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Stand structure, fuel loads, and fire behavior in riparian and upland forests, Sierra Nevada Mountains, USA; a comparison of current and reconstructed conditions

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ABSTRACT

Fire plays an important role in shaping many Sierran coniferous forests, but longer fire return intervals and reductions in area burned 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 streamside and aquatic habitat and water quality. Objectives of this study were to compare stand structure, fuel loads, and potential fire behavior between adjacent riparian and upland forests under current and reconstructed active-fire regime conditions. Current fuel loads, tree diameters, heights, and height to live crown were measured in 36 paired riparian and upland plots. Historic estimates of these metrics 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.

Riparian forests were significantly more fire prone under current than reconstructed conditions, with greater basal area (BA) (means are 87 vs. 29 m^2/ha), stand density (635 vs. 208 stems/ha), snag volume (37 vs. 2 m^3/ha), duff loads (69 vs. 3 Mg/ha), total fuel loads (93 vs. 28 Mg/ha), canopy bulk density (CBD) (0.12 vs. 0.04 kg/m^3), surface flame length (0.6 vs. 0.4 m), crown flame length (0.9 vs. 0.4 m), probability of torching (0.45 vs. 0.03), predicted mortality (31% vs. 17% BA), and lower torching (20 vs. 176 km/h) and crowning indices (28 vs. 62 km/h). Upland forests were also significantly more fire prone under current than reconstructed conditions, yet changes in fuels and potential fire behavior were not as large. Under current conditions, riparian forests were significantly more fire prone than upland forests, with greater stand density (635 vs. 401 stems/ha), probability of torching (0.45 vs. 0.22), predicted mortality (31% vs. 16% BA), and lower quadratic mean diameter (46 vs. 55 cm), canopy base height (6.7 vs. 9.4 m), and frequency of fire tolerant species (13% vs. 36% BA). Reconstructed riparian and upland forests were not significantly different. Our reconstruction results suggest that historic fuels and forest structure may not have differed significantly between many riparian and upland forests, consistent with earlier research suggesting similar historic fire return intervals. Under current conditions, however, modeled severity is much greater in riparian forests, suggesting forest habitat and ecosystem function may be more severely impacted by wildfire than in upland forests.

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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; USDA, 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

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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; Van de Water and North, 2010). 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 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 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 vs. historic conditions. We hypothesized that: (1) current riparian and upland stands have stand structure and fuel loads more conducive to high-intensity fire than reconstructed riparian and upland stands; (2) current riparian stands have stand structure and fuel loads more conducive to high-intensity fire than current upland stands; and (3) reconstructed riparian stands 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) (Van de Water and North, 2010). 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 119° 55′ W to 121° 30′ W, and latitudes ranged from 38° 55′ N to 40° 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 8000–9000 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 1900s (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.

Because data for this study was collected in conjunction with a study on historic riparian fire regimes (Van de Water and North, 2010), 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. 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 (Van de Water and North, 2010).

Table 1
Reconstruction approaches for stand-level characteristics.

Stand metric	Reconstruction approach
BA (m^2/ha)	Individual live tree BA calculated from DBH, expanded to hectare scale and summed
Stand density (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 2), then divided by total BA
Snag volume (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 # years elapsed between last and second-to-last fires at each site

2.2. Plot-level data collection

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 an analysis of fire history (Van de Water and North, 2010). 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 50–300 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, 50–80, and >80 cm DBH. Surface fuel loads (dead and down woody material, litter and duff) were measured along three transects at each plot using Brown's planar intercept method (Brown, 1974).

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 (Van de Water and North, 2010). 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 1).

Table 2
97th percentile fuel moisture and weather conditions used to model potential fire behavior.

	Fuel moisture (%)						Weather conditions		
	Dead woody				Live		6.1 m Wind (km/h)	RH (%)	Temp (°C)
	1 h	10 h	100 h	1000 h	Wood	Herb			
Tahoe	2	3	6	7	59	3	10	9	31
Lassen	2	3	6	7	69	2	19	7	34

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 1) (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.

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 1) (Van de Water and North, 2010). The limitations of reconstructing fuel loads vary by size class, with larger size classes (1000 h fuels) being more prone to error than smaller size classes (duff, litter, 1–100 h 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 h), local fuel moisture data (1–1000 h 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 2) 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).

2.4. Statistical analyses

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, 10, 100, 1000 h 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 was 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. Comparison between riparian/upland current/reconstructed conditions

While there was a great deal of variability in riparian and upland forests under current and reconstructed conditions (Fig. 1), the analysis revealed some striking differences. Current riparian forest conditions significantly differed from reconstructed riparian conditions in BA, stand density, snag volume, duff, 1, 10, 100 h, and total fuel loads, surface and crown fire flame length, probability of torching, torching index, crowning index, CBD, and mortality (Table 3). Current riparian stands have more than triple the BA and stem density (Fig. 2), 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 h fuels. Potential flame lengths in current riparian stands are 50% greater those of reconstructed conditions for surface fires, and 125% greater for crown fires. 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, 10 h, and total fuel load, crowning index, and CBD (Table 3). 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 (Fig. 3). 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 and 10 h 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.

Current riparian and upland forests had significantly different stand density, QMD, average CBH, species composition, probability of torching, and predicted mortality (Fig. 2). 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 as an online supplement.

3.2. 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 4). All reconstructed upland fuel-load variables (duff, litter, 1, 10, 100, 1000 h, total) were significantly correlated with upland C1 FRI. No other reconstructed upland variables were significantly correlated with C1 FRI in reconstructed upland stands.

3.3. 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 5). 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.

3.4. Comparison of sampling areas

While there was a great deal of variability within sampling areas, some interesting patterns emerge in the differences between them

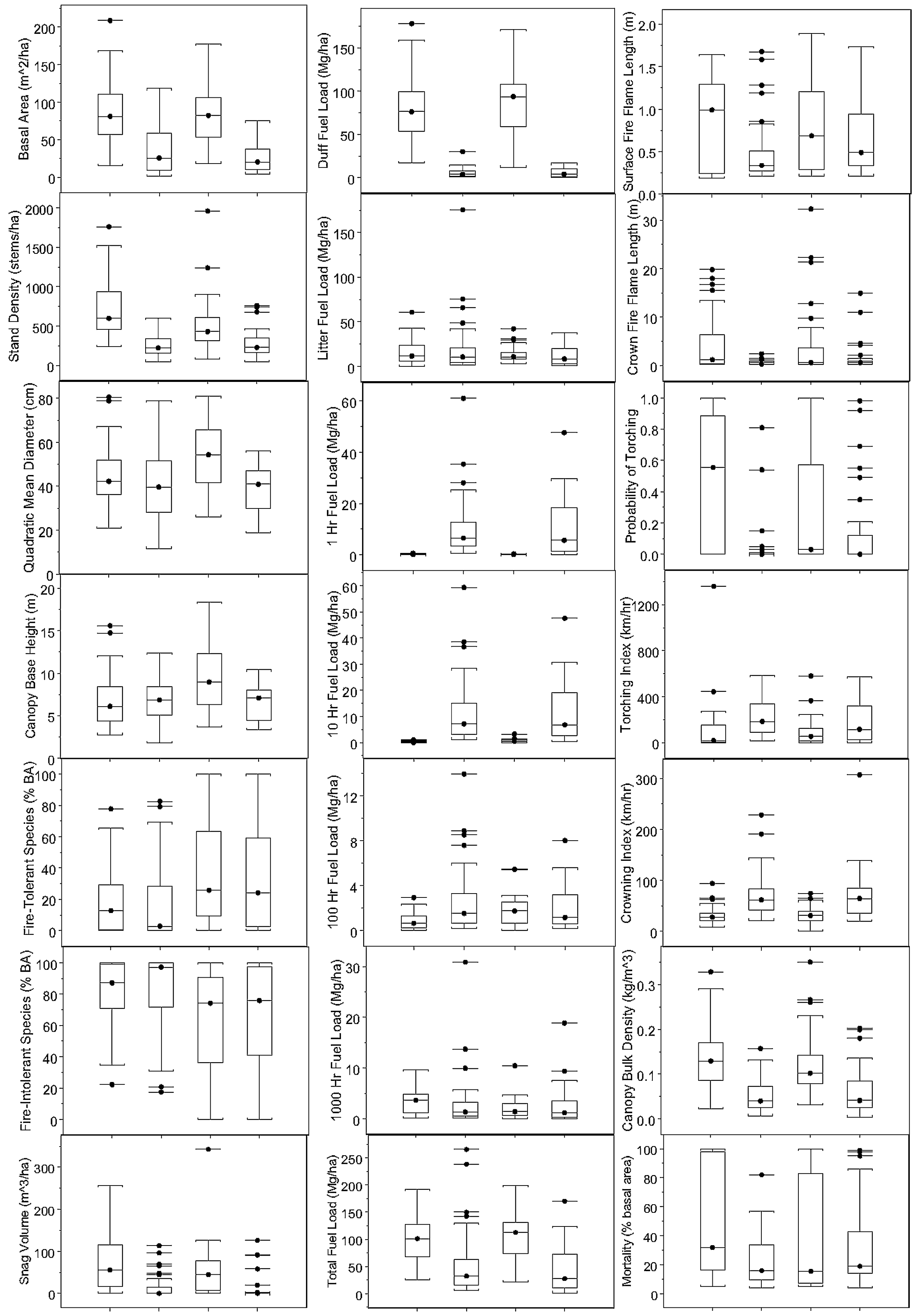

Fig. 1. Box and whisker plots of current and reconstructed stand structure, fuel load, and fire behavior and effects variables for riparian and upland forests. RC is riparian current, RR is riparian reconstructed, UC is upland current, UR is upland reconstructed. Boxes are the upper and lower quartiles divided at the median, whiskers are the maximum and minimum values, dots are outliers.

Table 3
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.

	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 density (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
% Composition (by BA)				
Fire tolerant[a]	13.4(0.5)ab	10.1(0.5)a	36.3(0.5)c	30.3(0.5)bc
Fire intolerant[b]	86.6(0.5)ab	89.9(0.5)a	63.7(0.5)c	69.7(0.5)bc
Snag volume (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 h	0.1(1.2)a	5.4(1.2)b	0.1(1.2)a	3.0(1.2)b
10 h	0.4(1.2)a	6.3(1.2)b	0.5(1.2)a	5.5(1.2)b
100 h	0.7(0.01)a	1.8(0.01)b	1.4(0.01)ab	1.5(0.01)ab
1000 h	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
Probability of torching	0.45(0.06)a	0.03(0.06)b	0.22(0.06)c	0.08(0.06)bc
Torching index (km/h)	20.1(0.4)a	176.3(0.4)b	47.1(0.4)ac	98.6(0.4)bc
Crowning index (km/h)	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

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.

[a] *Pinus jeffreyi*, *P. ponderosa*, *P. lambertiana*, *P. monticola*, and *Quercuz kelloggii*.

[b] *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*.

(Table 6). 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. 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 h 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 h classes in east Tahoe were

Table 4
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.

	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 h	0.013	0.507*
10 h	0.076	0.496*
100 h	0.206	0.501*
1000 h	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/h)	0.236	−0.153
Crowning index (km/h)	−0.150	−0.100
CBD (kg/m^3)	0.415*	0.065
Mortality (% BA)	−0.252	0.331

* 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).

Table 5
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.

	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 h	0.147	0.176
10 h	−0.036	0.190
100 h	−0.036	0.177
1000 h	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/h)	0.104	0.161
Crowning index (km/h)	−0.147	0.219
CBD (kg/m^3)	−0.093	−0.003
Mortality (% BA)	0.229	0.494*

* 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).

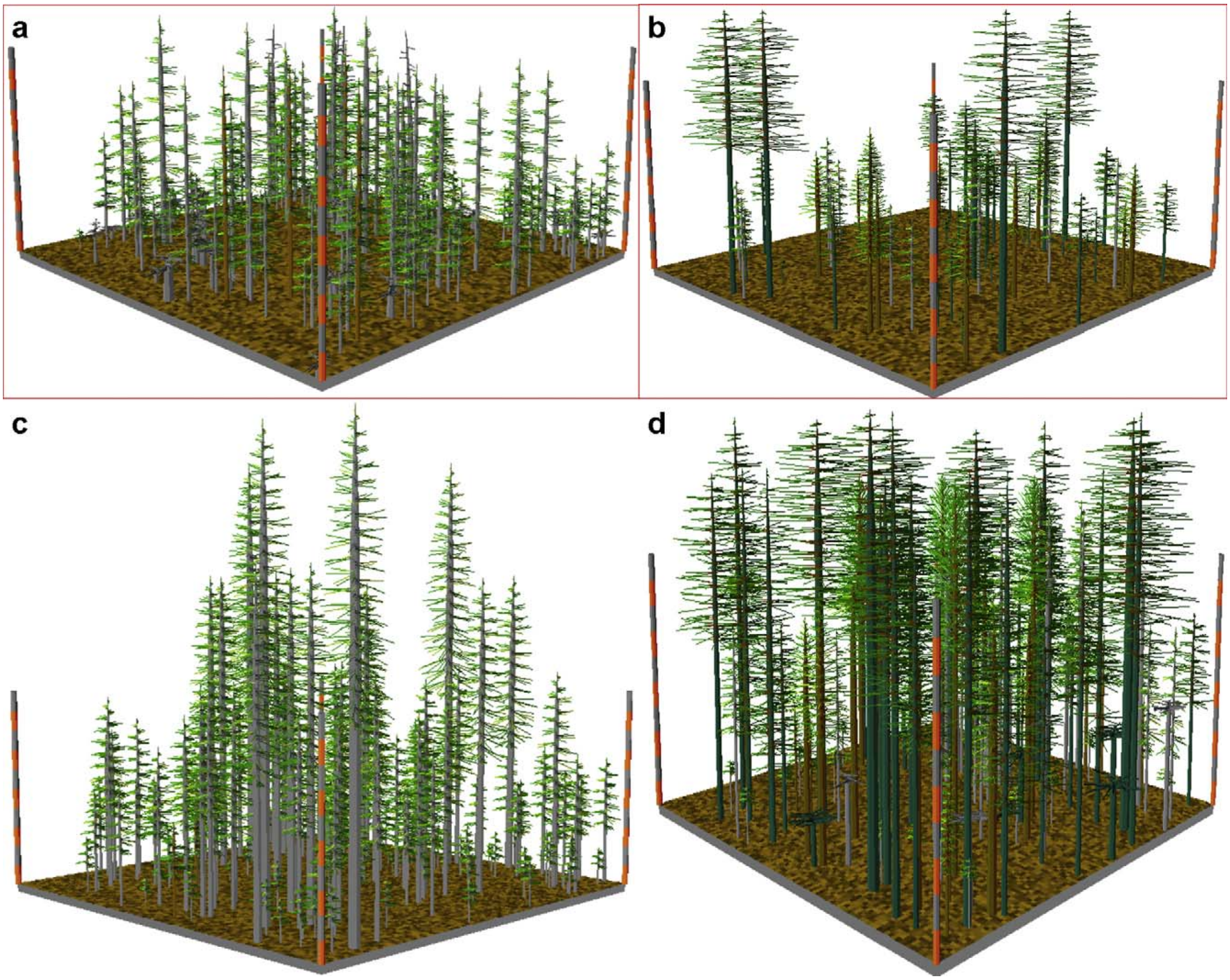

Fig. 2. Stand visualization simulation of typical conditions for (a) current riparian forest (Dollar Creek, 2009), and (b) reconstructed riparian forest (West Branch Feather River, 1886). The corresponding stands, (c) Dollar Creek riparian, reconstructed conditions in 1962, and (d) West Branch Feather 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.

less than half those observed in 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.

4. Discussion

While this study compares current and reconstructed riparian and upland 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 the case of Sierran coniferous forests such as the yellow pine and mixed conifer forests (generally occurring from 370 to 1700 m elevation in the northern Sierra, and from 760 to 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. Current vs. reconstructed 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 7). 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 h 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 3). The variability of riparian and upland forests is certainly subject to geographical variation, and caution should be taken when drawing gener-

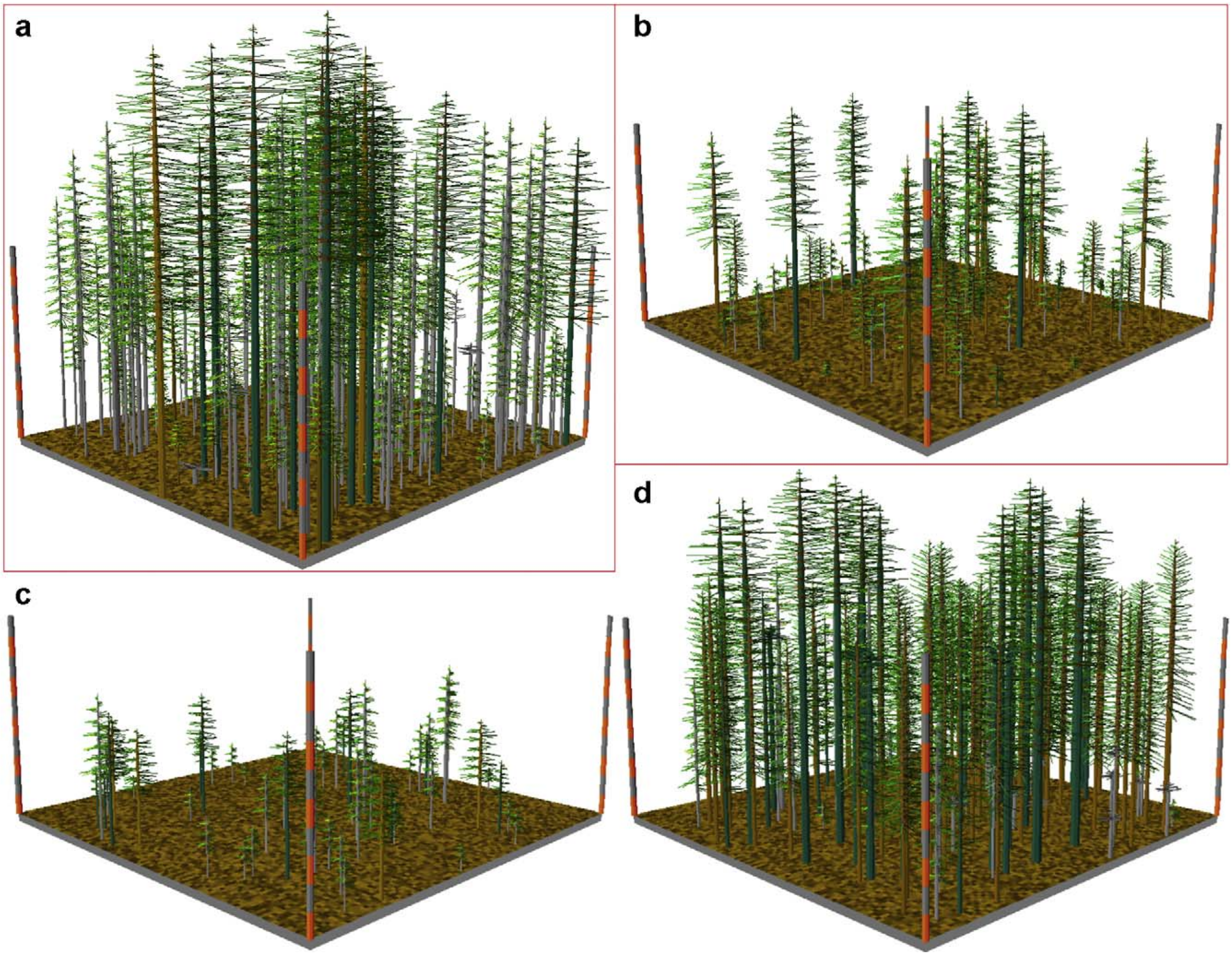

Fig. 3. Stand visualization simulation of typical conditions for (a) current upland forest (Jones Creek, 2009), and (b) reconstructed upland forest (B Fork Onion Creek, 1904). The corresponding stands, (c) Jones Creek upland, reconstructed conditions in 1869, and (d) B Fork Onion Creek, current conditions 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.

alizations about the differences between riparian and upland forests.

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 first 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 first hypothesis. These trends in current vs. 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, 2004; Roccaforte

Table 6
Comparison of stand structure, fuel loads, and potential fire behavior and effects least squares mean (standard error) values for the sampling areas.

	Lassen	Onion	W Tahoe	E Tahoe
BA (m^2/ha)	57.1(0.1)a	69.0(0.5)a	44.5(0.2)ab	31.3(0.3)b
Stand density (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
% Composition (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 volume (m^3/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 h	1.1(1.2)a	0.9(1.4)ab	0.5(1.2)b	0.2(1.3)c
10 h	2.3(1.1)a	1.9(1.3)ab	1.4(1.2)ab	1.1(1.2)b
100 h	1.6(0.01)a	1.5(0.02)a	1.3(0.01)a	0.8(0.02)a
1000 h	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
Probability of torching	0.30(0.06)a	0.09(0.11)a	0.22(0.06)a	0.17(0.09)a
Torching index (km/h)	40.7(0.3)a	117.5(0.7)a	66.6(0.4)a	52.6(0.5)a
Crowning index (km/h)	40.2(0.1)a	38.2(0.2)a	37.8(0.1)a	52.2(0.2)a
CBD (kg/m^3)	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

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.

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 39–66% 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 23–86% declines in crowning index found in other studies

Table 7
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	References
BA (m^2/ha)	28.5	21.4	8.0–59.7	Brown et al. (2008), Fulé et al. (2002), North et al. (2007), Scholl and Taylor (2010), Stephens et al. (2008), Stephens and Gill (2005), Taylor (2004)
Stand density (stems/ha)	207.7	201.1	16.2–280.0	Brown et al. (2008), Fulé et al. (2002), North et al. (2007), Scholl and Taylor (2010), Stephens et al. (2008), Stephens and Gill (2005), Taylor (2004)
QMD (cm)	40.0	38.4	33.0–67.5	North et al. (2007), Scholl and Taylor (2010), Stephens et al. (2008), Stephens and Gill (2005), Taylor (2004)
Avg CBH (m)	6.5	6.3	4.9–6.1	Brown et al. (2008), Fulé et al. (2002)
% Composition				
Fire tolerant	8.6	21.3	48.9–94.6	Fulé and Covington (1997), North et al. (2007), Scholl and Taylor (2010), Stephens et al. (2008), Taylor (2004)
Fire intolerant	91.4	78.7	5.4–51.1	Fulé and Covington (1997), North et al. (2007), Scholl and Taylor (2010), Stephens et al. (2008), Taylor (2004)
Snag density (snags/ha)	19.4	49.1	5.0–150.7	Fulé and Covington (1997), Savage (1997), Stephens (2000), Stephens (2004), Stephens et al. (2008)
Fuel loads (Mg/ha)				
Duff	3.3	3.0	NA	
Litter	8.8	6.9	0.4–23.9	Stephens (2004)
1 h	5.4	3.0	0.0–0.9	Stephens (2004)
10 h	6.3	5.5	0.0–7.0	Stephens (2004)
100 h	1.8	1.5	0.0–8.8	Stephens (2004)
1000 h	1.4	0.9	0.0–156.4	Stephens (2004)
Total	27.9	22.3	0.4–183.7	Huff et al. (1995), Stephens (2004)
Flame length (m)				
Surface	0.4	0.5	1.0–2.0	Fulé et al. (2002), Huff et al. (1995)
Crown	0.9	0.4	7.1–9.2	Roccaforte et al. (2008)
Probability of torching	0.03	0.08	NA	
Torching index (km/h)	176.3	98.6	22.0–67.0	Fulé et al. (2002), Roccaforte et al. (2008)
Crowning index (km/h)	61.6	61.9	48.0–371.0	Brown et al. (2008), Fulé et al. (2002, 2004), Roccaforte et al. (2008)
CBD (kg/m^3)	0.04	0.04	0.01–0.12	Brown et al. (2008), Fulé et al. (2002, 2004), Roccaforte et al. (2008)
Mortality (% BA)	16.5	21.0	21.9	Stephens et al. (2008)

(Fulé et al., 2002, 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 134–515% 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 first hypothesis.

However, differences in QMD, CBH, and 1–100 h fuels appear to contradict the first 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 (Fulé 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 1–100 h 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 1–100 h 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. Riparian vs. 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 second 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 second hypothesis.

Analysis of the correlation between current upland and riparian variables suggests that current 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.

4.3. Riparian vs. upland forests, reconstructed conditions

There is no significant difference between reconstructed riparian and upland forests for the variables analyzed in this study (supporting the third hypothesis), possibly due to the historical similarity of their fire regimes (Van de Water and North, 2010). 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 (Van de Water and North, 2010) 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.

4.4. Management implications

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 (Van de Water and North, 2010). This will produce heterogeneity at the landscape scale, while restoring forests conditions that will facilitate resilience under changing climatic conditions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2011.03.026.

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