becoming snags.

2.3.4 Forest Structure Reconstruction Limitations

Forest reconstruction is limited by the material currently existing on site, which may influence estimation of historical stand conditions. For example, the east side of the Tahoe Basin receives the least precipitation of the sampling areas and thus has numerous well-preserved stumps from 19th century logging which facilitate highly accurate forest reconstructions (i.e. Taylor, 2004). However, the sites in Lassen, Onion Creek and the west side of the Tahoe Basin receive higher precipitation and have faster decay rates, resulting in fewer snags, stumps and logs with intact tree ring records, which likely reduces reconstruction accuracy. These reconstruction methods are also extremely limited in their ability to estimate historic density of small trees (North et al., 2007). Current snags, logs, and stumps measured in each plot would under-represent small trees that died after the reconstruction period and fully decayed before 2009, especially those species with rapid decay rates such as white fir (Harmon et al., 1987; Morrison and Raphael, 1993). Reconstruction estimates of small tree density are likely to be conservative, thus affecting estimated stand density, basal area (BA), quadratic mean diameter (QMD), canopy base height (CBH), and species composition at the time of the last fire.

2.3.5 Fuel Load Reconstruction

Fuel loads for reconstructed stands were estimated using published species- and size-specific equations for deposition rates of different fuel classes (van Wagtendonk and Moore, 2010). These rates were applied to site-specific fuel accumulation times for each site, defined as the number of years between the last fire and the second-to-last fire, to obtain reconstructed fuel loads by fuel size class (Table 2). The limitations of reconstructing fuel loads vary by size class, with larger size classes (1000 hr fuels) being more prone to error than smaller size classes (duff, litter, 1-100 hr fuels). This can be attributed to the greater difficulty in sampling the more variable deposition rates of coarse woody debris produced largely by episodic tree mortality, relative to the more regular input of fine woody and herbaceous fuels from litterfall (Keane, 2008).

2.3.6 Fire Behavior and effects Modeling

The current and reconstructed fuel loads, stand structure, and species composition were entered into the Forest Vegetation Simulator (FVS) to produce stand visualizations, and run through the Fire and Fuels Extension (FFE) to model potential fire behavior, effects, and canopy bulk density (Dixon, 2002; Reinhardt and Crookston, 2003; Wykoff et al., 1982). FVS is a regionally calibrated growth and yield model that can, among numerous other applications, produce accurate visualizations of stand structure and species composition from plot-level data inputs such as status (live or dead), species, DBH, height, and crown ratio. The Western Sierra Nevada variant was used for Tahoe and Onion Creek sites, while the Inland California and Southern Cascades Variant was used for the Lassen sites (Dixon, 2002). The FFE links the stand structure and species composition data to plot-level fuel load data (duff, litter, 1-1000 hr), local fuel moisture data (1-1000 hr dead woody, duff, live woody and herbaceous), and weather data (temperature, relative humidity, wind) to produce estimates of potential fire behavior and effects (Reinhardt and Crookston, 2003).

The fuel moisture and weather inputs used to model potential fire behavior in FVS-FFE were 97th percentile conditions (Table 3) from historical data gathered by representative remote automated weather stations at Chester, CA (for Lassen sites) and Meyers, CA (for Tahoe and Onion Creek sites). Data was obtained from the National Interagency Fire Management Integrated Database via the Kansas City Fire Access Software, and 97th percentile conditions were calculated using FireFamily Plus software (Bradshaw and McCormick, 2000; U.S. Forest Service, 1993; U.S. Forest Service, 1996).

Table 3. 97th percentile fuel moisture and weather conditions used to model potential fire behavior.

	Fuel Moisture (%)						Weather Conditions		
	Dead Woody				Live		6.1 m Wind	RH	Temp
	1 hr	10 hr	100 hr	1000 hr	Wood	Herb	(km/h)	(%)	(˚C)
Tahoe	2	3	6	7	59		10	9	31
Lassen	2	3	6	7	69		19	7	34

2.4 Statistical Analyses

2.4.1 Fire History

Specimens were sanded using progressively finer sand paper, and fire scars were dated using standard crossdating procedures (Stokes and Smiley, 1977). The season of each fire event was determined from intra-annual ring position, and classified as occurring in earlywood (early, middle or late), latewood, or the dormant season after cessation of tree growth (Dieterich and Swetnam, 1984). Analysis of fire scar data was performed using FHX2 software (Grissino-Mayer, 2001). Fire return intervals were analyzed using two composite filters: a broad filter (C1) including every fire event recorded on every specimen to provide a liberal estimate of fire return interval, and a narrow filter (C10) including only fire events recorded on two or more specimens at a given site (about 10% of the specimens) to provide a more conservative estimate of fire return interval based on larger fire events (Swetnam and Baisan, 1996). The time period of fire events recorded in the specimens varied by site, and fire return interval analysis was restricted to time periods beginning when a fire event was recorded by two or more specimens at a given site. Percent dormant season fire scars, and mean C1 and C10 fire return intervals of adjacent riparian and upland sites were compared using a paired t test. Riparian and upland C1 fire return intervals before and after 1850, including the last incomplete interval in sites where fire was absent after 1850, were compared using a paired t test. An alpha value of 0.1 was used to determine statistical significance, due to the high level of spatial and temporal variability in fire return intervals.

Nonmetric multidimensional scaling (NMS), performed in PCORD (MjM Software Design; McCune and Grace, 2002), was used to assess forest, site and stream characteristics influencing riparian and upland fire return intervals under the C1 and C10 filters. Variables with highly skewed distributions were log-transformed accounting for the lowest non-zero value (McCune and Grace, 2002). Because different measurements are subject to different scales, all variables were relativized by adjusting values to the standard deviation of each variable's mean value. Outlier sites were assessed for their potential influence on the ordination, but none were removed from the analysis because none were >4 standard deviations from the mean, and all were considered to have important fire regime information. Because not all sites had a fire scar record sufficient to calculate all C1 and C10 fire return interval metrics used in the analysis (mean, median, Weibull modal, Weibull median, minimum, maximum), the ordination matrices were reduced to 34 sites for riparian C1 FRI, 20 sites for riparian C10 FRI, 35 sites for upland C1 FRI, and 25 sites for upland C10 FRI. NMS was run using the Sorenson distance measure, 4 starting axes, 15 iterations, and an instability criterion of 0.0001. A joint plot of significant ($r^2>0.1$) forest, site and stream variables was overlaid on the ordination of sites and fire return intervals.

Regression trees, a component of classification and regression tree analysis (CART) in S-Plus (Breiman et al., 1984; Moore et al., 1991), were used to further investigate forest, site and stream characteristics associated with the variability in C1 and C10 mean fire return intervals among riparian and upland sites. Regression tree analysis is a nonparametric, recursive model well suited to exploring ecological relationships that are difficult to detect using other multivariate analyses (De'ath, 2002; Vayssieres et al., 2000). Each regression tree was pruned to a minimum of 10 observations before a split, a minimum node size of 5 and a minimum node deviance of 0.5. Because not all sites had a fire scar record sufficient to calculate C10 FRI, the riparian and upland C10 FRI regression trees were restricted to 28 and 31 sites, respectively.

For investigation of fire-climate synchrony, we restricted our analysis to years in which two or more specimens were scarred at a site, and two or more sites recorded fire scars in the same year (Dieterich, 1980). Because most of our sites were widely separated, scars at different sites were not assumed to be produced by the same fire event, but separate fire events favored by climate conditions in the same year. Superposed epoch analysis (SEA) was used to compare climate six years before, the year of, and four years after each year in which fire occurred at two or more sites (Swetnam, 1993). We used data from the reconstructed Palmer Drought Severity Index (PDSI) gridpoint 46 (closest to our sample locations) and the NINO3 index, which represents the mid-tropical Pacific sea surface temperature fluctuations associated with the El Niño/Southern Oscillation (ENSO) (Cook, 2000; Cook et al., 1999). PDSI has been correlated with fire events on the west side of the Sierra Nevada (Norman and Taylor, 2003; Stephens and Collins, 2004; Swetnam and Baisan, 2003; Taylor and Beaty, 2005), while ENSO has been correlated with fire events in the Southwest (Grissino-Mayer and Swetnam, 2000; Skinner et al., 2008), the Sierra Nevada (Beaty and Taylor, 2008; Norman and Taylor, 2003), and the Pacific Northwest (Heyerdahl et al., 2008; Kitzberger et al., 2007). Values for both indices were standardized around a mean of zero, and 95% confidence intervals were calculated using Monte Carlo simulations with 1000 iterations.

2.4.2 Stand Structure, Fuel Loads and Fire Behavior

Measures of stand structure (BA, stand density, snag volume, QMD, average CBH), species composition (by percent of total BA, categorized fire-tolerant and -intolerant functional groups), fuel load (by duff, litter, 1 hr, 10 hr, 100 hr, 1000 hr classes), potential fire behavior (surface and crown fire flame lengths, probability of torching, torching index, crowning index), canopy bulk density (CBD), and mortality (by percent of total BA) were compared between current and reconstructed riparian and upland forests, as well as between sampling areas, using ANOVA. Variables were checked for normality of residuals using normal probability plots and the Shapiro-Wilk test (Shapiro and Wilk, 1965), and all variables except BA, QMD, CBH, and probability of torching were determined to have residual distributions with significant departures from normality. Homogeneity of variances was assessed using plots of residual vs. predicted values, and residual values vs. fixed factors, and the variances of all variables were determined to be heterogeneous. Various logarithmic, power, and arcsine transformations were applied to improve normality of residuals and heterogeneity of variances. Normality of residuals was achieved for all variables except species composition, and homogeneity of variances was achieved for all variables except snag volume, surface and crown fire flame length, probability of torching, and mortality. Results involving these variables should be treated with caution.

The experiment set up as a split plot repeated measures design, with site as the main plot, riparian vs. upland as the split plot, and current vs. reconstructed as a repeated measure. A linear mixed effects model was used to analyze the data, which included sampling area, riparian vs. upland, and current vs. reconstructed as fixed effects, and site and plot as random effects. All possible interactions were included in the model, and differences between the least squares means of current riparian, reconstructed riparian, current upland, and reconstructed upland variables, as well as differences among sampling areas, were compared using a Tukey's post-hoc test of the riparian vs. upland by current vs. reconstructed interaction, and of the sampling area factor.

In this study we were also interested in how fire history might affect reconstructed stand and fuel conditions, and whether riparian and upland conditions were correlated. To explore the relationships between site-specific broad filter fire return intervals (C1 FRI, derived from all fire events scarring one or more trees at a given site) and reconstructed stand structure, fuel loads, and potential fire behavior, we checked variables for normality and then used a Pearson's correlation coefficient analysis. Separate correlation matrices were set up for riparian and upland forests, with reconstructed stand structure, fuel loading and fire behavior variables correlated with FRI. A Pearson's correlation coefficient analysis was also used to examine the relationships between riparian and upland forests for both current and reconstructed conditions. Separate correlation matrices were set up for current and reconstructed conditions, with riparian stand structure, fuel loading and fire behavior variables correlated with the corresponding upland variables. ANOVAs were performed using SAS software, Version 9.1.3 of the SAS System for Windows, Copyright © 1998 SAS Institute Inc., while correlation analyses were conducted using Minitab Version 16 (McKenzie and Goldman, 1999).

One reconstructed riparian plot (Taylor Creek on the west side of the Tahoe Basin) had so few trees that torching index, crowning index, and canopy bulk density could not be calculated in FVS-FFE, resulting in a sample size of 35 for those variables in the reconstructed riparian plot category. One reconstructed upland plot (Burke Creek on the west side of Tahoe Basin) had no trees detectable by the reconstruction methods used, resulting in a sample size of 35 for all variables in the reconstructed upland plot category.

3. RESULTS

3.1 Riparian vs. Upland FRI and Seasonality

In total, 907 fire scar specimens were collected from 36 sites. The analysis included 849 specimens (58 could not be crossdated) with 1631 fire scars recording 760 independent fire events. Riparian fire scar samples, which were predominantly true fir and incense-cedar, exhibited more complacent ring series than upland samples, and were thus moderately more difficult to cross-date. This was likely due to a combination of higher soil moisture and a higher proportion of true firs and incense-cedars in riparian areas. The period of record ranged from 1387, the earliest ring on a Jeffrey pine stump from Burke Creek in the Lake Tahoe Basin, to 2009, the year sampling took place. The earliest fire event recorded was 1526 on a Jeffrey pine snag from Taylor Creek in the Lake Tahoe Basin, and the latest fire event recorded was 2005 on a live lodgepole pine from Tallac Creek in the Lake Tahoe Basin.

Riparian mean C1 FRI ranged from 8.4 years in Taylor Creek to 42.3 years in Blackwood Creek, both Jeffrey pine sites in the Tahoe sampling area. Upland mean C1 FRI varied from 6.1 years in Burke Creek, a Jeffrey pine site in the Tahoe sampling area, to 58.0 years in Shanghai Creek, a mixed-conifer site in the Lassen sampling area (Table 1).

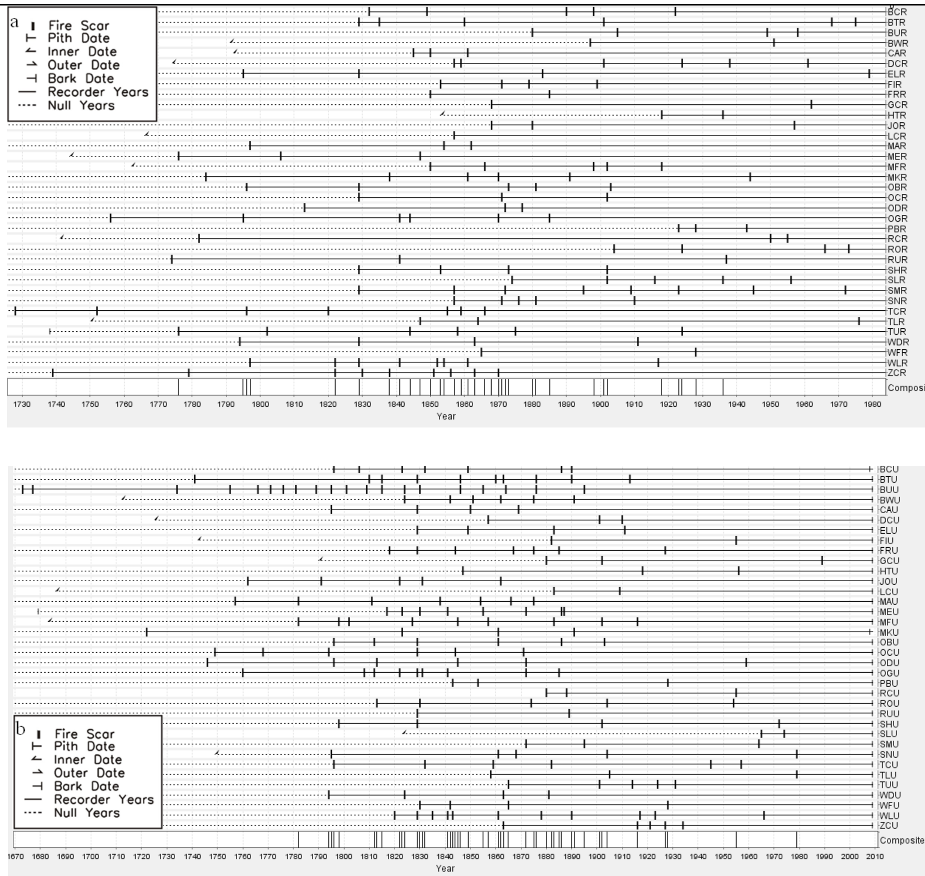

Figure 2. Composite fire occurrences for 36 sample sites in a) riparian and b) adjacent upland forests. Horizontal lines are the length of record at each sample site, with vertical ticks indicating years when two or more trees were scarred at a site. The composite record at the bottom indicates when two or more sites were scarred in the same year.

Across all sites, the average C1 FRI in the riparian and upland areas was 16.6 and 16.9 years, respectively. Riparian mean C10 FRI varied from 10.0 years in Philbrook Creek, a mixed-conifer site in the Lassen sampling area, to 86.5 years in the Red Cedar Creek, a mixed-conifer site in the Tahoe sampling area (Figure 2a). Upland mean C10 FRI varied from 10.0 years in Meeks Creek, a mixed-conifer site in the Tahoe sampling area, to 56.3 years in McKinney Creek, a Jeffrey pine site in the Tahoe sampling area (Figure 2b). Across all sites, the average C10 FRI in the riparian and upland areas was 30.0 and 27.8 years, respectively. The C10 FRI could not be calculated for 11 sites due to insufficient fire scar records.

Table 1. Forest, site and stream characteristics; forest type abbreviations are Jeffrey pine (PIJE), white fir (ABCO) and mixed-conifer (MC); C1 FRI (all fire events at a site after two trees are scarred), C10 FRI (fire events scarring two or more trees at a site) for each riparian and upland site, and p-values of paired t tests (* and ** indicate significance at α=0.1 and 0.05, respectively).

		Forest	Precip	Elev	Stream	Riparian	Stream	Stream	Channel	Area Sampled (ha)		C1 Mean FRI			C10 Mean FRI		
Area	Site	Type	Regime	(m)	Order	Width (m)	Width (m)	Depth (m)	Grad (°)	Riparian	Upland	Rip	Up	p Diff	Rip	Up	p Diff
Lassen National Forest	Butt (BT)	PIJE	W	1700	1	8	4.0	0.6	4	2	4	19.2	8.8	**0.0081	24.3	19.1	0.5806
	Carter (CA)	MC	W	1767	2	20	1.0	1.0	1	1	1	9.5	13.8	*0.0759	NA	24.7	NA
	Elam (EL)	MC	W	1746	2	21	6.0	2.0	7	1	1	21.4	16.5	0.7982	61.3	27.3	*0.0976
	Fish (FI)	MC	W	1548	2	70	10.2	1.2	3	1	2	12.5	12.3	0.6738	15.3	28.0	0.8949
	W Feather (FR)	MC	W	1536	3	35	25.0	5.0	5	1	2	14.5	13.9	0.8145	NA	18.2	NA
	Jones (JO)	PIJE	W	1623	2	12	12.0	0.8	2	1	2	17.7	13.0	0.1254	44.5	12.2	0.4908
	Last Chance (LC)	PIJE	W	1648	2	37	11.0	2.7	4	1	1	16.0	12.0	0.2319	NA	NA	NA
	Philbrook (PB)	MC	W	1531	3	35	35.0	10.0	8	1	1	13.0	42.5	0.2139	10.0	42.5	0.4255
	Rock (RO)	ABCO	W	1846	2	20	15.0	2.0	3	1	2	21.0	14.8	*0.076	23.0	35.3	NA
	Shanghai (SH)	MC	W	1694	2	16	10.0	1.1	6	3	5	15.7	58.0	**0.0105	24.3	52.0	0.1512
	Slate (SL)	ABCO	W	1900	1	20	20.0	1.5	2	3	3	20.5	11.8	**0.0499	20.5	NA	NA
	Sawmill Tom (SM)	ABCO	W	1754	2	15	12.0	2.0	6	3	3	11.9	13.5	0.5841	17.9	46.0	*0.0616
	Snag (SN)	ABCO	W	1724	2	85	13.0	1.1	2	2	1	15.9	23.0	0.5228	17.7	46.0	0.1935
	W Fish (WF)	MC	W	1557	2	20	15.0	2.0	4	2	1	25.7	31.8	0.6952	NA	32.7	NA
	Warner (WL)	PIJE	E	1543	4	25	9.5	2.0	1	7	7	8.5	10.8	0.3927	17.1	14.6	0.9216
Onion Creek	Onion B (OB)	MC	W	1954	1	11	9.0	1.7	7	1	2	22.2	15.8	0.3292	35.7	21.4	**0.0332
	Onion C (OC)	MC	W	1907	1	35	9.7	1.4	5	4	7	15.2	13.4	0.6314	36.5	20.3	*0.059
	Onion D (OD)	MC	W	1997	1	40	24.0	2.0	4	7	8	20.3	24.8	0.3551	32.0	42.6	0.6064
	Onion G (OG)	MC	W	1908	1	19	4.7	1.5	9	2	3	12.0	7.4	*0.0815	25.8	15.6	0.3051

Table 1. (Continued).

Lake Tahoe Basin	Bunker (BC)	MC	W	1972	1	45	0.8	0.2	8	1	1	20.2	13.8	0.6825	22.5	23.5	0.9159
	Burke (BU)	PIJE	E	2053	1	7	7.6	0.3	3	2	2	14.3	6.1	**0.0002	26.0	11.1	**0.0382
	Blackwood (BW)	PIJE	W	1868	2	75	14.0	1.4	2	15	12	42.3	19.4	*0.069	NA	13.4	NA
	Dollar (DC)	PIJE	W	1948	1	35	1.7	0.9	3	2	2	14.4	13.7	0.9708	20.8	26.5	0.6233
	General (GC)	MC	W	1951	3	163	14.5	1.5	1	3	5	16.0	17.4	0.7484	56.0	54.6	NA
	Horse Trail (HT)	PIJE	E	1952	1	37	1.8	1.3	1	1	1	9.0	10.7	0.8693	NA	NA	NA
	Marlette (MA)	PIJE	E	1941	2	23	3.0	0.9	2	2	2	22.1	16.9	0.3055	32.5	21.3	0.6818
	Meeks (ME)	MC	W	1902	2	420	6.0	1.0	1	2	2	15.6	11.7	0.3835	35.5	10.0	*0.0519
	McFaul (MF)	PIJE	E	2042	2	75	1.4	0.6	1	3	2	10.7	10.9	0.9594	17.0	16.8	0.8423
	McKinney (MK)	PIJE	W	1989	1	30	12.0	2.0	3	3	4	10.0	11.4	0.3127	32.0	56.3	0.2774
	Red Cedar (RC)	MC	W	1948	1	40	1.7	0.3	2	2	1	19.6	17.6	0.8351	86.5	37.5	0.5851
	Rubicon (RU)	MC	W	2065	1	26	1.0	0.2	5	2	2	14.8	29.3	0.1208	NA	NA	NA
	Taylor (TC)	PIJE	W	1914	3	86	23.0	4.0	1	10	10	8.4	15.1	0.1046	23.0	32.2	0.3540
	Tallac (TL)	MC	W	1901	2	355	5.0	0.6	1	12	13	16.1	11.6	0.4498	NA	NA	NA
	Tunnel (TU)	PIJE	E	1976	1	10	4.0	1.6	4	14	12	16.8	11.6	*0.0895	29.6	16.5	0.1792
	Ward (WD)	PIJE	W	1944	2	34	18.0	1.5	3	1	1	22.8	18.7	0.6126	39.0	29.0	0.2555
	Zephyr (ZC)	PIJE	E	1831	3	26	23.6	0.6	3	1	1	12.0	13.4	0.6504	14.6	14.2	0.8406

C1 FRI was significantly different between riparian and upland areas in only 9 out of 36 sites, with riparian FRI being shorter than upland FRI in two of these sites (Carter and Shanghai Creeks, both mixed-conifer sites in the Lassen sampling area) (Table 1). C10 FRI was significantly different between riparian and upland areas in only 6 out of 25 sites, with riparian FRI being shorter than upland FRI in one of these sites (Sawmill Tom Creek, a white fir site in the Lassen sampling area).

Fire seasonality varied by site but with the exception of six sites (Burke, Dollar, and Horse Trail Creeks, the riparian area of Bunker Creek, and the upland areas of Meeks and Zephyr Creeks), >50% of the scars were in the dormant season. Averaged across all sites, 88% and 79% of scars in the riparian and upland areas, respectively, were in the dormant season (Figure 3). There was no significant difference in the percent dormant season scars between the riparian and upland areas ($p=0.102$).

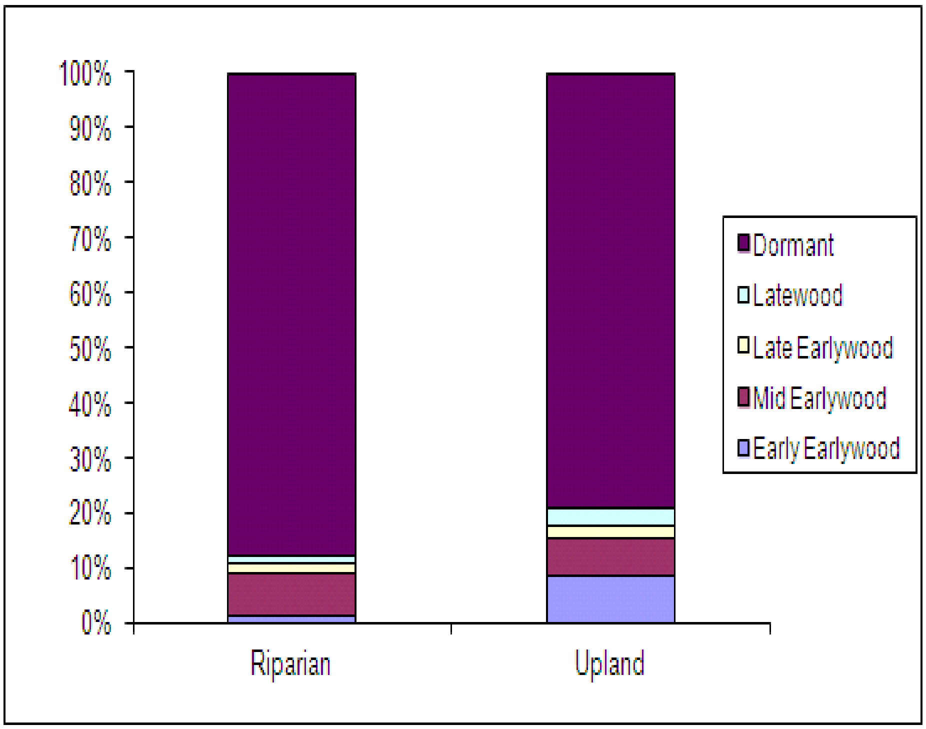

Figure 3. Cumulative proportion of intra-ring fire scar positions for all trees across all sites. Dormant typically represents fall and late summer fires, latewood represents mid-summer fires, earlywood represents spring and early summer fires.

3.2 Site Characteristics Associated with Riparian and Upland FRI

For the NMS analyses, the greatest reduction in stress was achieved with two axes. In the riparian C1 FRI analysis, the proportion of variance (the fit between distance in the ordination space and the original space) represented by the first and second axes was 0.572 and 0.385, respectively (cumulative 0.957). The joint plot of riparian C1 FRI (Figure 4a) shows a trend of decreasing FRI with decreasing channel width to depth ratio and increasing upland percent species composition occupied by pine. In the riparian C10 FRI analysis, the proportion of variance represented by the first and second axes was 0.133 and 0.827, respectively (cumulative 0.960). The joint plot of riparian C10 FRI (Figure 4b) reveals a trend of decreasing FRI with decreasing riparian zone width, decreasing channel gradient, and increasing upland and riparian percent species composition occupied by pine. In the upland C1 FRI analysis, the proportion of variance represented by the first and second axes was 0.359 and 0.629, respectively (cumulative 0.988). The joint plot of upland C1 FRI (Figure 4c) shows a trend of decreasing FRI with increasing upland percent species composition occupied by pine. In the upland C10 FRI analysis, the proportion of variance represented by the first and second axes was 0.865 and 0.117, respectively (cumulative 0.982). The joint plot of upland C10 FRI (Figure 4d) reveals a trend of decreasing FRI with increasing elevation and increasing upland percent species composition occupied by pine. All four NMS ordinations show a general clustering of east side sites in the quadrant of the ordination space where FRI is shorter.

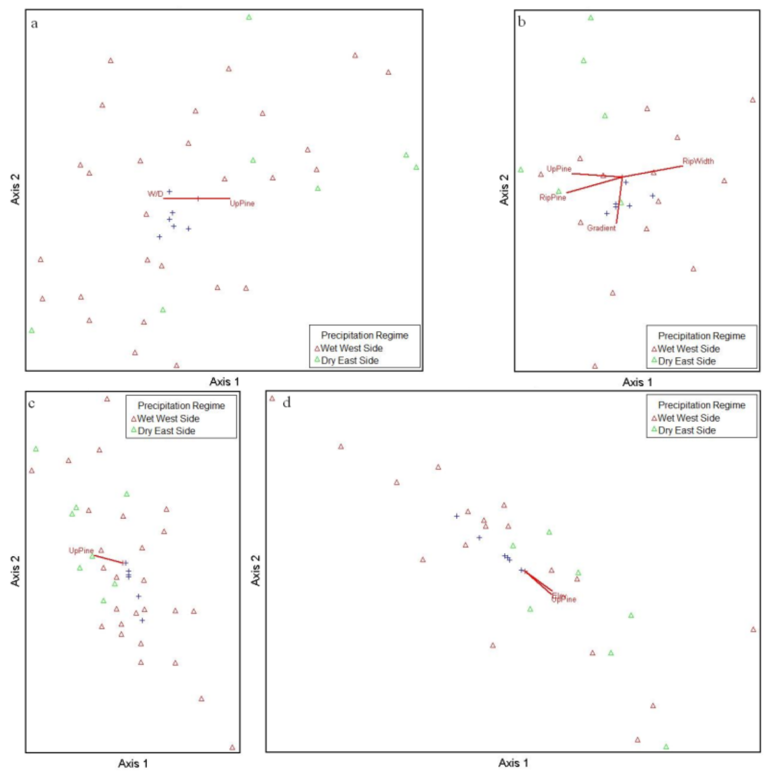

Figure 4. Nonmetric multidimensional scaling (NMS) ordination of a) riparian C1 FRI metrics at 34 sites (two sites not included due to insufficient fire scar record, i.e. site did not record enough fire events to allow calculation of all fire return interval metrics used in analysis); b) riparian C10 FRI metrics at 20 sites (16 sites not included due to insufficient fire scar record); c) upland C1 FRI at 35 sites (one site not included due to insufficient fire scar record); and d) upland C10 FRI at 25 sites (11 sites not included due to insufficient fire scar record). Triangle color represents precipitation regime of each site. The joint plots show the significant forest, site and stream characteristics associated with each fire occurrence record. Abbreviations: W/D is channel width/depth ratio, UpPine and RipPine are the upland and riparian percent species composition occupied by fire-tolerant pine, respectively, RipWidth is riparian zone width, and Gradient is channel gradient.

In the riparian C1 FRI regression tree (Figure 5a), the shortest mean FRI (13.9 years) is associated with channel width to depth ratio <6.2, while the longest mean FRI (22.9 years) is associated with bankfull width to depth ratio >6.2 and channel bankfull depth >1.3 m. In the riparian C10 FRI regression tree (Figure 5b), the shortest mean FRI (23.9 years) is associated with mixed-conifer forest type and incised channel shape, closely followed by a mean FRI of 24.9 years associated with Jeffrey pine and white fir forest types. The longest C10 mean FRI (45.9 years) is associated with mixed-conifer forest type, and broad and v-shaped channels. In the upland C1 FRI regression tree (Figure 5c), the shortest mean FRI (13.1 years) is associated with >22.7% upland species composition occupied by pine, while the longest mean FRI (31.5) is associated with <22.7% upland percent species composition occupied by pine and elevation <1709 m. In the upland C10 FRI regression tree (Figure 5d), the shortest mean FRI (19.5 years) is associated with >37.6% upland species composition occupied by pine, while the longest mean FRI (42.9 years) is associated with <37.6% upland species composition occupied by pine and elevation >1944 m.

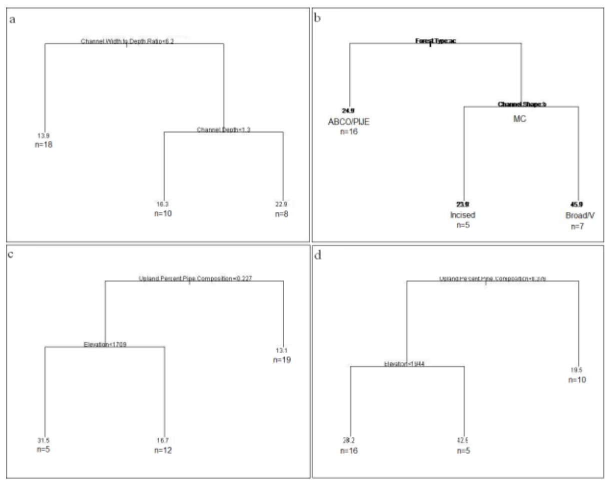

Figure 5. Regression tree of forest, site and stream characteristics associated with a) riparian C1 FRI, b) riparian C10 FRI, c) upland C1 FRI, and d) upland C10 FRI. The grouping of values in each split is indicated by the direction of the < symbol (i.e. in 5a, sites with channel depth <1.3 m are split off to the left of the dendrogram in the second split). The length of each branch is proportional to the amount of data variability explained by each split. Terminal values are the average FRI for all the sites classified in that node.

3.3 Climate Comparisons

SEA of years in which fires scarring two or more trees at a site occurred at two or more sites (the composite in Figures 2a and 2b) revealed a common pattern of fire-climate synchrony between the riparian and upland areas. SEA with PDSI identified a significant association between fire events and drought in the same year, but not in pre- or post-event years, in both riparian and upland areas (Figures 6a and 6b). There was a greater departure from mean PDSI in the upland areas (beyond the 99% confidence interval) than in the riparian areas (beyond the 95% confidence interval). SEA with the NINO3 index showed no significant associations between fire events and climate (not shown).

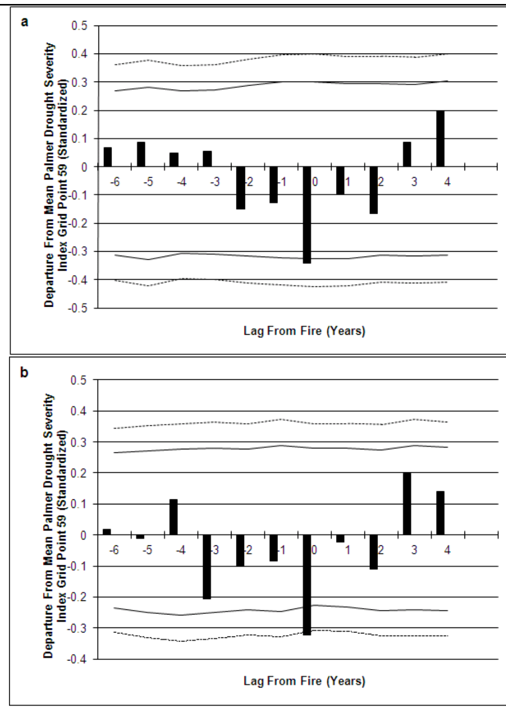

Figure 6. Superposed epoch analysis (SEA) for a) riparian and b) upland samples. Graphs show departure from the mean Palmer Drought Severity Index (PDSI) values with years when fires scarred two or more trees per site at the riparian areas of two or more sites. Horizontal lines are 95% and 99% confidence intervals.

3.4 Temporal Analysis

Temporal variation in FRI could not be analyzed for 10 riparian sites and four upland sites due to a lack of recorded fire occurrence before 1850 in those sites. C1 FRI was significantly different in two out of 26 riparian sites (Rubicon Creek, a mixed conifer site, and Taylor Creek, a Jeffrey pine site, both in the Tahoe sampling area), and two out of 32 upland sites (Butt Creek, a Jeffrey pine site, and Fish Creek, a mixed conifer site, both in the Lassen sampling area). In all four sites, C1 FRI was significantly shorter after 1850.

3.5 Comparison between Riparian/Upland Current/Reconstructed Stand Conditions

While there was a great deal of variability in riparian and upland forests under current and reconstructed conditions (Figure 7), the analysis revealed some striking differences. Current riparian forest conditions significantly differed from reconstructed riparian conditions in BA, stand density, snag volume, duff, 1 hr, 10 hr, 100 hr, and total fuel loads, surface and crown fire flame length, probability of torching, torching index, crowning index, CBD, and mortality (Table 4).

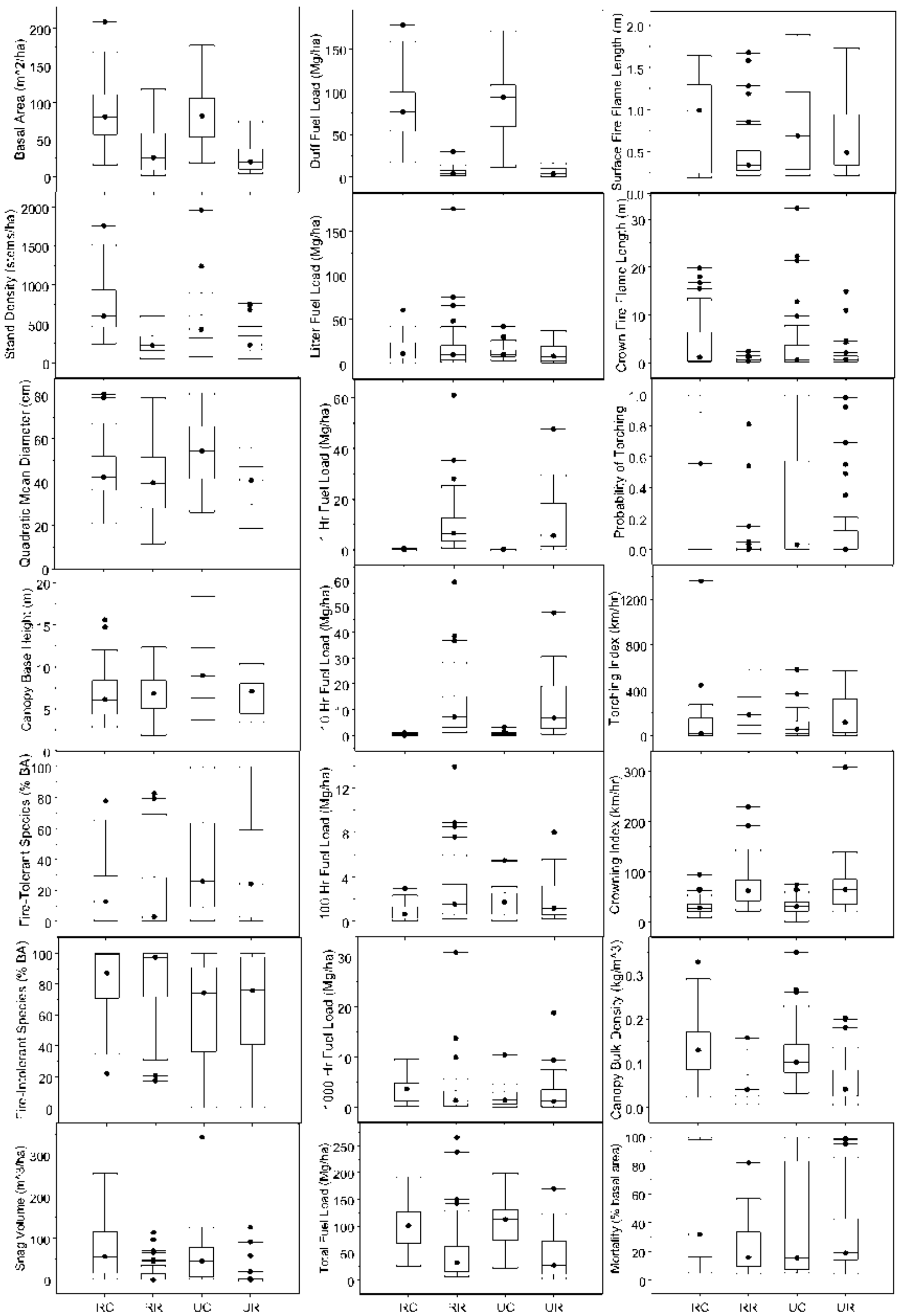

Figure 7. Box and whisker plots of current and reconstructed stand structure, fuel load, and fire behavior and effects variables for riparian and upland forests. RC is riparian current, RR is riparian reconstructed, UC is upland current, UR is upland reconstructed. Boxes are the upper and lower quartiles divided at the median, whiskers are the maximum and minimum values, dots are outliers.

Table 4. Comparison of riparian vs. upland and current vs. reconstructed stand structure, fuel loads, and potential fire behavior and effects least squares mean (standard error) values. BA is basal area, QMD is quadratic mean diameter, CBH is crown base height (average height to lowest green branch), CBD is canopy bulk density. Values in the same row followed by a different letter are significantly different (Tukey's post-hoc ANOVA, $p<0.05$), p-values are for the ANOVA global F test. Sample size is 36 for all variables in each column except riparian reconstructed (n=35 for torching index, crowning index, and CBD), and upland reconstructed (n=35 for all variables). Fire behavior calculated under 97th weather conditions.

	Riparian		Upland	
	Current	Reconstructed	Current	Reconstructed
BA (m^2/ha)	87.4(0.2)a	28.5(0.2)b	77.7(0.2)a	21.4(0.2)b
Stand Dens(stems/ha)	634.5(1.1)a	207.7(1.1)b	401.4(1.1)c	201.1(1.1)b
QMD (cm)	45.7(2.6)a	40.0(2.6)ab	55.3(2.6)c	38.4(2.6)b
Avg CBH (m)	6.7(0.01)a	6.5(0.01)a	9.4(0.01)b	6.3(0.01)a
% Comp (by BA)				
Fire Tolerant$_1$	13.4(0.5)ab	10.1(0.5)a	36.3(0.5)c	30.3(0.5)bc
Fire Intolerant$_2$	86.6(0.5)ab	89.9(0.5)a	63.7(0.5)c	69.7(0.5)bc
Snag Vol (m^3/ha)	36.8(0.4)a	2.4(0.4)b	24.0(0.4)a	0.5(0.4)b
Fuel Loads (Mg/ha)				
Duff	69.1(1.2)a	3.3(1.2)b	72.2(1.2)a	3.0(1.2)b
Litter	13.0(1.2)a	8.8(1.2)a	12.3(1.2)a	6.9(1.2)a
1 hr	0.1(1.2)a	5.4(1.2)b	0.1(1.2)a	3.0(1.2)b
10 hr	0.4(1.2)a	6.3(1.2)b	0.5(1.2)a	5.5(1.2)b
100 hr	0.7(0.01)a	1.8(0.01)b	1.4(0.01)ab	1.5(0.01)ab
1000 hr	2.8(0.0)a	1.4(0.0)ab	1.1(0.0)ab	0.9(0.0)b
Total	92.5(1.2)a	27.9(1.2)b	91.1(1.2)a	22.3(1.2)b
Flame Length (m)				
Surface	0.6(1.1)a	0.4(1.1)b	0.6(1.1)a	0.5(1.1)ab
Crown	0.9(1.1)a	0.4(1.1)b	0.6(1.1)ac	0.5(1.1)bc
Prob of Torch	0.45(0.06)a	0.03(0.06)b	0.22(0.06)c	0.08(0.06)bc
Torch Index (km/hr)	20.1(0.4)a	176.3(0.4)b	47.1(0.4)ac	98.6(0.4)bc
Crown Index (km/hr)	27.5(0.1)a	61.6(0.1)b	28.8(0.1)a	61.9(0.1)b
CBD (kg/m^3)	0.12(1.14)a	0.04(1.14)b	0.10(1.14)a	0.04(1.14)b
Mortality (% BA)	30.6(1.2)a	16.5(1.2)b	15.7(1.2)b	21.0(1.2)ab

$_1$Pinus jeffreyi, P. ponderosa, P. lambertiana, P. monticola, and Quercuz kelloggii

$_2$P. contorta ssp. murrayana, Populus tremuloides, P. balsamifera ssp. trichocarpa, Alnus incana ssp. tenuifolia, Salix spp., Abies concolor, A. magnifica, Calocedrus decurrens, and Pseudotsuga menziesii

Current riparian stands have more than triple the BA and stem density (Figure 8), more than 15 times the snag volume, more than 20 times the duff load, and more than triple the total fuel load of reconstructed riparian stands. However, woody fuel loads are much lower in current riparian forests in all size classes except the 1000 hr fuels. Potential flame lengths in current riparian stands are 50% greater than those of reconstructed conditions for surface fires, and 125% greater for crown fires.

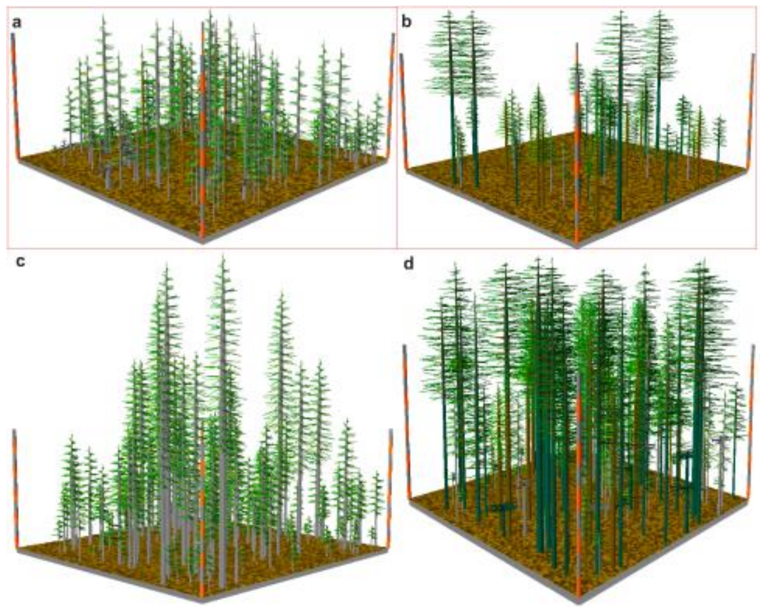

Figure 8. Stand visualization simulation of typical conditions for a) current riparian forest (Dollar Creek, 2009), and b) reconstructed riparian forest (West Branch Feather River, 1886). The corresponding stands, c) Dollar Creek riparian, reconstructed conditions in 1962, and d) West Branch Feather River, current conditions in 2009, are not representative of typical conditions but are displayed for comparison. Stands representative of typical conditions (outlined in red) were selected based on how close the stand density, basal area, and species composition values of the individual stands were to the mean values for all sites. Range pole intervals are approximately 3 m, ground area is approximately 0.75 ha.

The probability of torching has increased by a factor of 15, the torching index is an order of magnitude less, and the crowning index (i.e., the wind speed required to initiate active crown fire) is less than half that of reconstructed riparian stands. Current riparian stands have triple the CBD, and nearly double the predicted mortality of reconstructed riparian conditions.

Current and reconstructed upland stands were significantly different in BA, stand density, snag volume, QMD, average CBH, duff, 1 hr, 10 hr, and total fuel load, crowning index, and CBD (Table 4). Reconstructed upland stands have less than one third the BA, half the stem density, and two orders of magnitude lower snag volume of current upland stands (Figure 9). The QMD of current upland forests has increased by nearly 50%, while the CBH has increased by three meters. Duff load is over 24 times greater and total fuel load is double in current upland forests, while 1 hr and 10 hr woody fuel loads are lower by an order of magnitude. Crowning index under reconstructed upland forest conditions is more than double that of current conditions, while CBD is less than half.

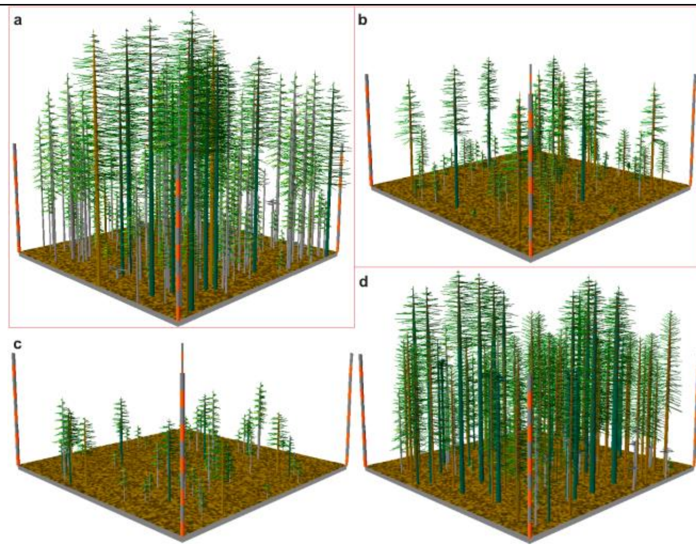

Figure 9. Stand visualization simulation of typical conditions for a) current upland forest (Jones Creek, 2009), and b) reconstructed upland forest (B Fork Onion Creek, 1904). The corresponding stands, c) Jones Creek upland, reconstructed conditions in 1869, and d) B Fork Onion Creek, current conditions in 2009, are not representative of typical conditions but are displayed for comparison. Stands representative of typical conditions (outlined in red) were selected based on how close the stand density, basal area, and species composition values of the individual stands were to the mean values for all sites. Range pole intervals are approximately 3 m, ground area is approximately 0.75 ha.

Current riparian and upland forests had significantly different stand density, QMD, average CBH, species composition, probability of torching, and predicted mortality (Figure 8). Current riparian forests have greater than 50% more stems per ha, a QMD nearly 20% lower, and a CBH that is nearly 3 m lower. In current riparian stands, fire-tolerant species comprise nearly 16 % less of the total basal area than current upland stands. The probability of torching in current riparian stands is more than double that of current upland stands, and the predicted mortality is nearly double.

Reconstructed riparian forests were not significantly different from reconstructed upland forests in any of the variables analyzed. Site-level data is provided here as a supplement.

SUPPLEMENTAL DATA

Site-level data for a) current riparian, b) reconstructed riparian, c) current upland, and d) reconstructed upland stands. BA is basal area, QMD is quadratic mean diameter, CBH is crown base height, % Comp is species composition by basal area lumped into fire-tolerant and fire-intolerant groups, Prob Torch is the probability of torching, CBD is canopy bulk density, C1 FRI is a broad filter fire return interval (one or more trees scarred per site), C10 FRI is a narrow filter fire return interval (two or more trees scarred per site), Recon Year is the year of reconstruction (year of the last fire), Fuel Accum Time is the fuel accumulation time (period between the last fire and the second to last fire).

Supplemental Data

a

Area	Site	BA (m^2/ha)	Stand Dens (stems/ha)	Snag vol (m^3/ha)	QMD (cm)	Avg CBH (m)	% Comp (by BA) Fire Tol	Fire Intol	Canopy Cover (%)	Seedlings (stems/ha)	Shrub Cover (%)	Fuel Load (Mg/ha) Duff	Litter	1 hr	10 hr	100 hr	1000 hr	Total	Flame Length (m) Surface	Crown	Prob Torch	Torch Index (km/hr)	Crown Index (km/hr)	CBD (kg/m^3)	Mortality (% BA)
Lassen National Forest	BT	138	880	9	51	9.4	30	70	64	0	1	34	11	0.1	0.4	0.9	0.3	46	0.2	18.0	0.00	251	18	0.23	100
	CA	147	950	68	47	11.8	9	91	83	0	2	70	13	0.1	0.8	0.9	5.2	90	0.2	19.8	0.00	445	15	0.29	100
	EL	149	610	3	67	8.2	34	67	47	2000	8	104	29	0.1	0.4	0.4	4.3	138	0.2	0.3	0.00	209	30	0.12	6
	FI	62	520	165	40	8.0	12	88	70	3000	4	83	11	0.2	0.4	1.5	4.1	100	1.3	1.2	0.54	27	28	0.13	32
	FR	145	340	116	79	14.7	66	34	47	3000	16	55	43	0.1	1.1	1.5	0.7	102	1.0	0.9	0.00	156	41	0.07	5
	JO	125	380	69	67	12.1	25	76	65	12000	1	87	26	0.1	0.2	0.4	5.4	119	0.7	0.6	0.00	111	42	0.07	16
	LC	79	620	115	42	10.2	13	87	67	3000	2	91	27	0.3	0.8	1.5	1.8	122	1.4	13.4	0.79	0	22	0.17	99
	PB	33	470	9	33	4.1	33	68	60	0	65	55	2	0.1	0.3	0.2	0.1	58	0.3	0.3	0.17	155	54	0.05	15
	RO	77	450	60	50	4.7	0	100	48	4000	16	74	9	0.1	0.3	0.2	2.0	86	1.4	6.1	0.75	7	28	0.13	96
	SH	101	520	56	55	5.3	29	71	45	15000	0	66	39	0.1	0.4	0.4	1.2	107	1.2	4.9	0.93	8	32	0.11	93
	SL	48	590	11	37	2.8	0	100	47	2000	12	53	3	0.1	0.3	0.0	6.6	63	1.3	6.1	0.90	2	31	0.11	98
	SM	76	760	102	38	4.2	0	100	78	1000	4	57	7	0.2	0.4	1.1	1.1	67	1.3	9.4	0.99	0	26	0.14	98
	SN	100	920	42	37	9.5	0	100	45	2000	25	70	18	0.4	0.7	0.7	3.8	94	1.2	18.0	0.67	11	20	0.20	99
	WF	144	1030	152	43	8.2	0	100	61	2000	1	136	7	0.1	0.5	0.2	0.5	143	1.2	1.2	0.83	21	30	0.12	18
	WL	47	960	23	26	4.1	1	99	48	1000	1	42	22	0.1	0.3	0.9	3.5	69	1.3	10.4	0.94	7	23	0.17	99
Onion Creek	OB	96	380	40	53	6.3	20	80	38	4000	58	17	5	0.1	0.4	1.7	7.3	32	0.2	0.3	0.00	135	20	0.18	13
	OC	209	420	48	81	15.6	4	96	61	15000	35	87	37	0.3	0.5	1.5	4.1	130	0.2	0.3	0.00	276	33	0.09	5
	OD	91	500	60	50	6.8	8	93	43	2000	51	87	13	0.1	0.6	0.9	4.6	106	0.2	0.3	0.00	130	40	0.07	10
	OG	169	840	114	54	8.6	3	97	70	0	12	119	18	0.6	0.3	0.7	0.8	139	1.6	16.8	0.82	0	17	0.16	99
Lake Tahoe Basin, West Side	BC	95	1465	29	44	2.9	3	97	100	400	37	159	7	0.1	0.4	1.3	1.1	169	0.6	0.9	0.95	0	38	0.08	37
	BW	83	910	139	30	4.9	38	62	55	1000	38	19	4	0.0	0.1	0.2	1.7	25	0.2	0.3	0.00	155	21	0.16	23
	DC	100	750	257	57	5.9	2	98	28	1000	15	74	6	0.1	0.3	0.7	6.6	88	0.2	0.3	0.00	194	24	0.15	15
	GC	58	1520	210	21	2.8	43	57	43	2000	27	106	6	0.1	0.5	0.4	3.4	116	1.0	4.6	1.00	1	15	0.28	98
	ME	15	240	21	29	4.0	0	100	46	1000	53	36	8	0.0	0.4	0.7	5.6	50	1.2	1.5	0.57	4	49	0.06	94
	MK	104	1010	239	62	5.3	27	73	68	900	30	95	14	0.1	0.5	2.9	2.1	115	0.2	0.3	0.00	239	13	0.33	14
	RC	56	410	161	46	5.9	21	79	44	1000	62	68	8	0.1	0.3	0.4	0.6	77	1.3	2.4	0.71	16	34	0.10	78
	RU	50	400	0	42	6.3	0	100	6	0	15	19	4	0.0	0.1	0.0	5.2	29	1.5	6.7	0.65	6	27	0.13	98
	TC	63	520	11	38	4.9	0	100	33	5000	20	121	61	0.2	0.5	0.2	9.7	192	0.9	0.9	0.87	10	23	0.16	26
	TL	39	650	5	40	3.8	0	100	50	11000	2	32	0	0.0	0.0	0.0	0.9	33	0.2	0.3	0.00	1360	94	0.02	38
	WD	36	480	20	36	6.8	49	51	43	1000	38	83	20	0.1	0.3	0.7	5.3	109	1.0	0.9	0.25	42	28	0.12	30
Lake Tahoe Basin, East Side	BU	18	280	22	29	3.4	78	22	21	1000	23	26	42	0.0	0.1	0.2	4.3	73	0.6	0.6	0.18	21	63	0.04	17
	HT	66	490	55	42	10.2	27	74	74	4000	66	78	18	0.1	0.2	1.5	2.7	101	1.0	1.2	0.42	8	31	0.10	26
	MA	64	530	121	41	6.7	23	77	53	2000	14	119	12	0.1	0.6	2.4	4.5	138	1.1	0.9	0.37	23	21	0.17	26
	MF	98	1350	108	31	6.6	3	97	59	1000	3	85	34	0.1	0.7	1.3	4.0	125	0.9	0.9	0.92	10	19	0.19	32
	TU	73	1760	0	27	4.8	33	67	60	9000	100	150	9	0.1	0.4	0.7	1.0	161	1.6	15.5	0.99	0	8	0.29	100
	ZC	117	1220	3	43	4.6	24	76	80	2000	38	178	5	0.0	0.3	0.0	3.8	187	1.0	1.5	0.90	0	65	0.04	30

b		C1 FRI	C10 FRI	Recon	Fuel Accum	BA	Stand Dens	Snag vol	QMD	Avg CBH	% Comp (by BA)		Fuel Loading (Mg/ha)							Flame Length (m)		Prob	Torch Index	Crown Index	CBD	Mortality
Area	Site	(yrs)	(yrs)	Year	Time (yrs)	(m^2/ha)	(stems/ha)	(m^3/ha)	(cm)	(m)	Fire Tol	Fire Intol	Duff	Litter	1 hr	10 hr	100 hr	1000 hr	Total	Surface	Crown	Torch	(km/hr)	(km/hr)	(kg/m^3)	(% BA)
Lassen National Forest	BT	19.2	24.3	1976	7	84	500	10	52	8.3	38	62	7	9	6.5	4.4	1.3	0.9	29	0.3	0.3	0.00	268	35	0.10	9
	CA	9.5	--	1862	11	9	150	0	27	5.0	15	85	1	5	2.3	2.3	0.4	0.4	12	0.5	0.3	0.00	185	92	0.03	34
	EL	21.4	61.3	1980	96	113	270	0	79	12.4	37	63	30	75	61.0	59.4	8.5	30.9	265	0.3	0.3	0.00	336	66	0.04	4
	FI	12.5	15.3	1900	20	10	260	0	23	4.0	8	92	3	4	4.9	4.9	0.7	0.8	19	0.4	0.3	0.00	147	81	0.03	29
	FR	14.5	--	1886	35	39	230	0	46	7.8	69	31	15	22	6.6	7.1	3.3	1.2	56	1.2	1.2	0.01	89	61	0.04	13
	JO	17.7	44.5	1958	77	99	440	0	54	7.7	49	51	14	66	10.1	28.4	8.9	3.2	130	0.7	0.6	0.00	94	42	0.08	8
	LC	16.0	--	1858	18	10	50	0	56	7.4	0	100	2	7	7.9	7.9	0.9	4.2	30	0.5	0.6	0.00	186	228	0.01	4
	PB	13.0	10.0	1944	15	1	120	0	12	1.8	0	100	3	2	1.7	1.9	0.2	0.1	8	0.5	0.6	0.03	102	144	0.01	57
	RO	21.0	23.0	1974	7	46	250	70	50	8.9	0	100	1	3	3.5	3.6	0.7	1.1	13	0.3	0.3	0.00	186	49	0.06	12
	SH	15.7	24.3	1903	29	28	210	0	40	7.1	27	73	7	13	10.6	10.8	2.0	2.9	47	0.4	0.3	0.00	186	63	0.04	13
	SL	20.5	20.5	1957	20	20	310	0	33	6.0	0	100	2	11	3.2	2.8	0.7	0.6	20	1.7	1.5	0.81	21	57	0.05	56
	SM	11.9	17.9	1973	27	37	340	113	39	6.7	0	100	4	9	11.1	11.2	1.7	2.8	40	1.6	2.4	0.54	14	39	0.08	82
	SN	15.9	17.7	1911	75	5	200	0	17	3.0	0	100	11	13	16.2	16.1	1.8	2.0	59	0.4	0.3	0.00	96	67	0.04	42
	WF	25.7	--	1929	63	83	220	0	68	10.6	0	100	10	49	22.9	36.7	13.9	9.9	142	0.3	0.3	0.00	442	58	0.05	7
	WL	8.5	17.1	1918	56	5	60	0	33	6.3	0	100	8	20	25.3	25.1	2.8	5.7	87	0.5	0.6	0.00	338	95	0.02	23
Onion Creek	OB	22.2	35.7	1904	22	25	140	0	48	6.7	3	97	4	12	4.0	7.2	3.4	1.9	32	0.3	0.3	0.00	586	61	0.04	6
	OC	15.2	36.5	1903	31	74	340	96	52	9.5	3	97	5	16	12.1	14.4	4.4	3.3	55	0.2	0.3	0.00	409	37	0.08	12
	OD	20.3	32.0	1878	5	25	170	0	41	5.8	0	100	1	2	0.8	1.3	0.5	0.2	5	0.3	0.3	0.00	130	84	0.03	13
	OG	12.0	25.8	1886	15	31	240	0	41	6.8	0	100	2	6	6.8	7.1	1.1	2.2	26	0.4	0.3	0.00	338	54	0.04	13
Lake Tahoe Basin, West Side	BC	20.2	22.5	1923	24	56	200	0	60	8.6	2	98	4	16	6.2	11.3	4.9	2.3	45	0.2	0.3	0.00	425	49	0.06	6
	BW	42.3	--	1952	16	42	430	48	38	6.9	18	82	2	6	5.9	6.3	0.8	1.5	22	0.2	0.3	0.00	290	22	0.16	16
	DC	14.4	20.8	1962	23	118	600	0	53	8.8	1	99	3	11	13.4	13.4	1.5	5.3	47	0.2	0.3	0.00	197	27	0.13	10
	GC	16.0	56.0	1963	94	72	400	20	54	8.6	16	85	13	42	35.3	38.5	7.6	13.7	150	0.2	0.3	0.00	212	40	0.07	9
	ME	15.6	35.5	1848	41	24	210	0	39	7.9	0	100	4	48	6.9	4.1	1.6	1.2	66	1.3	1.2	0.15	45	62	0.04	47
	MK	10.0	32.0	1945	53	98	410	0	71	12.2	30	71	7	27	22.2	23.7	3.1	0.4	84	0.2	0.3	0.00	208	37	0.08	6
	RC	19.6	86.5	1956	5	61	450	0	42	7.9	7	93	1	2	2.6	2.6	0.3	0.8	9	0.3	0.3	0.00	499	28	0.13	16
	RU	14.8	--	1938	96	10	180	0	27	5.4	0	100	13	40	28.1	26.2	3.2	4.9	115	0.3	0.3	0.00	171	62	0.04	40
	TC	8.4	23.0	1860	7	3	50	0	25	2.4	0	100	1	2	1.4	1.7	0.3	0.2	7	0.3	0.3	0.00	--	--	--	35
	TL	16.1	--	1977	112	8	50	4	46	10.4	0	100	12	175	25.0	15.6	6.0	4.5	238	0.3	0.3	0.00	506	105	0.02	36
	WD	22.8	39.0	1912	48	3	100	65	21	3.9	79	21	6	10	4.0	6.8	1.4	0.4	28	0.8	0.9	0.00	62	191	0.01	33
Lake Tahoe Basin, East Side	BU	14.3	26.0	1959	9	17	260	35	29	5.2	24	76	1	3	2.4	2.7	0.4	0.5	10	0.6	0.6	0.00	56	44	0.07	22
	HT	9.0	--	1937	36	28	430	45	29	6.4	25	76	5	10	7.8	9.5	1.9	1.4	36	0.2	0.3	0.00	227	64	0.04	27
	MA	22.1	32.5	1863	8	14	220	0	27	4.5	57	44	1	2	1.5	1.9	0.3	0.3	7	0.3	0.3	0.00	168	75	0.03	24
	MF	10.7	17.0	1919	16	26	240	44	38	7.0	1	99	2	12	4.6	4.1	0.7	1.1	24	0.3	0.3	0.00	195	66	0.04	28
	TU	16.8	29.6	1924	49	7	160	0	24	3.7	83	17	7	10	5.2	8.0	1.6	0.5	32	0.4	0.6	0.00	87	89	0.02	19
	ZC	12.0	14.6	1864	7	5	80	0	29	3.9	40	60	1	2	0.7	1.3	0.4	0.1	5	0.9	0.9	0.05	65	141	0.01	16

c		BA	Stand Dens	Snag vol	QMD	Avg CBH	% Comp (by BA)		Canopy	Seedlings	Shrub	Fuel Load (Mg/ha)							Flame Length (m)		Prob	Torch Index	Crown Index	CBD	Mortality
Area	Site	(m^2/ha)	(stems/ha)	(m^3/ha)	(cm)	(m)	Fire Tol	Fire Intol	Cover (%)	(stems/ha)	Cover (%)	Duff	Litter	1 hr	10 hr	100 hr	1000 hr	Total	Surface	Crown	Torch	(km/hr)	(km/hr)	(kg/m^3)	(% BA)
Lassen National Forest	BT	85	410	0	54	6.8	30	70	45	100	2	106	11	0.2	1.1	2.6	2.6	123	0	0	0.00	248	33	0.11	11
	CA	178	380	0	78	15.9	24	76	69	1000	1	68	8	0.2	0.6	1.3	4.6	83	0	0	0.00	365	28	0.13	5
	EL	69	340	81	53	5.9	26	74	68	5000	8	104	10	0.1	0.3	0.7	0.6	115	0	0	0.00	132	44	0.07	9
	FI	92	750	47	41	18.4	14	86	83	0	0	95	16	0.3	0.7	2.0	4.6	119	1	22	0.00	37	15	0.27	100
	FR	156	350	48	76	15.1	25	75	62	4000	36	34	9	0.1	0.2	1.2	0.3	44	1	13	0.64	12	22	0.10	95
	JO	113	540	43	56	13.6	35	65	50	2000	1	110	15	0.1	0.5	2.4	2.1	130	1	1	0.00	73	39	0.08	9
	LC	71	750	93	36	8.1	50	50	73	0	0	157	17	0.2	1.0	2.8	1.0	179	1	2	0.74	16	32	0.11	69
	PB	69	620	4	39	13.0	9	91	83	0	0	172	18	0.3	3.3	5.4	0.2	199	0	0	0.00	582	32	0.11	17
	RO	100	450	34	56	8.4	0	100	42	3000	15	106	17	0.1	0.6	2.0	0.9	126	1	4	0.57	7	37	0.09	95
	SH	96	440	17	55	7.7	23	77	40	16000	17	104	8	0.2	1.5	2.8	3.6	120	2	21	0.74	0	19	0.18	100
	SL	104	630	14	50	9.7	0	100	54	1000	0	51	4	0.1	0.1	0.7	1.7	58	1	8	0.70	0	30	0.11	97
	SM	39	500	105	37	5.6	63	37	39	0	3	119	10	0.1	0.7	0.4	1.7	131	1	3	0.81	16	29	0.12	72
	SN	107	900	56	41	9.3	3	97	80	2000	5	89	18	0.1	0.5	2.0	1.0	110	1	22	0.55	8	16	0.26	100
	WF	138	430	47	68	14.0	10	90	44	0	10	114	9	0.2	1.0	5.5	1.3	131	1	7	0.57	0	37	0.09	94
	WL	40	280	1	49	5.5	85	16	55	1000	0	127	11	0.1	0.6	1.1	10.5	150	1	1	0.39	28	61	0.05	16
Onion Creek	OB	113	310	47	74	12.1	40	60	23	12000	0	78	42	0.1	0.4	2.4	4.4	128	0	0	0.00	155	35	0.08	7
	OC	116	470	71	64	12.0	6	94	42	13000	25	84	7	0.2	0.5	1.5	0.6	94	0	0	0.06	59	28	0.09	5
	OD	110	320	126	51	16.4	1	99	72	0	0	121	30	0.2	1.5	0.4	3.1	156	0	0	0.00	234	25	0.14	12
	OG	79	430	93	50	7.6	0	100	73	0	0	102	31	0.1	0.7	2.0	2.4	138	1	1	0.49	16	31	0.10	19
Lake Tahoe Basin, West Side	BC	89	870	118	41	5.7	38	63	72	200	2	92	3	0.1	0.0	0.5	2.3	98	2	32	1.00	0	0	0.35	100
	BW	107	345	0	66	8.6	63	37	70	0	19	96	15	0.1	0.6	2.5	0.1	114	0	0	0.00	108	55	0.05	7
	DC	19	80	62	63	11.0	58	42	25	0	21	58	12	0.1	0.5	3.1	1.2	75	1	1	0.00	120	45	0.06	8
	GC	48	455	75	51	5.8	22	78	45	1320	14	112	13	0.0	0.3	1.9	3.8	131	1	2	0.38	5	36	0.08	42
	ME	71	190	36	81	8.3	10	91	10	0	16	134	16	0.2	0.8	1.9	3.1	156	0	0	0.00	190	43	0.06	6
	MK	104	451	342	78	6.7	64	36	50	2700	7	95	7	0.0	0.2	0.7	0.0	103	0	0	0.60	40	17	0.23	6
	RC	76	675	120	59	10.3	12	88	70	60	2	38	6	0.1	0.8	2.6	1.4	49	1	1	0.46	19	21	0.17	17
	RU	71	270	0	55	3.7	0	100	10	0	18	20	4	0.0	0.2	1.0	0.8	27	0	0	0.00	96	26	0.12	18
	TC	35	115	1	73	13.3	86	14	10	120	9	27	5	0.0	0.1	0.0	0.0	32	1	1	0.18	23	74	0.03	6
	TL	62	1960	101	26	5.0	23	77	75	0	4	98	15	0.1	1.2	1.7	2.9	119	1	10	0.98	2	11	0.35	99
	WD	162	600	34	61	10.0	83	18	70	360	23	46	14	0.0	0.3	0.3	0.0	61	1	1	0.00	79	16	0.23	10
Lake Tahoe Basin, East Side	BU	25	180	0	42	9.3	92	8	35	0	9	36	10	0.0	0.4	0.5	0.8	47	1	1	0.00	77	65	0.04	10
	HT	48	230	0	66	12.6	100	0	20	60	5	62	8	0.0	0.3	0.7	0.6	72	1	1	0.00	183	52	0.05	6
	MA	97	315	52	76	10.5	4	97	40	300	5	61	27	0.1	0.4	3.1	4.7	96	0	0	0.00	234	32	0.10	6
	MF	33	410	41	38	5.9	84	17	45	0	40	84	11	0.0	0.5	3.0	1.9	100	1	1	0.00	98	28	0.11	15
	TU	58	390	10	46	7.1	100	0	41	0	17	74	6	0.0	0.6	1.1	1.3	83	1	1	0.00	102	38	0.08	8
	ZC	42	1240	21	31	4.8	91	9	35	0	31	12	9	0.0	0.0	0.0	0.2	21	1	1	0.25	51	19	0.15	34

d		C1 FRI	C10 FRI	Recon	Fuel Accum	BA	Stand Dens	Snag vol	QMD	Avg CBH	% Comp (by BA)		Fuel Loading (Mg/ha)							Flame Length (m)		Prob	Torch Index	Crown Index	CBD	Mortality
Area	Site	(yrs)	(yrs)	Year	Time (yrs)	(m^2/ha)	(stems/ha)	(m^3/ha)	(cm)	(m)	Fire Tol	Fire Intol	Duff	Litter	1 hr	10 hr	100 hr	1000 hr	Total	Surface	Crown	Torch	(km/hr)	(km/hr)	(kg/m^3)	(% BA)
Lassen National Forest	BT	8.8	19.1	1914	23	16	170	0	34	5.9	52	48	3	8	6.5	7.7	1.2	1.2	28	0	0	0.00	21	74	0.03	16
	CA	13.8	24.7	1870	19	23	200	0	38	7.2	41	59	5	8	5.7	5.8	1.2	1.1	27	0	0	0.00	133	64	0.04	17
	EL	16.5	27.3	1931	28	34	240	0	40	7.5	24	76	6	13	13.9	13.6	1.8	3.6	52	0	0	0.00	336	49	0.06	16
	FI	12.3	28.0	1956	73	25	740	0	23	4.0	10	90	13	18	18.3	17.9	2.4	2.6	72	0	0	0.00	170	19	0.20	34
	FR	13.9	18.2	1928	42	68	270	0	53	9.2	21	79	10	25	20.7	22.1	4.1	9.4	92	1	1	0.00	319	40	0.06	8
	JO	13.0	12.2	1869	6	9	190	0	26	4.8	47	53	1	2	1.3	1.3	0.2	0.2	6	1	1	0.17	30	82	0.03	37
	LC	12.0	--	1910	26	6	200	0	20	3.6	59	41	3	5	3.0	4.1	0.7	0.4	16	1	1	0.49	18	83	0.03	86
	PB	42.5	42.5	1929	75	6	230	0	19	3.4	0	100	11	15	16.6	17.1	2.5	2.2	64	0	1	0.00	101	83	0.03	54
	RO	14.8	35.3	1955	50	47	270	0	47	9.2	0	100	7	23	24.2	25.6	4.8	7.3	92	0	0	0.00	204	38	0.08	16
	SH	58.0	52.0	1973	70	52	420	20	41	7.3	31	69	15	29	26.8	26.8	4.5	6.1	109	2	4	0.35	0	42	0.07	95
	SL	11.8	--	1975	9	59	470	2	43	7.9	0	100	1	3	3.0	3.3	0.7	0.8	12	2	5	0.55	11	31	0.11	98
	SM	13.5	46.0	1965	69	32	680	0	31	4.5	6	94	10	20	17.6	19.2	2.0	2.8	72	1	11	0.92	9	22	0.18	98
	SN	23.0	46.0	1980	29	45	320	58	34	6.3	2	98	4	9	11.7	11.8	1.4	2.8	41	1	15	0.69	16	20	0.20	99
	WF	31.8	32.7	1929	63	49	350	0	44	7.7	22	79	9	27	27.5	29.5	4.8	7.6	106	1	2	0.12	20	34	0.10	34
	WL	10.8	14.6	1967	43	19	220	0	40	5.5	93	7	6	12	3.3	6.8	1.8	0.6	31	1	1	0.21	51	99	0.02	16
Onion Creek	OB	15.8	21.4	1904	17	24	240	0	41	7.0	63	37	3	6	3.3	4.2	0.6	0.0	17	1	1	0.02	61	48	0.06	15
	OC	13.4	20.3	1872	10	19	130	0	42	7.8	0	100	1	4	4.6	4.8	0.9	1.2	17	0	0	0.00	395	46	0.05	17
	OD	24.8	42.6	1960	87	75	400	0	48	7.9	0	100	13	38	47.7	47.6	5.6	18.8	170	0	0	0.00	267	31	0.10	13
	OG	7.4	15.6	1886	13	10	210	0	23	3.5	0	100	2	3	3.2	3.3	0.6	0.7	13	0	0	0.00	117	82	0.03	28
Lake Tahoe Basin, West Side	BC	13.8	23.5	1890	4	27	155	0	53	8.3	4	97	1	2	1.1	1.5	0.5	0.4	6	0	0	0.00	400	40	0.06	8
	BW	19.4	13.4	1892	16	12	235	0	26	5.0	60	41	2	5	2.0	3.1	0.6	0.4	13	0	0	0.00	216	76	0.03	35
	DC	13.7	26.5	1911	9	9	45	0	56	8.7	68	32	1	4	1.4	2.6	0.6	0.7	10	1	1	0.00	153	135	0.01	4
	GC	17.4	54.6	1990	87	32	355	91	47	8.3	27	73	13	29	28.2	30.7	4.1	5.9	110	0	0	0.00	354	27	0.11	19
	ME	11.7	10.0	1888	1	20	95	0	45	6.5	4	96	0	1	0.0	0.3	0.2	0.0	1	0	0	0.00	373	85	0.03	9
	MK	11.4	56.3	1892	30	45	250	0	50	9.0	41	59	4	13	6.2	9.7	3.2	1.8	38	0	0	0.00	405	36	0.09	10
	RC	17.6	37.5	1957	67	38	225	92	55	10.4	37	63	17	36	29.7	29.9	4.9	7.3	124	0	0	0.00	426	43	0.07	11
	RU	29.3	--	1930	60	28	120	0	42	8.0	0	100	9	27	22.5	25.9	8.0	5.7	98	0	0	0.00	281	114	0.02	19
	TC	15.1	32.2	1883	12	5	55	0	32	4.4	100	0	1	3	0.1	1.4	0.5	0.0	6	1	1	0.03	49	307	0.00	14
	TL	11.6	--	1980	74	20	760	126	30	3.6	7	93	10	11	10.5	11.8	1.6	1.9	47	1	2	0.98	1	25	0.14	67
	WD	18.7	29.0	1882	18	10	360	0	20	3.4	56	44	2	3	0.6	1.9	0.5	0.1	9	1	1	0.05	39	101	0.02	43
Lake Tahoe Basin, East Side	BU	6.1	11.1	1896	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	HT	10.7	--	1957	38	18	230	0	45	7.2	100	0	5	11	0.3	4.9	1.7	0.1	22	1	1	0.02	58	79	0.03	44
	MA	16.9	21.3	1867	9	13	165	0	33	4.4	3	97	2	3	0.6	1.7	1.1	0.3	9	0	0	0.00	155	92	0.02	14
	MF	10.9	16.8	1917	14	14	70	0	49	9.0	3	97	2	8	9.2	9.3	1.1	3.1	32	0	0	0.00	575	139	0.01	10
	TU	11.6	16.5	1932	7	9	220	0	24	4.1	100	0	1	2	0.0	0.7	0.2	0.0	3	1	1	0.04	49	99	0.02	29
	ZC	13.4	14.2	1935	7	10	100	0	43	7.1	97	3	1	2	1.0	1.7	0.4	0.1	6	1	1	0.00	46	75	0.03	20

3.6 Correlation of Reconstructed Variables with Fire Return Interval

Reconstructed riparian CBD was the only variable significantly correlated with C1 FRI in reconstructed riparian stands (Table 5). All reconstructed upland fuel-load variables (duff, litter, 1 hr, 10 hr, 100 hr, 1000 hr, total) were significantly correlated with upland C1 FRI. No other reconstructed upland variables were significantly correlated with C1 FRI in reconstructed upland stands.

Table 5. Pearson's correlation coefficients exploring the relationships between a broad filter fire return interval (C1 FRI, derived from all fire events scarring one or more trees at a given site) and reconstructed riparian and upland stand structure, fuel loads, and potential fire behavior and effects. * indicates significant correlation ($p<0.05$). Sample size is 36 for all variables in each column except riparian (n=35 for torching index, crowning index, and CBD), and upland (n=35 for all variables).

	Riparian	Upland
BA (m^2/ha)	0.207	0.289
Stand Density (stems/ha)	0.190	0.111
QMD (cm)	0.223	-0.035
Avg CBH (m)	0.190	0.040
% Composition (by BA)		
Fire Tolerant	0.133	-0.170
Fire Intolerant	-0.133	0.170
Snag Volume (m^3/ha)	0.094	0.046
Fuel Loads (Mg/ha)		
Duff	0.062	0.524*
Litter	0.044	0.488*
1 hr	0.013	0.507*
10 hr	0.076	0.496*
100 hr	0.206	0.501*
1000 hr	0.140	0.380*
Total	0.070	0.520*
Flame Length (m)		
Surface	-0.094	0.311
Crown	-0.112	0.12
Probability of Torching	0.003	0.037
Torching Index (km/hr)	0.236	-0.153
Crowning Index (km/hr)	-0.150	-0.100
CBD (kg/m^3)	0.415*	0.065
Mortality (% BA)	-0.252	0.331

3.7 Correlation of Current and Reconstructed Riparian and Upland Variables

Current riparian and upland stands have significantly correlated BA, snag volume, CBH, surface fire flame length, and probability of torching (Table 6). There were significant correlations between reconstructed riparian and upland QMD, average CBH, species composition, surface and crown fire flame length, probability of torching, and potential mortality. No other variables were significantly correlated between current or reconstructed riparian and upland stands.

Table 6. Pearson's analysis exploring the relationships between riparian and upland stand structure, fuel loads, and potential fire behavior and effects variables for both current and reconstructed conditions. * indicates significant correlation ($p<0.05$). Sample size is 36 for all variables in each column except reconstructed (n=35 for all variables except n=34 torching index, crowning index, and CBD).

	Current	Reconstructed
BA (m^2/ha)	0.384*	0.139
Stand Density (stems/ha)	0.172	-0.096
QMD (cm)	0.319	0.417*
Avg CBH (m)	0.485*	0.467*
% Composition (by BA)		
Fire Tolerant	0.322	0.355*
Fire Intolerant	0.322	0.355*
Snag Volume (m^3/ha)	0.511*	-0.107
Fuel Loads (Mg/ha)		
Duff	-0.098	0.153
Litter	-0.207	0.027
1 hr	0.147	0.176
10 hr	-0.036	0.190
100 hr	-0.036	0.177
1000 hr	0.088	0.101
Total	-0.215	0.137
Flame Length (m)		
Surface	0.527*	0.366*
Crown	0.024	0.424*
Probability of Torching	0.418*	0.495*
Torching Index (km/hr)	0.104	0.161
Crowning Index (km/hr)	-0.147	0.219
CBD (kg/m^3)	-0.093	-0.003
Mortality (% BA)	0.229	0.494*

3.8 Comparison of Sampling Areas

While there was a great deal of variability within sampling areas, some interesting patterns emerge in the differences between them (Table 7). The east side of the Tahoe Basin consistently had the least fire-prone forest structure and fuel loads, while the Lassen National Forest was usually the most fire prone.

Table 7. Comparison of stand structure, fuel loads, and potential fire behavior and effects least squares mean (standard error) values for the sampling areas. Values in the same row followed by a different letter are significantly different (Tukey's post-hoc ANOVA, p<0.05), p-values are for the ANOVA global F test. Sample size is 36 for all variables in each column except riparian reconstructed (n=35 for torching index, crowning index, and CBD), and upland reconstructed (n=35 for all variables). Fire behavior calculated under 97th weather conditions.

	Lassen	Onion	W Tahoe	E Tahoe
BA (m²/ha)	57.1(0.1)a	69.0(0.5)a	44.5(0.2)ab	31.3(0.3)b
Stand Dens(stems/ha)	370.5(1.1)a	308.8(1.2)a	310.7(1.1)a	299.4(1.2)a
QMD (cm)	44.4(2.5)a	50.7(4.8)a	46.1(2.9)a	38.1(3.9)a
Avg CBH (m)	7.5(0.01)a	8.5(0.02)a	6.6(0.01)a	6.3(0.02)a
% Comp (by BA)				
Fire Tolerant	13.3(0.3)ab	4.1(1.3)a	17.2(0.5)ab	42.5(0.9)b
Fire Intolerant	87.7(0.3)ab	95.9(1.3)a	82.8(0.5)ab	57.5(0.9)b
Snag Vol (m³/ha)	6.5(0.3)a	10.1(0.6)a	9.5(0.3)a	4.7(0.5)a
Fuel Loads (Mg/ha)				
Duff	21.1(1.1)a	14.7(1.2)ab	14.5(1.1)ab	10.9(1.2)b
Litter	11.9(1.1)a	11.3(1.3)a	9.6(1.2)a	7.5(1.2)a
1 hr	1.1(1.2)a	0.9(1.4)ab	0.5(1.2)b	0.2(1.3)c
10 hr	2.3(1.1)a	1.9(1.3)ab	1.4(1.2)ab	1.1(1.2)b
100 hr	1.6(0.01)a	1.5(0.02)a	1.3(0.01)a	0.8(0.02)a
1000 hr	2.0(0.0)a	2.0(0.0)ab	1.2(0.0)ab	0.9(0.0)b
Total	64.2(1.1)a	51.5(1.2)ab	47.6(1.1)ab	33.3(1.2)b
Flame Length (m)				
Surface	0.8(1.1)a	0.4(1.3)b	0.5(1.1)b	0.6(1.2)ab
Crown	2.9(1.1)a	5.7(1.2)b	4.2(1.1)ab	3.8(1.2)ab
Prob of Torch	0.30(0.06)a	0.09(0.11)a	0.22(0.06)a	0.17(0.09)a
Torch Index (km/hr)	40.7(0.3)a	117.5(0.7)a	66.6(0.4)a	52.6(0.5)a
Crown Index (km/hr)	40.2(0.1)a	38.2(0.2)a	37.8(0.1)a	52.2(0.2)a
CBD (kg/m³)	0.08(1.11)a	0.07(1.23)a	0.07(1.13)a	0.05(1.19)a
Mortality (% BA)	31.7(1.2)a	12.9(1.3)a	20.6(1.2)a	19.8(1.3)a

East Tahoe had 55% the BA of Lassen, and 45% the BA of Onion Creek. Fire-tolerant species comprised 38.4% more of the BA in east Tahoe than in Onion Creek. Lassen had nearly double the duff fuel loads of east Tahoe. Fuel loads in the 1 hr size class in east Tahoe were 40% lower than Onion Creek, nearly 50% lower than west Tahoe, and more than 80% lower than Lassen. Fuel loads in the 10 and 1000 hr classes in east Tahoe were both more than 50% less than those of Lassen. Surface fire flame lengths in Lassen were nearly double those in Onion Creek and west Tahoe, while crown fire flame lengths in Lassen were nearly half those in Onion Creek.

3.9 Riparian vs. Upland Canopy Cover, Seedling Density, and Shrub Cover

Notable differences emerged when riparian and upland canopy cover, seedling density, and shrub cover were analyzed by sampling area (Table 8). Across all four sampling areas combined, canopy cover was very similar between riparian and upland forests. The same pattern is evident for the Lassen, Onion Creek, and West Side Tahoe sampling areas. On the east side of the Tahoe Basin, however, canopy cover of upland forests is 22% lower on average than that of riparian forests (Table 8).

Table 8. Current riparian and upland mean canopy cover, seedling density, and shrub cover for the data set overall and by sampling area.

	Riparian			Upland		
	Canopy Cover (%)	Seedlings (stems/ha)	Shrub Cover (%)	Canopy Cover (%)	Seedlings (stems/ha)	Shrub Cover (%)
Overall	54	3175	25	51	1812	10
Lassen	58	3333	11	59	2340	6
Onion Creek	53	5250	39	53	6250	6
West Side Tahoe	47	2209	30	46	433	12
East Side Tahoe	58	3167	41	36	60	18

Similarly, riparian seedling density was nearly twice as high that of upland forests for all study areas combined (Table 8). This pattern is largely driven by the East Side Tahoe sampling area, in which riparian seedling density is 53 times higher than upland seedling density. A similar trend of lower magnitude is noted in the West Side Tahoe and Lassen sampling areas, while the opposite trend is noted in Onion Creek, the most mesic of the sampling areas.

Shrub cover is generally higher in riparian than in upland forests for all sampling areas combined (Table 8). This trend holds when each sampling area is analyzed individually, although there is a strong gradient of differences. In Lassen, riparian shrub cover is 4% higher than upland shrub cover, while the difference in shrub cover is as high as 33% in Onion Creek. The east and west sides of the Tahoe Basin have intermediate differences between riparian and upland shrub cover of 23% and 18%, respectively.

4. Discussion

While this study compares current and reconstructed riparian and upland fire regimes and forest conditions, it does not imply that forests should be restored to reconstructed historical conditions, which may be neither feasible nor desirable in the context of altered anthropogenic influences and climatic conditions (Anderson and Moratto, 1996; Douglass and Bilbao, 1975; Millar and Woolfenden, 1999; Pierce et al., 2004; Rowley, 1985). A more effective restoration strategy may be to approximate the processes and conditions under which the target ecosystem evolved, which include frequent low-intensity fire in of the case of Sierran yellow pine and mixed conifer forests (generally occurring from 370 to 1700 m elevation in the northern Sierra, and from 760-2700 m in the southern part of the range) (Agee et al., 1978; Falk, 1990; Kilgore and Taylor, 1979; Parsons and DeBenedetti, 1979; SER, 1993; Vankat and Major, 1978). Rather than providing specific standards for restoring forests, the comparisons drawn in this study are intended to highlight the differential departure of current riparian and upland conditions from historic conditions, and offer a reference for the stand structure, species composition, and fuel loads produced by an active fire regime (Falk, 1990; White and Walker, 1997).

4.1 Fire Regimes

4.1.1 Riparian vs. Upland FRI

Riparian fire histories of the sites we sampled were very similar to their adjacent upland forests, but with a few important differences. At most sites, there was no significant difference between riparian and upland fire return intervals under the C1 and C10 filters, which fails to support our first hypothesis but is consistent with some studies comparing riparian and upland fire histories (Charron and Johnson, 2006; Olson and Agee, 2005). At these sites, the similarity of riparian and upland fire return intervals suggests that streams may not act as an effective buffer to fire activity and movement through the landscape. However, approximately one fourth of the sites did exhibit a significant difference between riparian and upland fire return intervals under both the C1 and C10 filters, similar to other studies of riparian fire history (Everett et al., 2003; Skinner, 2003), although riparian and upland FRI may not be directly comparable if the areas sampled are not of similar size. This suggests that riparian areas may reduce fire frequency and act as a buffer to fire movement in some cases, as proposed in our first hypothesis (Camp et al., 1997; Skinner and Chang, 1996; Taylor and Skinner, 2003).

At three sites, the riparian areas had significantly shorter fire return intervals than the upland areas, directly contradicting our first hypothesis and suggesting that riparian areas may have occasionally acted as a corridor for fire movement through the landscape (Dwire and Kauffman, 2003; Pettit and Naiman, 2007). Riparian zones typically exhibit higher soil moisture, and are thus often characterized by higher site quality than adjacent upland areas (Agee, 1998). This may result in more rapid rates of fuel production and, in some cases, more frequent fire return intervals in the riparian zone than in adjacent upland areas, where fuel may be limiting fire spread through the landscape. Additionally, these sites had extensive meadow systems associated with portions of the riparian area, which may have been centers of native American travel and use (Lindstrom et al., 2000; Olson and Agee, 2005). Numerous indigenous tribes in the Sierra Nevada used fire for a variety of purposes, and likely had an influence on fire regimes (Anderson and Moratto, 1996). The ferns, sedges and rushes common to extensive meadow systems were often used in Native American basketry, and would have been burned frequently to maintain their quality (Anderson, 2006). Areas which historically experienced heavy use by Native American populations are associated with shorter fire return intervals (Barrett and Arno, 1982), possibly due to the prevalence of anthropogenic ignitions, although the actual ignition source of most historic fires cannot be known and FRI calculated from different sample area sizes may not be directly comparable.

4.1.2 Riparian vs. Upland Seasonality

In both riparian and upland areas, a majority of the fire scars occurred during the dormant season (late summer to early fall in this region), which is consistent with other fire history studies in the Sierra Nevada (Moody et al., 2006; Stephens and Collins, 2004; Taylor and Beaty, 2005). Four of the six sites that exhibited a greater proportion of non-dormant season fires were in Jeffrey pine forest type, indicating that pine-dominated forests may have experienced more spring and early-summer fires than other forest types (Table 1). Although not significantly different, there is a trend of more early earlywood fire scars in upland areas, indicating that earlier season fires may be more prevalent in upland areas than in riparian areas, as proposed in our second hypothesis (Figure 3). This may result from riparian areas having cooler microclimates that retain snow longer into the summer drying period. These mesic conditions, which maintain higher fuel moisture into the late spring and early summer, possibly limit fire from spreading into riparian areas during the spring season.

4.1.3 Forest Characteristics

Riparian and upland fire return intervals are shorter in sites surrounded by upland forests with a high proportion of fire-tolerant pine species under both the C1 and C10 filters (>22.7% and >37.6%, respectively), suggesting that fires may move into riparian areas more easily in pine-dominated forests. Similarly, the NMS results for riparian C10 fires suggest a shorter fire return interval in riparian forests with a higher proportion of pine, supporting our third hypothesis. Although the CART results indicate that the shortest riparian C10 fire return intervals are in mixed-conifer forests, similarly short fire return intervals are found in Jeffrey-pine and white fir forest types. The association of shorter fire return intervals with pine-dominated sites has been well-demonstrated in numerous studies of upland forests (Gill and Taylor, 2009; McKelvey et al., 1996; Skinner and Chang, 1996; Stephens, 2001), and appears to hold true in some riparian forests as well.

4.1.4 Precipitation Regimes

Both riparian and upland fire return intervals of our east-side sites were some of the shortest we found amongst all our samples under both the C1 and C10 filters, supporting our fourth hypothesis. However, the fire return intervals of these sites were well within the range of our west-side sites. Similarity of east-side and west-side fire regimes by forest type have been documented in several studies (Gill and Taylor, 2009; North et al., 2009; Stephens, 2001; Taylor, 2004; Taylor and Beaty, 2005; Vaillant and Stephens 2009). All 7 of our east-side sites were in Jeffrey pine forest type, which tend to have shorter fire return intervals than other forest types. Furthermore, the eastern slope of the Sierra Nevada experiences a pronounced rain shadow effect, in which storms moving inland from the Pacific Ocean drop most of their precipitation west of the Sierra crest. The drier conditions of the east side may create more consistently favorable burning conditions (North et al., 2009), resulting in shorter fire return intervals.

4.1.5 Site Characteristics

Upland return interval appears to be shorter at higher elevation (>1709 m) under the C1 filter, appearing to contradict our fifth hypothesis. Similarly, the upland C10 NMS results show a trend of decreasing fire return interval with increasing elevation. However, the upland C10 regression tree indicates that fire return intervals are shorter at lower elevation (<1944 m), appearing to support our fifth hypothesis. This apparent contradiction is primarily driven by 6 sites in the CART analysis that could not be included in the NMS analysis because the fire scar record was insufficient for calculating some fire return interval metrics. Five of these sites are <1944 m elevation and have a mean upland C10 fire return interval <40 years. The tendency of fire return interval to increase with elevation has been demonstrated in some studies (Bekker and Taylor, 2001; Caprio and Swetnam, 1995; Gill and Taylor, 2009; Heyerdahl et al., 2001; Swetnam et al., 2000; Taylor, 2000), while others have suggested that forest type and stand isolation may be more important for determining fire return interval in some cases (North et al., 2009; Stephens, 2001). The trend of shorter C1 fire return intervals at higher elevation in our data may be explained by the large number of fire events that were recorded on only one tree per site at high elevations. This may be due to an increase in number of lightning strikes with elevation (van Wagtendonk and Cayan, 2008), which could result in many small fires each scarring only one tree. These fires may fail to spread due to sparse fuels, low fuel production rates (Agee et al., 1978; Stohlgren, 1988; Swetnam et al., 2000), higher fuel moisture, and lower fuel packing ratios (Albini, 1976; Martin et al., 1979; Rothermel, 1983; van Wagtendonk et al., 1998). Low elevations, conversely, provide fuel conditions favorable to greater fire rate of spread (Gill and Taylor, 2009), resulting in the pattern of longer C10 fire return intervals at lower elevations in our CART analysis.

4.1.6 Stream Characteristics

Under the C1 filter, riparian fire return intervals were shorter on more incised (width to depth ratio <6.3), smaller streams (depth <1.3 m), suggesting that wider, deeper streams may be more effective barriers to small-scale fire activity and spread in some cases. Similarly, riparian fire return intervals under the C10 filter are shorter on narrower streams with lower gradient, partially supporting (width, depth, width/depth ratio) and partially contradicting (gradient) our sixth hypothesis. Agee (1993) hypothesized that streams with wider riparian zones would experience longer fire return intervals than those with narrow riparian zones. While some studies found no significant difference between the fire-return intervals of small and large streams (Olson and Agee, 2005), others indicate that small headwater streams are influenced by fire to a greater degree than larger streams, which are influenced more by fluvial processes (Charron and Johnson, 2006). Similar studies comparing riparian fire return intervals have found that first order, high gradient streams in ravines have shorter fire return intervals than second and third order, low gradient streams in wide valleys (Everett et al., 2003; Skinner, 2003).

4.1.7 Fire-Climate Synchrony

Increased occurrence of fire in both riparian and upland forests across all sample sites was significantly correlated with drought cycles, as recorded in the PDSI. This correlation was stronger in the upland areas than in the riparian areas, indicating that upland fire return intervals are more highly synchronized with summer drought conditions, seemingly contradicting our seventh hypothesis. The correlation between years of heightened regional fire activity in upland areas and PDSI dry years has been demonstrated in numerous fire history studies (Swetnam, 1993; Swetnam and Baisan, 2003; Taylor and Beaty, 2005), but has yet to be studied in riparian areas. Because riparian areas typically feature higher moisture and lower temperature conditions, they may be effective buffers to fire movement under all but the most severe drought conditions when their high fuel loads may permit higher severity fire than adjacent upland areas would experience (Dwire and Kauffman, 2003; Pettit and Naiman, 2007; Skinner and Chang, 1996).

4.1.8 Temporal Variability in FRI

While many fire history studies have recorded a sharp decline in fire frequency following Euro-American settlement (Beaty and Taylor, 2001; Beaty and Taylor, 2008; Caprio and Swetnam, 1995; Moody et al., 2006; Olson and Agee, 2005; Stephens, 2001; Stephens and Collins, 2004; Taylor, 2000; Taylor, 2004; Taylor and Skinner, 2003), most of our sample sites showed no significant difference in mean FRI before and after 1850, and four sites had a significantly shorter FRI after 1850. Although temporal analysis of FRI could not be conducted for some sites due to a lack of recorded fire events before 1850, many sites continue to record fire events well into the 20th century (Figures 2a and 2b). Patterns of pre-settlement fire frequencies continuing into the post-settlement (Scholl and Taylor, 2010) and even post-fire suppression (North et al., 2009) periods have been documented in some fire history studies. Our Lassen and Tahoe sampling areas experienced extensive railroad logging during the post-settlement period, which was accompanied by frequent slash fires (Lawson and Elliot, 2008; Lindstrom et al., 2000), which may explain the continuity, or decrease, in FRI at most of our sample sites. A database of fire perimeters in California shows that fires have continued to burn in these areas throughout the 20th and into the 21st century (FRAP, 2009), indicating that fires still occur in some of our sampling areas, even if fire regimes have been altered.

4.2 Stand Structure, Fuel Loads, and Fire Behavior

4.2.1 Current versus Reconstructed Forest Conditions

Overall, most of the reconstructed values for riparian and upland variables were within the range of variability described in other forest reconstructions, historic inventory data, and studies of forests with currently active fire regimes (i.e. recurrent fire at intervals similar to the range of variability found prior to EuroAmerican settlement) (Table 9). Variability was generally higher in riparian forests under both current and reconstructed conditions, except for reconstructed stand density, snag volume, probability of torching, torching and crowning indices, and mortality; current QMD, CBH, species composition, 10 and 100 hr fuel loads; and species composition, crown flame length, and CBD in both current and reconstructed stands, which had higher standard errors in upland forests (Table 4). The variability of riparian and upland forests is certainly subject to geographical variation, and caution should be taken when drawing generalizations about the differences between riparian and upland forests.

Table 9. Reconstructed riparian and upland forest conditions compared with the range of variability under an active fire regime as described in existing literature.

	Reconstructed		Range of	
	Riparian	Upland	Variability	Reference
BA (m^2/ha)	28.5	21.4	8.0-59.7	a, c, e, i, l, m, n
Stand Density (stems/ha)	207.7	201.1	16.2-280.0	a, c, e, i, l, m, n
QMD (cm)	40.0	38.4	33.0-67.5	e, i, l, m, n
Avg CBH (m)	6.5	6.3	4.9-6.1	a, c
% Composition				
Fire Tolerant	8.6	21.3	48.9-94.6	b, e, i, l, n
Fire Intolerant	91.4	78.7	5.4-51.1	b, e, i, l, n
Snag Density (snags/ha)	19.4	49.1	5.0-150.7	b, h, j, k, l
Fuel Loads (Mg/ha)				
Duff	3.3	3.0	NA	
Litter	8.8	6.9	0.4-23.9	k
1 hr	5.4	3.0	0.0-0.9	k
10 hr	6.3	5.5	0.0-7.0	k
100 hr	1.8	1.5	0.0-8.8	k
1000 hr	1.4	0.9	0.0-156.4	k
Total	27.9	22.3	0.4-183.7	f, k
Flame Length (m)				
Surface	0.4	0.5	1.0-2.0	c, f
Crown	0.9	0.4	7.1-9.2	g
Probability of Torching	0.03	0.08	NA	
Torching Index (km/hr)	176.3	98.6	22.0-67.0	c, g
Crowning Index (km/hr)	61.6	61.9	48.0-371.0	a, c, d, g
CBD (kg/m^3)	0.04	0.04	0.01-0.12	a, c, d, g
Mortality (% BA)	16.5	21.0	21.9	l

[a] Brown et al. (2008)
[b] Fule and Covington (1997)
[c] Fule et al. (2002)
[d] Fule et al. (2004)
[e] North et al. (2007)
[f] Ottmar et al. (1995)
[g] Roccaforte et al. (2008)
[h] Savage (1997)
[i] Scholl and Taylor (2010)
[j] Stephens (2000)
[k] Stephens (2004)
[l] Stephens et al. (2008)
[m] Stephens and Gill (2005)
[n] Taylor (2004)

Both riparian and upland forests currently have significantly greater BA, stand density, snag volume, CBD, duff and total fuel load, and lower torching and crowning indices than their respective reconstructed conditions, supporting the ninth hypothesis. Additionally, current riparian stands have significantly higher potential surface and crown fire flame lengths, probability of torching, and mortality than reconstructed riparian stands, also supporting the ninth hypothesis. These trends in current versus historical stand structure are similar to those found in other reconstructions of historical Sierran coniferous forests, and comparisons with early 20th century forest inventory data (Bouldin, 1999; Lieberg, 1902; North et al., 2007; Scholl and Taylor, 2010; Sudworth, 1900; Taylor, 2004). While some studies have found that current BA is not significantly different from reconstructed BA in drier forest conditions (North et al., 2007; Taylor, 2004), other studies in more mesic conditions have found that current BA has approximately doubled since the time of the last fire, similar to the results of this study (Scholl and Taylor, 2010; Taylor, 2004).

Most studies have found that stand density has increased dramatically since the active fire period (i.e. the period of time when fires occurred at intervals within the range variation found prior to EuroAmerican settlement), by factors ranging from 3 to 33, which is a larger increase than is found in this study (North et al., 2007; Scholl and Taylor, 2010; Taylor, 2004). The trend of increasing stand density is corroborated by historical data suggesting that early 19th century Sierran coniferous forests had stem densities much lower than current conditions in this study (Bouldin, 1999; Lieberg, 1902; Sudworth, 1900).

Although it seems intuitive that the higher snag volumes in current riparian and upland stands are the result of the absence of frequent fires that would have historically consumed snags, it is possible that the reconstructions in this study failed to detect snags that were standing at the time of the last fire, but fell and decayed prior to data collection. Without other reconstructions or historical measurements of snag volume, it is impossible to determine whether the trend of increased snag volume is a real effect or an artifact of the reconstruction methods. However, snag densities in a current mixed-conifer forest with an active fire regime in northern Mexico are much lower than those in forests that have experienced fire suppression, suggesting that the absence of fire may indeed lead to increased snag density and volume (Barbour et al., 2002; Ganey, 1999; Savage, 1997; Stephens, 2004; Stephens and Finney, 2002).

The greater BA and stand density of current riparian and upland forests are reflected in the greater canopy fuels as well. The two- to three-fold increases in current riparian and upland CBD from reconstructed conditions are within the range of other comparisons between current and reconstructed stand conditions in the southwestern US and the Black Hills, which found increases ranging from 48% to 750% (Brown et al., 2008; Fulé et al., 2002; Fulé et al., 2004; Roccaforte et al., 2008). Similar trends occur for some classes of surface fuels, with duff loads increasing by an order of magnitude and total fuel loads approximately tripling from reconstructed to current conditions. Other comparisons of reconstructed and current total fuel loads found increases ranging from 2% to 43% in some river basins and watersheds, but decreases in others (Huff et al., 1995).

These changes in stand structure and fuels have made current riparian and upland forests more susceptible to high-intensity fire. Potential torching indices in current riparian and upland stands have decreased by 88% and 52%, respectively, which appears to be a greater change than the 39% to 66% declines in torching index found in other studies modeling current and reconstructed fire behavior (Fulé et al., 2002; Roccaforte et al., 2008). Similarly, potential crowning indices in current riparian and upland stands have decreased by 57% and 54%, respectively, which is within the range of the 23% to 86% declines in crowning index found in other studies (Fulé et al., 2002; Fulé et al., 2004; Roccaforte et al., 2008). The surface and crown fire flame lengths in current riparian forests have increased by 50% and 125%, respectively, which is less than the 134% to 515% increases in flame length predicted by other studies comparing potential fire behavior in current and reconstructed forests (Fulé et al., 2002; Roccaforte et al., 2008). The probability of torching in current riparian forests is 15 times that of reconstructed forests, and the predicted basal area mortality has increased from 16.5% to 30.6%. Observed fire-caused mortality in a forest with an active fire regime in northwestern Mexico was 21.8% which, when compared with the 40-95% mortality in fire-suppressed forests in southern California, reveals a similar trend (Franklin et al., 2006; Stephens et al., 2008). Differences in many stand structure and fuel load variables have resulted in current riparian and upland stands exhibiting greater potential for high-intensity fire than their reconstructed counterparts, supporting the ninth hypothesis.

However, differences in QMD, CBH, and 1 to 100 hr fuels appear to contradict the ninth hypothesis. This study was not designed to directly identify the mechanisms driving stand structure and fuel load differences, so we can only offer the following hypotheses as possible explanations. Upland forests currently have a significantly larger QMD than reconstructed upland stands, and riparian stands show a similar but non-significant trend, contrary to the significant decreases in QMD attributed to infilling of small trees observed in other reconstruction studies (Fule et al., 2002; North et al., 2007). In this study, the rapid growth of small trees in the absence of fire may result from highly productive site conditions and more than a century of growth between the reconstruction period and current measurements at many sites. Many of the trees aged (56%) were >40 cm DBH but <150 years old.

Higher upland CBH and lower 1 to 100 hr fuels were found in current forests than in the reconstructed stands. This may result from high stem densities in current stands and the delay between foliage and branch shedding as trees self-prune under low-light conditions (Fitzgerald, 2005). Many current stands have high canopy cover with the lower limbs of most trees dead and denuded of foliage. CBH, which measures distance from ground to green branches, was often high and duff fuel loads were very high. Fuel loads in the 1 to 100 hr classes were low possibly because trees had not yet begun shedding their dead lower limbs. The fuel accumulation equations used (van Wagtendonk and Moore, 2010) were developed in relatively low-density stands (average BA of 41.6 m^2/ha) that may be more representative of an active fire regime and conditions reconstructed in this study (FRAP, 2010), which have a greater input of woody fuels from fire-killed limbs.

4.2.2 Riparian versus Upland Forests, Current Conditions

Current riparian stands had significantly higher stem density, lower QMD, lower CBH, lower proportion of fire-tolerant species, higher probability of torching, and greater predicted mortality than current upland stands, supporting the tenth hypothesis. Current stem density was approximately 58% greater in riparian than upland stems, a trend similar to the observations of higher stem density closer to water bodies and stream channels in boreal (about four times greater), mixed-conifer, and pinyon pine forests (138% higher), although the opposite trend was found in a coastal Douglas-fir forest with hillslope stem density twice as high as that in the riparian areas (Harper and Macdonald, 2001; Russell and McBride, 2001; Segura and Snook, 1992; Wimberly and Spies, 2001). Highly productive riparian zones may be able to support greater infilling of small trees, resulting in a current QMD 17% lower than adjacent upland areas, a trend also found in pinyon pine and coastal Douglas-fir forests (Segura and Snook, 1992; Wimberly and Spies, 2001). While current average CBH in this study is nearly 3 m lower in the riparian forests than in the upland, visual assessment of vertical structure in drawn-to-scale illustrations of coastal Douglas-fir forests shows no trend in height to live crown with increasing distance from the stream channel (Poage, 1994).

The current proportion of species composition accounted for by fire-tolerant species was 16% greater in upland stands than riparian stands, which is consistent with findings of 13-52% greater prevalence of fire-tolerant species with increasing distance from the stream channel in coastal Douglas-fir forests (McGarigal and McComb, 1992; Nierenberg and Hibbs, 2000; Pabst and Spies, 1999; Wimberly and Spies, 2001). In boreal forests, however, the proportion of the more fire-tolerant balsam poplar (*Populus balsamifera ssp. balsamifera*) decreases relative to the less fire-tolerant quaking aspen as distance from the lakeshore increases (Harper and Macdonald, 2001). Similarly, prevalence of fire-intolerant conifers was more highly correlated with distance from the stream channel than prevalence of fire-tolerant conifers in a mixed-conifer forest, possibly indicating that upland forests may be more strongly associated with fire-intolerant than fire-tolerant species in some cases (Russell and McBride, 2001).

Denser riparian stands composed of primarily fire-intolerant species with more vertical continuity of canopy fuels may result in higher riparian fire severity. The doubling of the probability of torching and predicted mortality in current riparian stands compared to current upland stands found in this study is consistent with observations of greater occurrence of crown fire near stream channels in pinyon pine forests (Segura and Snook, 1992). In contrast, no difference in percent crown scorch between riparian and upland stands was found in mixed-evergreen, mixed-conifer, and ponderosa pine forest types of southwestern and northeastern Oregon (Halofsky and Hibbs, 2008). While other factors such as differences in topography between riparian areas and uplands may also influence fire behavior, differences in stand structure, composition, and potential fire behavior found in this study suggest that riparian forests currently may be more susceptible to high-intensity fire than upland forests, supporting the tenth hypothesis.

Analysis of the correlation between current upland and riparian variables suggests that currently there is greater similarity between adjacent riparian and upland stand structure than there was historically. Some stand structure variables such as BA and snag volume are significantly correlated under current conditions, but not under reconstructed conditions. Similarly, current average CBH is more highly correlated than reconstructed average CBH. This may be attributable to infilling of small trees facilitated by fire suppression, and accumulation of snags in the absence of an active fire regime (North et al., 2007; Stephens 2004).

While riparian and upland QMD were significantly correlated in reconstructed stands, the lack of significant correlation under current conditions may be the result of differential infilling of small trees due to differences in riparian and upland productivity (Camp et al., 1997; Olson and Agee, 2005; Segura and Snook, 1992; Skinner and Chang, 1996). The same productivity-driven differential infilling of fire-intolerant species in riparian areas may be responsible for the current non-significance of the correlation between riparian and upland species composition. In contrast, the significant correlation between riparian and upland species composition under reconstructed conditions may be associated with a higher proportion of fire-tolerant species across the landscape maintained by a historically active fire regime (North et al., 2007; Taylor, 2004). There is no consistent correlation between riparian and upland fuel classes under current or reconstructed conditions, suggesting that differences in productivity may drive fuel accumulation and decomposition on a site-specific basis, despite there being no significant difference between riparian and upland mean fuel loads. Increasing homogeneity in stand structure of adjacent riparian and upland forests may contribute to increased susceptibility to high-intensity fire across the landscape (Fulé et al., 2004), as evidenced by the higher correlation between riparian and upland surface flame lengths under current conditions.

In contrast, there appears to be less similarity between riparian and upland forests in other fire behavior variables under current compared to reconstructed conditions. Current riparian and upland crown fire flame length is not correlated, possibly reflecting greater susceptibility of riparian areas to high-intensity fire and torching (Segura and Snook, 1992). However, crown fire flame length was highly correlated for upland and riparian forests under reconstructed conditions, with both forests having low values. Similarly, while the probability of torching was more highly correlated between riparian and upland forests under reconstructed conditions with mostly low values, it is slightly less correlated under current conditions, perhaps due to the greater probability of torching in riparian areas. Finally, riparian and upland potential mortality was highly correlated, with predominately low values under reconstructed conditions, but is currently not significantly correlated due to increased predicted mortality in riparian forests under current conditions. Although homogeneity between riparian and upland forests may be increasing in some stand structure variables due to infilling of small trees, fire behavior appears to be diverging, with riparian forests becoming more susceptible to high-intensity fire.

Current differences between riparian and upland canopy cover, seedling density, and shrub cover can likely be attributed to the relative disparity in moisture conditions, which varies across sampling areas. The much higher canopy cover in riparian forests relative to upland forests on the east side of the Tahoe Basin are likely indicative of the difference in soil moisture between riparian and upland microclimates and soil moisture in this driest sampling area (DRI, 2009). Similarly, seedling density is more than an order of magnitude higher in east side Tahoe riparian forests than upland forests in the same sampling area, likely due to high moisture conditions in riparian areas relative to the much drier upland conditions on the east side (DRI, 2009). The opposite trend in seedling density for Onion Creek may represent the relative similarity of riparian and upland soil moisture in this wettest sampling area (DRI, 2009). Although the relationship between moisture conditions and the gradient of differences between riparian and upland shrub cover across sampling areas is more difficult to discern, the general trend of higher shrub cover in riparian areas can be attributed to the abundance of mesophytic shrubs such as *Alnus incana ssp. tenuifolia* and *Salix spp.* Although no attempt is made in this study to reconstruct historic canopy cover, seedling density, and shrub cover conditions, it is likely that differences between riparian and upland areas were generally of lower magnitude, given the similarity of riparian and upland fire regimes noted in this study.

4.2.3 Riparian versus Upland Forests, Reconstructed Conditions

There is no significant difference between reconstructed riparian and upland forests for the variables analyzed in this study (supporting the eleventh hypothesis), possibly due to the historical similarity of their fire regimes. Reconstructed upland fuel loads appear to be highly correlated with historic fire return interval, alluding to the fuel-driven occurrence of fire in these Sierran coniferous forest types (Jensen and McPherson, 2008). Interestingly, reconstructed riparian fuel loads are not highly correlated with FRI for any size classes, possibly suggesting a greater influence of weather conditions on fire occurrence. The significant correlation between reconstructed riparian CBD and FRI indicates that crown fuels accumulate uniformly with time since the last fire (Fulé et al., 2004), perhaps due to greater moisture availability in riparian zones. However, the fact that no other variables were significantly correlated with FRI suggests a great deal of heterogeneity in historic riparian and upland fire regimes at the landscape level.

5. CONCLUSION

Our study suggests that coniferous riparian forests in the Sierra Nevada historically experienced frequent fire, often at intervals similar to the adjacent upland forests. This relationship, however, does vary as a function of forest, site, stream and climate conditions. Managers should take into account local conditions when developing treatment prescriptions for riparian areas, considering how forest, site and stream characteristics would have likely influenced fire return intervals and subsequent fire effects. Riparian areas surrounded by forests with a high proportion of fire-tolerant pine species (about one third of the basal area or greater), especially those east of the Sierra crest, likely experienced more frequent fire than riparian areas in other forest types, and could be treated similarly to upland areas. Less intensive treatment, such as hand thinning and pile burning small trees, should be considered for riparian areas in other forest types. Riparian areas at higher elevation typically experienced longer fire return intervals under the C10 filter and therefore could be treated less intensively than the adjacent upland areas. Riparian areas at lower elevations could be treated similarly to upland areas. Riparian areas bordering small incised headwater streams historically experienced fire at frequencies similar to those of upland areas, and could thus be treated the same. Wider streams likely acted as an effective barrier to fire under some conditions, resulting in longer fire return intervals in adjacent riparian areas which could receive less intensive treatment than adjacent upland areas.

Results suggest that coniferous riparian forests in the northern Sierra Nevada historically had forest structure, composition, fuel loads, and fire behavior similar to adjacent uplands. However, both riparian and upland stands currently appear to be more fire prone than their historic conditions, with riparian areas significantly more so than adjacent upland areas. While active management of riparian forests is becoming more common (Holmes et al., 2010; Stone et al., 2010), riparian forests could be considered a high priority for restoration and fuel reduction treatments, with objectives similar to adjacent upland forests. If reintroduction of an active fire regime similar to historic conditions is desirable, treatments might focus on reducing basal area and stand density by removing small fire-intolerant tree species, and reducing surface fuel loads, especially the duff layer. Such treatments may reduce flame lengths, probability of torching, crowning index, and probability of mortality to their historic range of variability, which was likely similar for many adjacent riparian and upland forests. However, prescriptions should take local conditions such as species composition, precipitation regime, elevation, stream channel size and incision into account, which may have historically influenced the relationship between riparian and upland fire regimes. This will produce heterogeneity at the landscape scale, while restoring forests conditions that will facilitate resilience under changing climatic conditions.

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