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# Fire history of coniferous riparian forests in the Sierra Nevada

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ABSTRACT

Fire is an important ecological process in many western U.S. coniferous forests, yet high fuel loads, rural home construction and other factors have encouraged the suppression of most wildfires. Using mechanical thinning and prescribed burning, land managers often try to reduce fuels in strategic areas with the highest fuel loads. Riparian forests, however, are often designated as areas where only limited management action can take place within a fixed-width zone. These highly productive forests have developed heavy fuel loads capable of supporting stand-replacing crown fires that can alter wildlife habitat and ecosystem function, and contribute to stream channel erosion. Objectives of this study were to determine whether adjacent coniferous riparian and upland forests burned historically with different frequencies and seasonalities, and whether these relationships varied by forest, site, and stream characteristics. We measured dendrochronological fire records in adjacent riparian and upland areas across a variety of forest, site and stream conditions at 36 sites in three sampling areas in the northern Sierra Nevada.

Riparian fire return intervals (FRI) ranged from 8.4 to 42.3 years under a liberal filter (mean 16.6), and 10.0 to 86.5 years under a conservative filter (mean 30.0). Upland FRI ranged from 6.1 to 58.0 years under a liberal filter (mean 16.9), and 10.0 to 56.3 years under a conservative filter (mean 27.8). Riparian and upland fire return intervals were significantly different in only one quarter of the sites we sampled. Riparian and upland areas did not burn with different seasonalities, and fire events occurred primarily during the late summer-early fall dormant season in both riparian and upland areas (88% and 79% of scars, respectively). FRI was shorter in forests with a higher proportion (>22.7–37.6%) of fire-tolerant pine (*Pinus* spp.), sites east of the Sierra crest, lower elevation sites (<1944 m), and riparian zones bordering narrower, more incised streams (width/depth ratio <6.2). Upland areas exhibited a greater degree of fire–climate synchrony than riparian areas. Our study suggests that Sierra Nevada coniferous riparian forests bordering many montane streams might be managed for fuel loads and fire return intervals similar to adjacent upland forests.

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## 1. Introduction

Fire is an important ecological process in many western U.S. coniferous forests, significantly influencing stand structure, species composition, and ecosystem processes such as mortality and nutrient and carbon cycling (Dwire and Kauffman, 2003; Pyne, 1982; Skinner and Chang, 1996). Reduction of Native American ignitions, introduction of non-native ungulate grazers, and fire suppression following settlement by Euro-Americans have resulted in reduced fire frequency and annual area burned in most forest types (Anderson and Moratto, 1996; Douglass and Bilbao, 1975; Stephens et al., 2007). Productive forest types that historically had frequent low- to moderate-intensity fire regimes have accumulated high fuel loads and tree densities as a result of more than a century of fire exclusion, increasing the risk of high-intensity fire (McKelvey and Busse, 1996; Stephens and Moghaddas, 2005). While the need to reintroduce fire to these forest types is acknowledged by most land management agencies, high fuel loads and rural home construction still encourage the suppression of most wildfires (Jensen and McPherson, 2008).

Using mechanical thinning and prescribed burning, managers often try to reduce fuels in strategic areas with the highest fuel loads using treatments which have demonstrably reduced fire severity (McCaffery et al., 2008; Safford et al., 2009). Riparian forests, however, are often designated as areas where only limited management action can take place within a fixed-width zone (FEMAT, 1993; USDA, 2004). These highly productive zones have developed heavy fuel loads capable of supporting stand-replacing crown fires that lead to stream channel erosion, eliminate important wildlife habitat and degrade ecosystem function (Camp et al., 1997; Olson and

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Agee, 2005; Segura and Snook, 1992; Skinner and Chang, 1996). While upland forest areas may receive fuel treatments, risk of high-intensity fire may remain very high in adjacent untreated riparian areas, allowing them to serve as a wick (as occurred during the 2007 Angora Fire in the Tahoe Basin), propagating high-intensity fire through the landscape under some conditions (Pettit and Naiman, 2007). While the higher fuel moistures and lower temperatures in riparian areas may allow them to act as a barrier to fire movement through the landscape under non-drought conditions (Skinner and Chang, 1996), they may burn at similar frequencies or even act as a primary path for fire spread during drought conditions (Agee, 1998; Dwire and Kauffman, 2003; Pettit and Naiman, 2007). Although the historically important role of fire in some riparian areas has been widely recognized, few studies have documented the relationship between historical fire frequency in adjacent riparian and upland forests (Charron and Johnson, 2006; Everett et al., 2003; Olson and Agee, 2005; Skinner, 2003), and none in the Sierra Nevada. Identifying factors that influence variability in riparian fire regimes could facilitate effective restoration of forest ecosystems degraded by fire exclusion.

Objectives of this study are 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, and whether fire synchrony with climate conditions differed between riparian and upland forests. 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; and (8) both riparian and upland forests would show a reduction in fire return interval after Euro-American settlement.

## 2. Methods

### 2.1. Study area

We focused our sampling in three 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 Lake Tahoe Basin (17 sites) (Fig. 1). 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 121°30′W to 119°55′W, and latitudes ranged from 38°55′N to 40°20′N. Most precipitation occurs during the winter as snow, and average annual totals from 1903 to 2009 varied from 460 mm on the east side of the Lake Tahoe Basin to 800 mm on the west side (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*) and Douglas-fir (*Pseudotsuga menziesii*) 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. We confined our sampling to Sierra Nevada forests that historically had frequent (<30 years), low to mixed severity fire regimes.

Anthropogenic influence in all sampling areas has likely had a profound effect on fire history. The ancestors of the Washoe Indians 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. The first major pack trail into the Lake Tahoe Basin was completed in the 1850s, logging commenced 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 Nevada's Comstock Lode mining. Accumulation of logging slash and introduction of new ignition sources such as sawmills, railroads and logging equipment likely influenced fire frequency during this era. The cutover lands were then heavily grazed by sheep and cattle, and fires were deliberately set by herders for range improvement (Lindstrom et al., 2000). The Almanor Ranger District of the Lassen National Forest is in Plumas county, which was also logged and grazed extensively 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, 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 fire scar record, we concentrated our sampling on remnant late-successional forest patches.

### 2.2. Data collection

Potential sites were identified by first consulting US Forest Service maps of late-successional forest patches likely to contain a long fire record, then scouting to ensure the prevalence of numerous fire-scarred trees, stumps, and logs. Sites were non-randomly chosen to provide a long record of fire history (prevalence of large old fire-scarred trees), and to represent the variability of forest types and riparian area characteristics present in Sierra Nevada forests influenced by fire exclusion (Table 1). Sites in some forest type 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 15 sites with Jeffrey pine forest type, 17 sites with mixed-conifer forest type, and 4 sites with white fir forest type; 29 sites with west side precipitation regimes, and 7 sites with east side precipitation regimes. The riparian zone was determined by a combination of stream channel incision and understory plant community composition (i.e. riparian indicator species that were highly abundant throughout our study area, such as *Rubus parviflorus*, *Pteridium aquilinum*, *Alnus incana* spp. *tenuifolia*, and *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.

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 sample 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

**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.

| Area | Site | Forest type | Precip regime | Elev (m) | Stream order | Riparian width (m) | Stream width (m) | Stream depth (m) | Channel grad (°) | Area sampled (ha) | | C1 Mean FRI | | | C10 Mean FRI | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | 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 |
| 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 |

* Significance at $\alpha = 0.1$.
** Significance at $\alpha = 0.05$.

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. Species composition and basal area were measured in 0.1 ha fixed radius plots, recording all trees larger than 5 cm diameter at breast height. We defined first order streams as

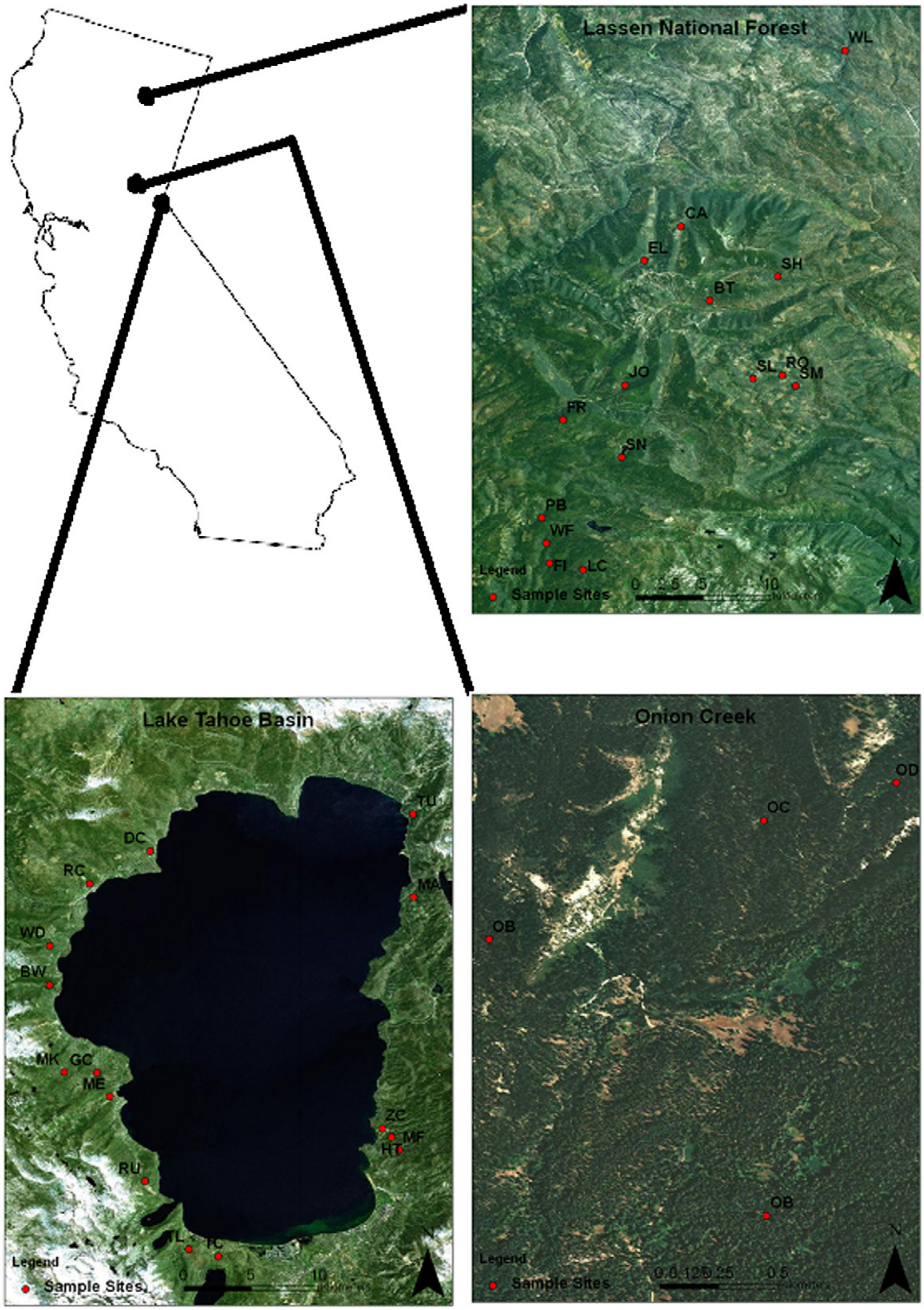


**Fig. 1.** Location of the three sample areas in California (upper left), and of sample sites within each area.

the smallest streams visible on standard USGS 7.5 min topographic maps, second order streams as those formed by the junction of two first order streams, etc. (Strahler, 1952).

### 2.3. Statistical analyses

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 5 observations before a split, a minimum node size of 10 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 2 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.

## 3. Results

### 3.1. Riparian vs. upland FRI and seasonality

In total, 907 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 crossdate. 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). 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 (Fig. 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 (Fig. 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.

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

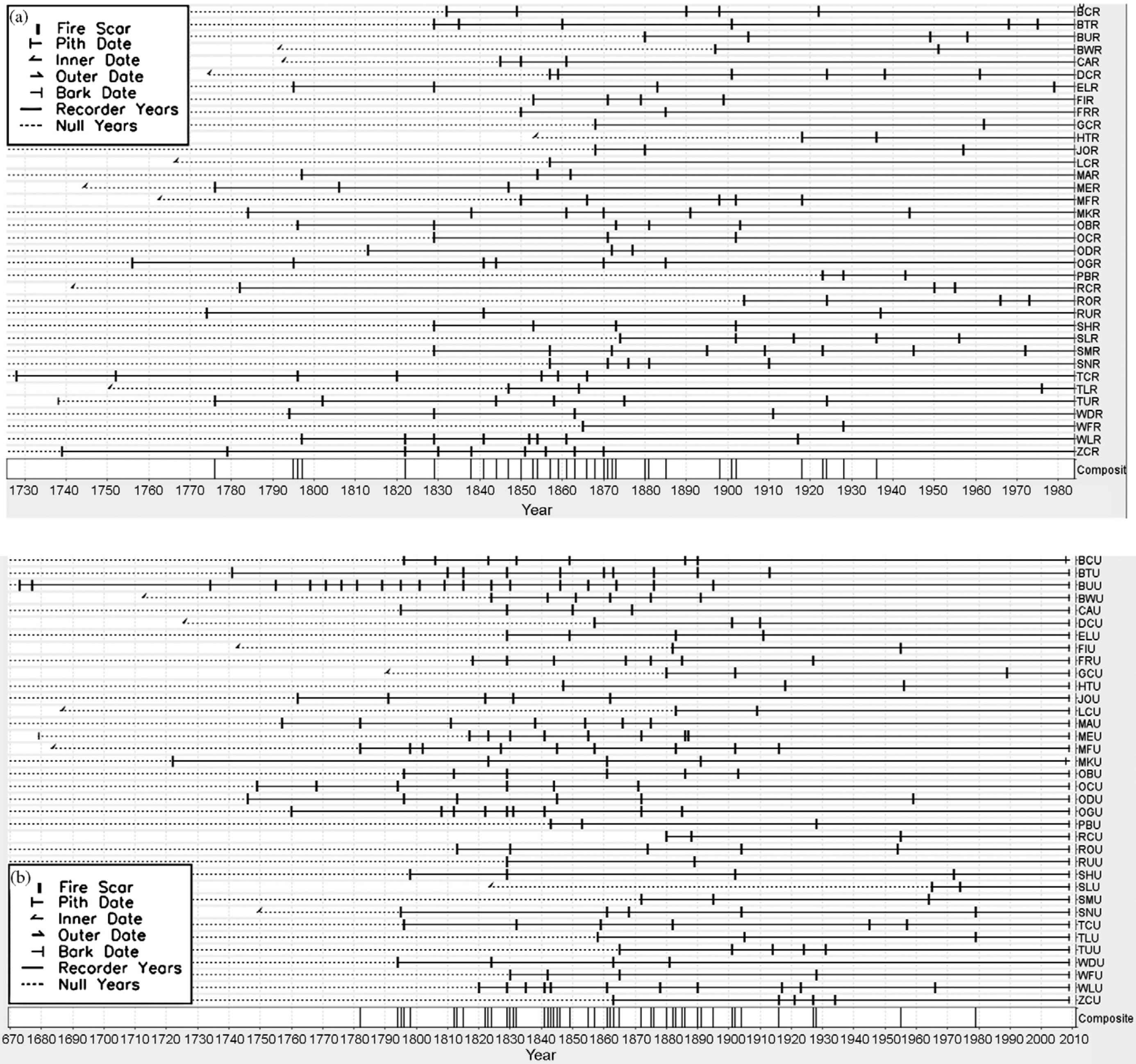


**Fig. 2.** Composite fire occurrences for 36 sample sites in (a) riparian and (b) adjacent upland forests. Horizontal lines are the length of record at each sample site, with vertical ticks indicating years when two or more trees were scarred at a site. The composite record at the bottom indicates when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

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 6 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 (Fig. 3). There was no significant difference in the percent dormant season scars between the riparian and upland areas ($p = 0.102$).

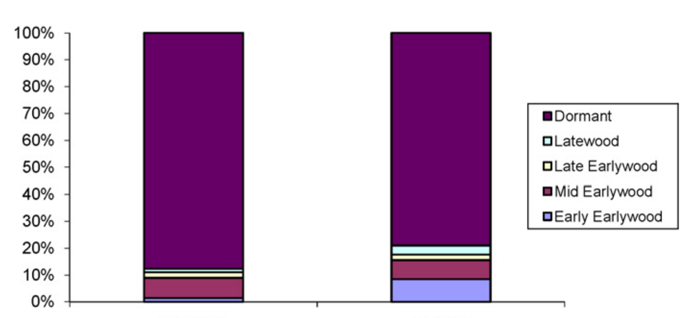


**Fig. 3.** Cumulative proportion of intra-ring fire scar positions for all trees across all sites. Dormant typically represents fall and late summer fires, latewood represents mid-summer fires, earlywood represents spring and early-summer fires.

### 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 propor-

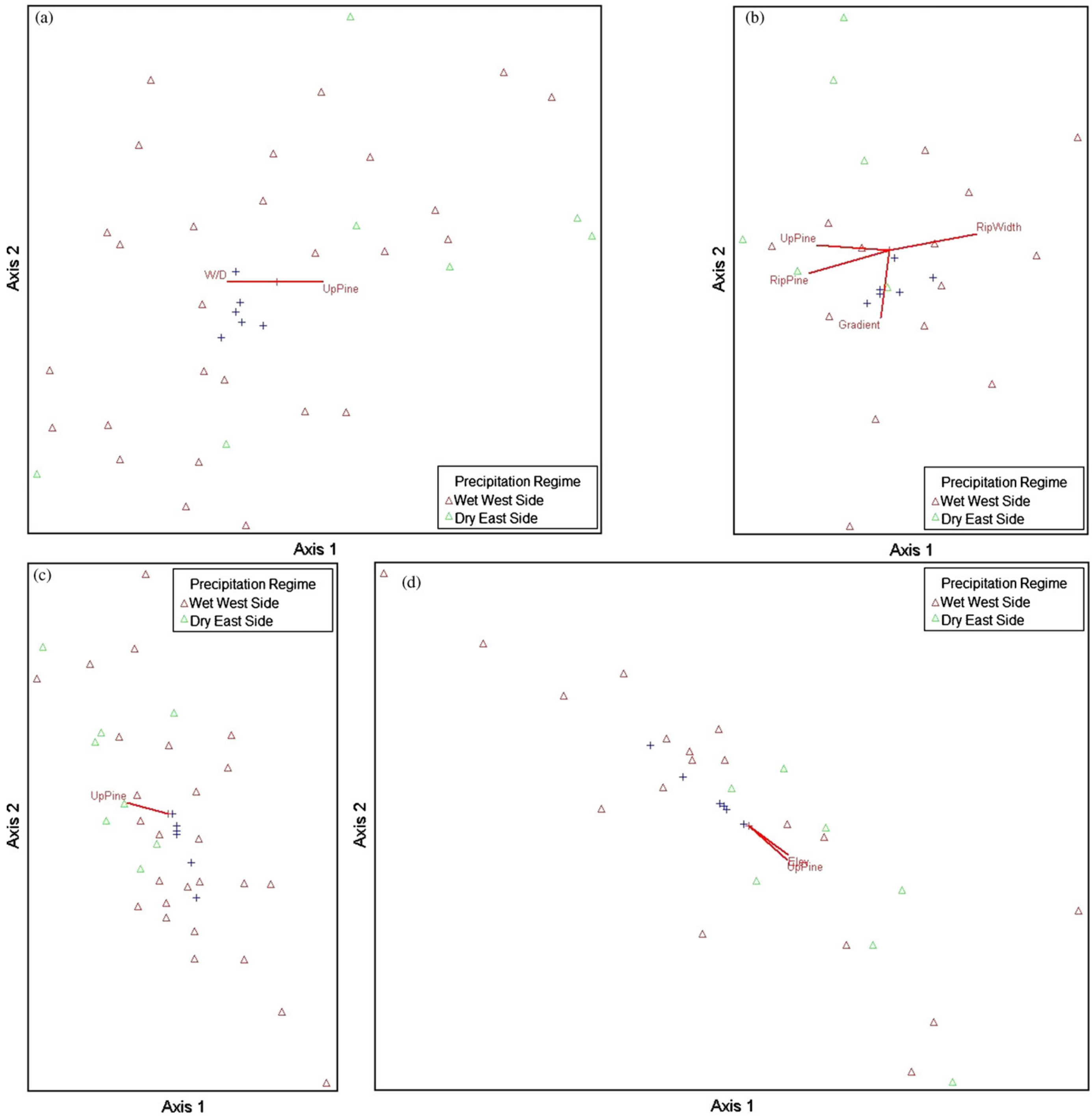


**Fig. 4.** Nonmetric multidimensional scaling (NMS) ordination of (a) riparian C1 FRI metrics at 34 sites (2 sites not included due to insufficient fire scar record, i.e. site did not record enough fire events to allow calculation of all fire return interval metrics used in analysis); (b) riparian C10 FRI metrics at 20 sites (16 sites not included due to insufficient fire scar record); (c) upland C1 FRI at 35 sites (1 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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

tion 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 (Fig. 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 (Fig. 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

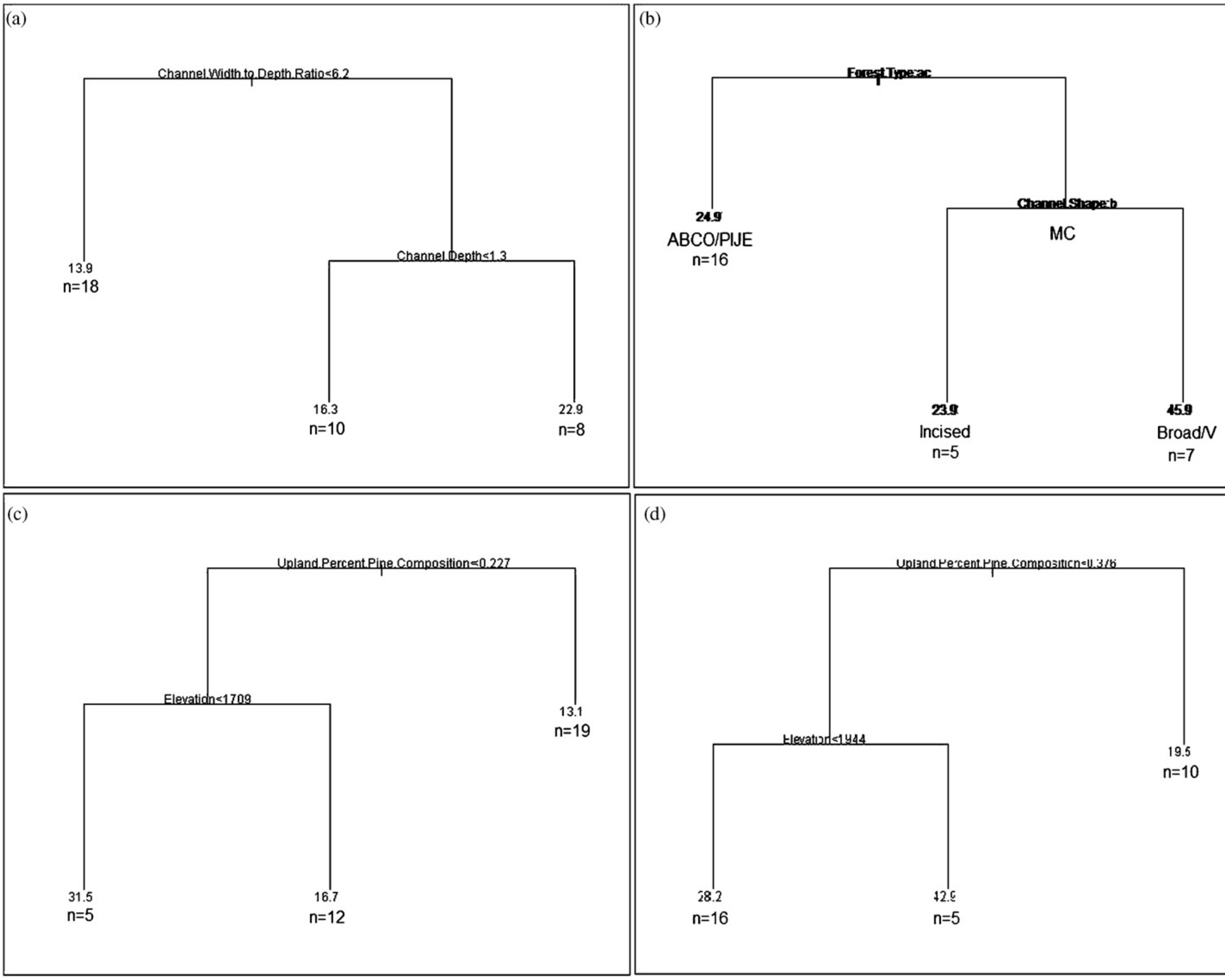


**Fig. 5.** Regression tree of forest, site and stream characteristics associated with (a) riparian C1 FRI, (b) riparian C10 FRI, (c) upland C1 FRI, and (d) upland C10 FRI. The grouping of values in each split is indicated by the direction of the < symbol (i.e. in a, sites with channel depth <1.3 m are 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.

plot of upland C1 FRI (Fig. 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 (Fig. 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.

In the riparian C1 FRI regression tree (Fig. 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 (Fig. 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 (Fig. 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. In the upland C10 FRI regression tree (Fig. 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.

### *3.3. Climate comparisons*

SEA of years in which fires scarring two or more trees at a site occurred at 2 or more sites (the composite in Fig. 2a and b) 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 (Fig. 6a and b). 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).

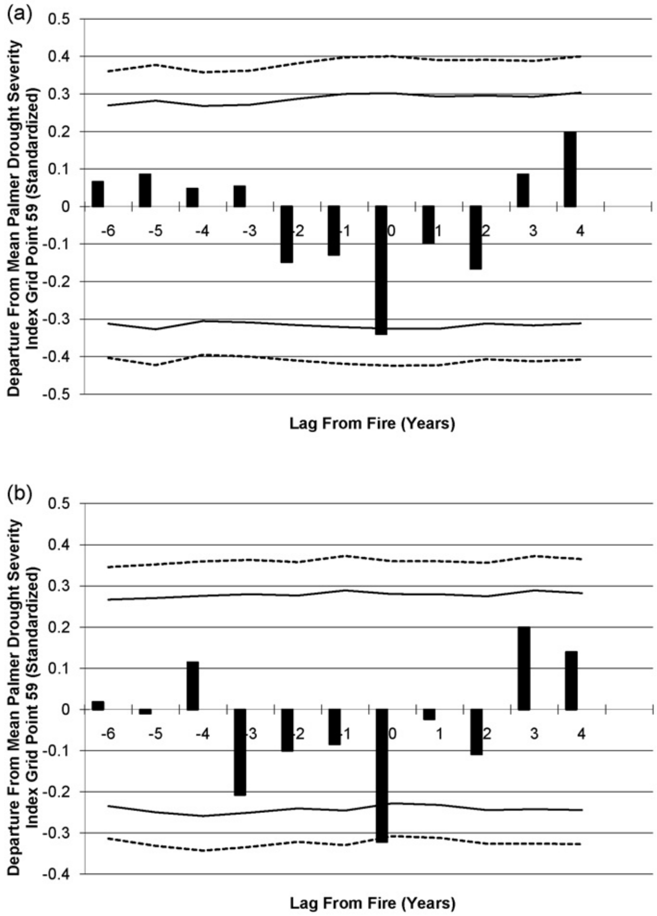


**Fig. 6.** Superposed epoch analysis (SEA) for (a) riparian and (b) upland samples. Graphs show departure from the mean Palmer Drought Severity Index (PDSI) values with years when fires scarred two or more trees per site at the riparian areas of 2 or more sites. Horizontal lines are 95% and 99% confidence intervals.

### 3.4. Temporal analysis

Temporal variation in FRI could not be analyzed for 10 riparian sites and 4 upland sites due to a lack of recorded fire occurrence either 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 4 sites, C1 FRI was significantly shorter after 1850.

## 4. Discussion

### 4.1. Riparian vs. upland FRI

Riparian fire histories of the sites we sampled were very similar to those of the upland areas, but with a few important differences. Averaged across all sites, both riparian and upland areas exhibited similar mean C1 (16.6 and 16.9 years, respectively) and C10 (30.0 and 27.8 years, respectively) fire return intervals, contradicting our first hypothesis. These were within the range of other Sierra Nevada yellow pine, mixed-conifer and true fir forests (McKelvey et al., 1996; Skinner and Chang, 1996).

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 3 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.

### 4.2. 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 (Fig. 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.

### 4.3. 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.

### 4.4. Precipitation regimes

Both riparian and upland fire return intervals of our east-side sites were some of the shortest we found among 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.

### 4.5. 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.

### 4.6. 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).

### 4.7. 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).

### 4.8. 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, 2008; Caprio and Swetnam, 1995; Moody et al., 2006; Olson and Agee, 2005; Stephens, 2001; Stephens and Collins, 2004; Taylor, 2000, 2004; Taylor and Skinner, 2003), most of our sample sites showed no significant difference in mean FRI before and after 1850, and 4 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 (Fig. 2a and b). Patterns of pre-settlement fire frequencies continuing into the post-settlement (Scholl and Taylor, in press) 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.

### 4.9. Management implications

Our study suggests that coniferous riparian forests in the Sierra Nevada historically experienced frequent fire, often at intervals not significantly different from 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.

## 5. Conclusion

While some riparian areas (forest types with little pine, high elevation, wide streams) may have acted as effective buffers to fire activity and movement under non-drought conditions, they likely accumulated higher fuel loads between less frequent fires and burned at higher severity under extreme drought conditions. Because fire, and management activities intended to mimic the effects of fire have been excluded from most riparian areas for more than a century, these zones often have accumulated high stem densities and fuel loads that would support uncharacteristically severe fire under current forest conditions. Our study suggests most coniferous riparian forests would benefit by being included in upland fuels treatments designed to reintroduce fire and promote ecosystem resilience.

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## References

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, DC.
Agee, J.K., 1998. The landscape ecology of western forest fire regimes. Northwest Sci. 72, 24–34.
Agee, J.K., Wakimoto, R.H., Biswell, H.H., 1978. Fire and fuel dynamics of Sierra Nevada conifers. Forest Ecol. Manage. 1, 255–265.
Albini, F.A., 1976. Estimating wildfire behavior and effects. US For. Serv. Gen. Tech. Rep., INT-GTR-30.
Anderson, M.K., 2006. The use of fire by Native Americans in California. In: Sugihara, N.G., van Wagtendonk, J.W., Fites-Kaufman, J., Shaffer, K.E., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, pp. 417–430.
Anderson, M.K., Moratto, J.J., 1996. Native American land-use practices and ecological impacts. In: Sierra Nevada Ecosystem Project: Final Report to Congress, Vol. II, Assessments and Scientific Basis for Management Options, Wildland Resources Center Report No. 37. Centers for Water and Wildland Resources, University of California Press, Davis, pp. 187–206.
Arno, S.F., Sneck, K.M., 1977. A method for determining fire history in coniferous forests of the mountain west. US For. Serv. Gen. Tech. Rep., INT-GTR-42.
Barrett, S.W., Arno, S.F., 1982. Indian fires as an ecological influence in the northern Rockies. J. Forest. 80, 647–651.
Beaty, R.M., Taylor, A.H., 2001. Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, Southern Cascades, California, USA. J. Biogeogr. 28, 955–966.
Beaty, R.M., Taylor, A.H., 2008. Fire history and the structure and dynamics of a mixed conifer forest landscape in the northern Sierra Nevada, Lake Tahoe Basin, California, USA. Forest Ecol. Manage. 255, 707–719.
Bekker, M.F., Taylor, A.H., 2001. Gradient analysis of fire regimes in montane forests of the southern Cascade Range, Thousand Lakes Wilderness, California, USA. Plant Ecol. 155, 15–28.
Berg, N.H., 1990. Experimental forests and ranges: field research facilities of the Pacific Southwest Research Station. US For. Serv. Gen. Tech. Rep., PSW-GTR-119.
Breiman, L., Freidman, J.H., Olshen, R.A., Stone, C.J., 1984. Classification and Regression Trees. Chapman & Hall, New York.
Camp, A., Oliver, C., Hessburg, P., Everett, R., 1997. Predicting late-successional fire refugia pre-dating European settlement in the Wenatchee Mountains. Forest Ecol. Manage. 95, 63–77.
Caprio, A.C., Swetnam, T.W., 1995. Historic fire regimes along an elevational gradient on the west slope of the Sierra Nevada, California. In: Brown, J.K., Mutch, R.W., Spoon, C.W., Wakimoto, R.H. (Eds.), Proceedings on Fire in Wilderness and Park Management. US For. Serv. Gen. Tech. Rep., 8–14, INT-GTR-320.
Charron, I., Johnson, E.A., 2006. The importance of fires and floods on tree ages along mountainous gravel-bed streams. Ecol. Appl. 16, 1757–1770.
Cook, E.R., 2000. Nino 3 index reconstruction. International Tree-Ring Data Bank. IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series #2000-052. NOAA/NGDC Paleoclimatology Program, Boulder, Colorado, USA. <http://www.ncdc.noaa.gov/paleo/recons.html> (accessed 10.05.09).
Cook, E.R., Meko, D.M., Stahle, D.W., Cleaveland, M.K., 1999. Drought reconstructions for the continental United States. J. Clim. 12, 1145–1162.
De'ath, G., 2002. Multivariate regression trees: a new technique for modeling species environment relationships. Ecology 83, 1105–1117.
Dieterich, J.H., 1980. The composite fire interval—a tool for more accurate interpretation of fire history. In: Stokes, M.A., Dieterich, J.H. (Eds.), Proceedings of the Fire History Workshop. US For. Serv. Gen. Tech. Rep., 8–14, GTR-RM-81.
Dieterich, J.H., Swetnam, T.W., 1984. Dendrochronology of a fire scarred ponderosa pine. Forest Sci. 30, 238–247.
Douglass, W.A., Bilbao, J., 1975. Amerikanuak: Basques in the New World. University of Nevada Press, Reno.
DRI, 2009. Western Regional Climate Center. http://www.wrcc.dri.edu (accessed 31.03.10).
Dwire, K.A., Kauffman, J.B., 2003. Fire and riparian ecosystems in landscapes of the western USA. Forest Ecol. Manage. 168, 71–74.
Everett, R., Schellhaas, R., Ohlson, P., Spurbeck, D., Keenum, D., 2003. Continuity in fire disturbance between riparian and adjacent sideslope Douglas-fir forests. Forest Ecol. Manage. 175, 31–47.
FEMAT (Forest Ecosystem Management Assessment Team), 1993. Forest Ecosystem Management: An Ecological, Economic, and Social Assessment: Report of the Forest Ecosystem Management Team, July 1993: USDA, Forest Service; USDC, National Marine Fisheries Service; USDI, Bureau of Land Management, Fish and Wildlife Service and National Park Service; Environmental Protection Agency. U.S. Government Printing Office, Portland.
FRAP (Fire and Resource Assessment Program), 2009. Fire Perimeters. http://frap.cdf.ca.gov/data/frapgisdata/select.asp (accessed 06.03.10).
Gill, L., Taylor, A.H., 2009. Top-down and bottom-up controls on fire regimes along an elevational gradient on the east slope of the Sierra Nevada, California, USA. Fire Ecol. 5, 57–75.
Grissino-Mayer, H.D., 2001. FHX2: software for the analysis of fire history from tree rings. Tree-Ring Res. 57, 113–122.
Grissino-Mayer, H.D., Swetnam, T.W., 2000. Century-scale climate forcing of fire regimes in the American Southwest. Holocene 10, 213–220.
Heyerdahl, E.K., Brubaker, L.B., Agee, J.K., 2001. Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. Ecology 82, 660–678.
Heyerdahl, E.K., McKenzie, D., Daniels, L.D., Hessl, A.E., Littell, J.S., Mantua, N.J., 2008. Climate drivers of regionally synchronous fires in the inland Northwest (1651–1900). Int. J. Wildland Fire 17, 40–49.

Jensen, S.E., McPherson, G.R., 2008. Living with Fire. University of California Press, Berkeley.
Kitzberger, T., Brown, P.M., Heyerdahl, E.K., Swetnam, T.W., Veblen, T.T., 2007. Contingent Pacific-Atlantic ocean influence on multi-century wildfire synchrony over western North America. Proc. Natl. Acad. Sci. U.S.A. 104, 543–548.
Lawson, S.J., Elliot, D.R., 2008. Logging in Plumas County. Arcadia Publishing, San Francisco.
Lindstrom, S., Rucks, P., Wigand, P., 2000. A contextual overview of human land use and environmental conditions. In: Murphey, D.D., Knopp, C.M. (Eds.), Lake Tahoe Watershed Assessment: Volume II. US For. Serv. Gen. Tech. Rep, PSW-GTR-175.
Martin, R.E., Anderson, H.E., Boyer, W.D., 1979. Effects of fire on fuels: a state-of-knowledge review. US For. Serv. Gen. Tech. Rep., GTR-WO-13.
McCaffery, S., Moghaddas, J.J., Stephens, S.L., 2008. Survey results from fire and fire surrogate fuel treatments in a Sierran mixed conifer forest, California, USA. Int. J. Wildland Fire 17, 224–233.
McCune, B., Grace, J.B., 2002. Analysis of Ecological Communities. MjM Software Design, Gleneden Beach.
McKelvey, K.S., Busse, K.K., 1996. Twentieth century fire patterns on Forest Service lands. Sierra Nevada Ecosystem Project, Final Report to Congress, Assessments and Scientific Basis for Management Options, vol. II. Centers for Water and Wildland Resources, University of California Press, Davis, pp. 1119–1138.
McKelvey, K.S., Skinner, C.N., Chang, C., Erman, D.C., Husari, S.J., Parsons, D.J., van Wagtendonk, J.W., Weatherspoon, P.C., 1996. An overview of fire in the Sierra Nevada. In: Sierra Nevada Ecosystem Project: Final Report to Congress, Vol. II, Assessments and Scientific Basis for Management Options. Centers for Water and Wildland Resources, University of California Press, Davis, pp. 1033–1040.
Moody, T.J., Fites-Kaufman, J., Stephens, S.L., 2006. Fire history and climate influences from forests in the northern Sierra Nevada, USA. Fire Ecol. 2, 115–141.
Moore, B.M., Lee, B.G., Davey, S.M., 1991. A new method for predicting vegetation distributions using decision tree analysis in a geographic information system. Environ. Manage. 15, 59–71.
Norman, S.P., Taylor, A.H., 2003. Tropical and north Pacific teleconnections influence fire regimes in pine-dominated forests of Northeastern California, USA. J. Biogeogr. 30, 1081–1092.
North, M.P., Van de Water, K.M., Stephens, S.L., Collins, B.M., 2009. Climate, rain shadow, and human-use influences on eastern Sierra Nevada fire regimes. Fire Ecol. 5, 20–34.
Olson, D.L., Agee, J.K., 2005. Historical fires in Douglas-fir dominated riparian forests of the southern Cascades, Oregon. Fire Ecol. 1, 50–74.
Pettit, N.E., Naiman, R.J., 2007. Fire in the riparian zone: characteristics and ecological consequences. Ecosystems 10, 673–687.
Pyne, S.J., 1982. Fire in America: A Cultural History of Wildland and Rural Fire. Princeton University Press, Princeton.
Rothermel, R.C., 1983. How to predict the spread and intensity of wildfires. US For. Serv. Gen. Tech. Rep., GTR-INT-143.
Safford, H.D., Schmidt, D.A., Carlson, C.H., 2009. Effects of fuel treatments on fire severity in an area of wildland-urban interface, Angora Fire, Lake Tahoe Basin, California. Forest Ecol. Manage. 258, 773–787.
Scholl, A.E., Taylor, A.H., in press. Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA. Ecol. Appl.
Segura, G., Snook, L.C., 1992. Stand dynamics and regeneration patterns of a pinyon pine forest in east central Mexico. Forest Ecol. Manage. 47, 175–194.
Skinner, C.N., 2003. A tree-ring based fire history of riparian reserves in the Klamath Mountains. In: Faber, P.M. (Ed.), California Riparian Systems: Processes and Floodplains Management, Ecology, and Restoration, Riparian Habitat and floodplains Conference Proceedings. Sacramento, CA, March 12–15, 2001. Riparian Habitat Joint Venture, Sacramento, pp. 116–119.
Skinner, C.N., Burk, J.H., Barbour, M., Franco-Vizcaino, E., Stephens, S.L., 2008. Longer-term influences of climate on fire regimes in montane forests of northwestern Mexico. J. Biogeogr. 35, 1436–1451.
Skinner, C.N., Chang, C., 1996. Fire regimes, past and present. In: Sierra Nevada Ecosystem Project, Final Report to Congress, Vol. II: Assessments and Scientific Basis for Management Options. Center for Water and Wildland Resources, University of California Press, Davis, pp. 1041–1069.
Stephens, S.L., 2001. Fire history differences in adjacent Jeffrey Pine and upper montane forests of the eastern Sierra Nevada. Int. J. Wildland Fire 10, 161–167.
Stephens, S.L., Collins, B.M., 2004. Fire regimes of mixed conifer forests in the north-central Sierra Nevada at multiple spatial scales. Northwest Sci. 78, 12–23.
Stephens, S.L., Martin, R.E., Clinton, N.E., 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands and grasslands. Forest Ecol. Manage. 251, 205–216.
Stephens, S.L., Moghaddas, J.J., 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a mixed conifer forest. Forest Ecol. Manage. 215, 21–36.
Stokes, M.A., Smiley, T.L., 1977. An Introduction to Tree-ring Dating. University of Chicago Press, Chicago.
Stohlgren, T., 1988. Litter dynamics in two Sierran mixed conifer forests I. Litter fall and decomposition rates. Can. J. Forest Res. 18, 1127–1135.
Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topology. Geol. Soc. Am. Bull. 63, 1117–1142.
Swetnam, T.W., 1993. Fire history and climate change in sequoia groves. Science 262, 885–889.
Swetnam, T.W., Baisan, C.H., 1996. Historical fire regime patterns in the southwestern United States since AD 1700. In: Allen, C. (Ed.), Fire Effects in Southwestern Forests, Proceedings of the Second La Mesa Fire Symposium, Los Alamos, New Mexico, March 29–31, 1994. US For. Serv. Gen. Tech. Rep., 11–32, RM-GTR-286.
Swetnam, T.W., Baisan, C.H., 2003. Tree ring reconstructions of fire and climate history in the Sierra Nevada and southwestern United States. In: Veblen, T.T., Baker, W., Montenegro, G., Swetnam, T.W. (Eds.), Fire and Climatic Change in Temperate Ecosystems of the Western Americas. Springer-Verlag, New York.
Swetnam, T.W., Baisan, C.H., Morino, M., Caprio, A.C., 2000. Fire history along elevational transects in the Sierra Nevada, California. In: Final Report to Sierra Nevada Global Change Research Program, United States Geological Survey, Biological Resources Division, Sequoia, Kings Canyon, and Yosemite National Parks. University of Arizona Press, Tucson.
Taylor, A.H., 2000. Fire regimes and forest changes in mid and upper montane forests of the southern Cascades, Lassen Volcanic National Park, USA. J. Biogeogr. 27, 87–104.
Taylor, A.H., 2004. Identifying forest reference conditions on early cut-over lands, Lake Tahoe Basin, USA. Ecol. Appl. 14, 1903–1920.
Taylor, A.H., Beaty, R.M., 2005. Climatic influences on fire regimes in northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA. J. Biogeogr. 32, 425–438.
Taylor, A.H., Skinner, C.N., 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecol. Appl. 13, 704–719.
USDA, 2004. Sierra Nevada Forest Plan Amendment Final Supplemental Environmental Impact Statement. US For. Serv., Pacific Southwest Region.
Vaillant, N.M., Stephens, S.L., 2009. Fire history of a lower elevation Jeffrey pine mixed-conifer forest in the eastern Sierra Nevada, California, USA. Fire Ecol. 5, 4–19.
van Wagtendonk, J.W., Benedict, J.M., Sydoriak, W.M., 1998. Fuel bed characteristics of Sierra Nevada conifers. West. J. Appl. Forest. 13, 73–84.
van Wagtendonk, J.W., Cayan, D.R., 2008. Temporal and spatial distribution of lightning strikes in California in relation to large-scale weather patterns. Fire Ecol. 4, 34–56.
Vayssieres, M.P., Plant, R.E., Allen-Diaz, B.H., 2000. Classification trees: an alternative nonparametric approach for predicting species distributions. J. Veg. Sci. 11, 679–694.