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Riparian and adjacent upland forests burned synchronously during dry years in eastern Oregon (1650–1900 CE), USA

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Abstract. Riparian forests link terrestrial and freshwater communities and therefore understanding the landscape context of fire regimes in these forests is critical to fully understanding the landscape ecology. However, few direct studies of fire regimes exist for riparian forests, especially in the landscape context of adjacent upland forests or studies of long-term climate drivers of riparian forest fires. We reconstructed a low-severity fire history from tree rings in 38 1-ha riparian plots and combined them with existing fire histories from 104 adjacent upland plots to yield 2633 fire scars sampled on 454 trees. Historically (1650–1900), low-severity fires burned more frequently in upland than in riparian plots, but this difference was not significant ($P = 0.15$). During more than half of the fire years at both sites, fires were extensive and burned synchronously in riparian and upland plots, and climate was significantly dry during these years. However, climate was not significantly dry when fires burned in only one plot type. Historically, entire riparian zones likely burned in these two study sites of the Blue Mountains during dry years. This study suggests that riparian and upland forests could be managed similarly, especially given the projected increases to fire frequency and intensity from impending climate change.

Additional keywords: Blue Mountains, dendrochronology, drought, fire, mixed-conifer forests.

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Introduction

Riparian forests in the American West are important interfaces between terrestrial and freshwater communities. As linear, dendritic features, riparian zones can biophysically influence the landscapes they traverse (Pettit and Naiman 2007). Due to the ecological sensitivity and diverse biotic composition of riparian forests, understanding the spatial variation of fire regimes in these areas is a critical component of the broader landscape ecology (e.g. Verkaik *et al.* 2013; Bendix and Cowell 2010*a*, 2010*b*, 2013; Wonkka *et al.* 2018). Riparian forests may act as fire breaks inhibiting the spread of wildfires if they have high fuel moisture levels, but under other conditions characterised by fuel accumulation and drought, fire can spread through riparian forests and into adjacent upland forests (Agee 1998; Dwire and Kauffman 2003; Pettit and Naiman 2007; North *et al.* 2012). Understanding historical fire frequency in riparian forests, and the climate conditions under which fires occur, can inform the management of these ecologically important forests (e.g. Charron and Johnson 2006; Harley *et al.* 2018).

Riparian zones can serve as topographical interfaces that link higher-elevation plant assemblages to the lower elevations of a drainage (Crowe and Clausnitzer 1997). A longstanding and logical assumption is that riparian forests burn less frequently than adjacent upland forests (e.g. Dwire and Kauffman 2003; Everett *et al.* 2003). Additionally, compared with adjacent uplands, riparian forests often differ in hydrology, vegetation structure and function, geomorphology, fuel loads and microclimate and these differences could lead to dissimilar fire regimes (frequency, severity and spatial extent). For example, in the Klamath Mountains of northern California, fires occurred half as frequently on average in riparian than in upland plots and were also more variable (Skinner 2003). Fire frequency was also significantly different in riparian and upland forests in the Sierra Nevada Mountains of California (Van de Water and North 2010). In the Klamath Mountains of south-west Oregon, riparian forests developed with frequent fire (Messier *et al.* 2012). In mesic mixed-conifer forests of the central western Cascades of Oregon, upland forests were more prone than riparian forests to repeated fire (Tepley *et al.* 2013). Other than a few studies (e.g. Skinner 2003; Everett *et al.* 2003; Olson and Agee 2005; Charron and Johnson 2006; Messier *et al.* 2012), no direct studies of fire regimes exist for riparian forests, especially concerning landscape-scale fire synchrony (e.g. fire spread between riparian forests and adjacent uplands).

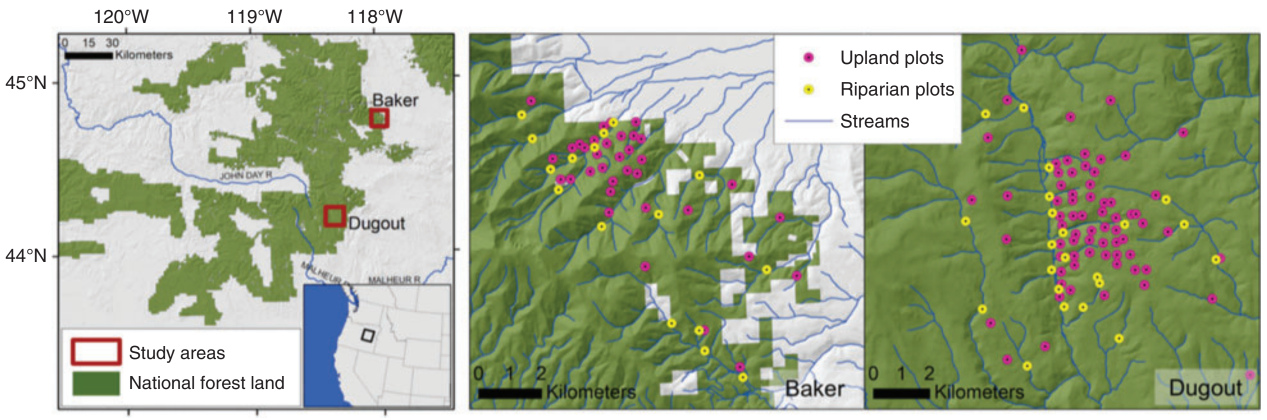

Fig. 1. Location of Baker and Dugout study areas and riparian and upland plots in the Blue Mountains of eastern Oregon, USA. Most of the riparian plots were sampled for this study and most of the upland plots were sampled for an existing study (Heyerdahl *et al.* 2001).

Riparian and upland forests occur in the same landscapes and thus are subject to the same top-down climate drivers, but few studies have investigated the influence of climate on fire in riparian forests. Modern fires (1990–2010) in some, but not all, riparian areas in California are strongly driven by climate (e.g. summer maximum temperature and Sierra Nevada fires; Bendix and Commons 2017). Also in the Sierra Nevada, fuel and forest structures did not differ between many riparian and upland forests in the past, but they do currently, which will likely result in higher fire severity in riparian areas (Van de Water and North 2011).

The Blue Mountains of eastern Washington and Oregon (USA) are considered a classic fire environment, whereby environmental factors such as topography, weather, fuels and abundant ignition combine to form a landscape conducive to frequent, extensive fires (Agee 1996). Variation in topography and a variety of adjacent forest types make the Blue Mountains a favourable area to compare riparian and upland fire regimes. Fire exclusion starting in the late 19th century precludes the use of modern fire records. However, dendrochronology has long been used for the reconstruction of past fire regimes (e.g. Dieterich and Swetnam 1984) and fire-scarred trees are abundant in the extensive mixed-conifer forests of both riparian and upland forests of the Blue Mountains. Extensive fire histories have been reconstructed for the upland forests (Heyerdahl *et al.* 2001; Johnston *et al.* 2017).

Systematically sampled fire histories of upland forests are common and extensive, but the importance of riparian forests within landscapes invokes the need for management agencies to know more about them. Riparian forests in the Blue Mountains maintain riparian microclimates and provide wildlife habitat and large woody debris for streams (Dwire and Mellmann-Brown 2017). Riparian forests may act as fire breaks or fire conduits and this landscape-scale role likely varies through time based on climate and fuel conditions. Although low-severity fires were historically frequent in upland forests of the Blue Mountains (Heyerdahl *et al.* 2001), fire synchrony between riparian and upland forests is poorly understood.

We used techniques of tree-ring science to reconstruct the occurrence of low-severity fires in riparian plots located near upland plots with existing fire histories (Heyerdahl *et al.* 2001) at two sites in the Blue Mountains of eastern Oregon. We compared fire frequency, synchrony and fire–climate relationships between riparian forests and adjacent uplands. We asked: (1) Did the frequency of low-severity fires differ between riparian and upland forests during the period 1650–1900 CE in the Blue Mountains? (2) Did riparian fires burn synchronously with adjacent upland forests? and (3) Did climate influence the synchrony of fire in riparian and upland forests?

Methods

Study area

The Blue Mountains span 10 500 km^2 from north-eastern Oregon to south-eastern Washington (Fig. 1). Summers (June–August) are hot (mean maximum July temperature 26°C) and winters (December–February) are cold (mean minimum January temperature –8°C). Mean annual precipitation is 63 cm, of which only 10% falls during the fire season (July–September 1895–2017; Oregon climate division 8, https://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php, last accessed 12 September 2018). We sampled riparian forests at two sites where extensive upland fire histories were reconstructed previously using techniques of dendrochronology (Fig. 1, Heyerdahl *et al.* 2001).

Baker is in the Wallowa-Whitman National Forest and Dugout is in the Malheur National Forest (Fig. 1). Both of these forests are currently revising the Land and Resource Management Plans that will govern all land management activities for the next 15 years. Draft plans emphasise maintenance of critical riparian functions within a Riparian Habitat Conservation Area that extends for ~46–91 m on both sides of streams (Dwire *et al.* 2018). We sampled riparian plots within this riparian buffer for streams of a range of sizes (bankfull widths ranging from 0.8 to 13.3 m). Riparian plots at Dugout were 27 m from streams on average (range 0.30–137 m) and those at Baker were 24 m on average (range 2.5–55 m). All the riparian plots were installed more than 46 m and downslope from existing upland plots (range 49–939 m, mean = 316 m; Heyerdahl *et al.* 2001) where fire scars were visible on either live or dead trees and within the riparian buffer. Dugout straddles the North Fork of the Malheur River and the topography is undulating. The riparian plots at Dugout averaged 1551 ± 112 m (average ± standard deviation)

Table 1. Amount of evidence used to reconstruct historical fire regimes in the Blue Mountains, eastern Oregon, USA during the period 1650–1900 CE

Most of the riparian plots were sampled for this study and most of the upland plots were sampled for an existing study (Heyerdahl *et al.* 2001). One of the 16 riparian plots at Baker had only single-scar years and so was excluded from further analyses

	Plots (*n*)		Trees (*n*)		Cross-dated fire scars (*n*)	
	Riparian	Upland	Riparian	Upland	Riparian	Upland
Baker	16	35	62	109	248	962
Dugout	22	69	75	208	403	1020
Total	38	104	137	317	651	1982

and the upland plots averaged 1666 ± 98 m. Most plots were on the westerly aspect. Baker is on the north-eastern face of the Elkhorn Mountains and contains several deeply incised stream channels separating small topographic facets. The riparian plots at Baker averaged 1486 ± 137 m and the upland plots averaged 1540 ± 132 m. We sampled plots on a range of aspects at Baker.

The mixed-conifer forests that dominate both sites include a range of overstory species and were assigned to locally identified plant associations that vary along a gradient of moisture and other factors, a classification system based on the species of trees, shrubs and herbs that would dominate in the absence of disturbance (Johnson and Simon 1987; Johnson and Clausnitzer 1992; Crowe and Clausnitzer 1997; Heyerdahl *et al.* 2001; see Table S1 available as Supplementary Material to this paper). We divided the plant associations into two broad groups: mesic and dry (Heyerdahl *et al.* 2001). At Dugout, most of the upland and riparian plots were sampled in dry plant association types (100% and 82%, respectively; Table S1). At Baker, most upland plots were also sampled in dry associations, but most riparian plots were sampled in mesic associations (89% and 81%, respectively). However, the modern understory of all the plots is likely different than it was before fires were excluded in the late 1800s (see Fig. S1, available as Supplementary Material to this paper).

Evidence of past fires

To reconstruct fire occurrence in riparian forests, we used data from 16 plots at Baker and 22 plots at Dugout ($n = 38$), all of which occurred near streams (27 ± 21 m). These included four of the existing plots (1 at Baker and 3 at Dugout) that we classified as riparian plots because they were near streams (Table 1; Heyerdahl *et al.* 2001). At Dugout, we sampled riparian plots along the major streams throughout the extent of the upland plots. However, at Baker we only sampled riparian plots at low elevation along the major streams (below 1770 m) because visible fire scars did not occur at high elevations at this site. At the riparian plots sampled for this study, we used a chain saw to remove fire-scarred partial cross-sections from an average of five trees (range 2–9) over ~1 ha. We sanded all wood samples until we could see the cell structure with a binocular microscope. We assigned calendar years to tree rings by visually cross-dating ring widths against existing ring-width chronologies (Swetnam and Lynch 1993; Heyerdahl *et al.* 2001), occasionally assisted by cross-correlation of measured ring-width series (Holmes 1983). We identified the calendar year of fire occurrence as the date of the tree ring in which a fire scar formed. We assigned scars that formed on the boundary between two rings to the preceding calendar year, assuming that historical fires burned during the late summer/fall season (August–October); that is, the same season as modern fires in eastern Oregon (Bartlein *et al.* 2008).

We compared this new and existing (Heyerdahl *et al.* 2001) data from riparian plots with existing data from 104 upland plots (35 at Baker and 69 at Dugout; Heyerdahl *et al.* 2001). For each plot (riparian or upland), we combined the fire-scar dates into plot-composite fire chronologies, excluding dates recorded by only one tree across a site (38 scars or 1% of all scars eliminated). This eliminated one riparian plot at Baker, which had only single-scar years. We computed plot-composite fire intervals (hereafter fire intervals) as the number of years between fires and then pooled them by site and plot type. Fire intervals were positively skewed, as such distributions commonly are (Falk and Swetnam 2003), so we computed median fire intervals as the 50th percentile of two-parameter Weibull distributions fit to our fire-interval data (SAS PROC UNIVARIATE; SAS Institute 2011). The Weibull distribution fit the distribution of intervals in all four categories (riparian and upslope at both Dugout and Baker); we assessed this fit using probability plots because the number of intervals was large (92–1007 fire intervals).

Although both riparian and upland forests at both sites had some fire scars in the 1500s and early 1600s, we analysed fires only from 1650, when at least 20% of plots were recording in each forest type at each site, through 1900, just after the exclusion of frequent low-severity fires in the Blue Mountains (Heyerdahl *et al.* 2001). Recording plots had trees that had been scarred at least once and thus were more likely to record subsequent fires than plots lacking such trees (Lentile *et al.* 2005).

Riparian versus upland fire frequency and synchrony

To test for a significant difference between fire frequency in riparian versus upland forests, we created a mixed linear model with fire interval as a response and plot type (riparian vs upland) as a predictor variable. We included site (Baker or Dugout) as a random effect to account for spatial autocorrelation in model residuals. Data departed somewhat from normality assumptions and included more upland ($n = 104$) than riparian ($n = 38$) plots, so we used a penalised quasilikelihood model with a log-normal distribution appropriate for non-normal data and unbalanced samples. Model fitting was performed using the MASS package in R (Venables and Ripley 2013; R Core Team 2018).

To infer the influence of climate on the synchrony of fire in riparian and upland plots, we assessed whether the summer Palmer Drought Severity Index (PDSI) (June–August, Living Blended Drought Atlas grid point 44.75°N–118.25°W; Cook *et al.* 2010) differed significantly during the fire year or the preceding or following years (−3 to +1 years) using superposed epoch analysis (SEA; Swetnam and Baisan 1996). We assessed two categories of fire years separately for each site: (a) synchronous years (i.e. years when fires burned in both riparian and upland plots) and (b) non-synchronous years (i.e. years when fires burned either riparian or upland plots, but not both). We identified significant climate departures as those

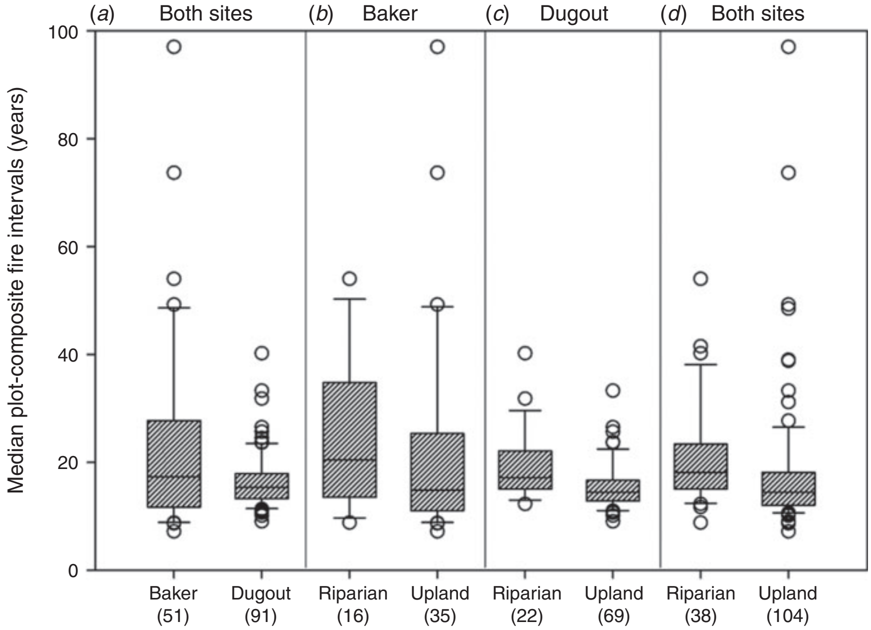

Fig. 2. Fire frequency reconstructed from tree rings at two sites, Baker and Dugout, in the Blue Mountains, eastern Oregon, USA (1650–1900). Analysis is partitioned at various spatial scales, including (*a*) across both sites partitioned by site, (*b*, *c*) plot type and (*d*) across both sites partitioned by riparian versus upland. Numbers in parentheses on *x*-axis labels are plot counts. Plot-composite fire intervals were computed over areas of ~1 ha. Most of the riparian plots were sampled for this study and most of the upland plots were sampled in a similar manner for an existing study (Heyerdahl *et al.* 2001). Boxes enclose the 25–75th percentiles of the distribution of fire intervals; whiskers enclose the 10–90th percentiles, and the horizontal line is the median. Values falling outside the 10–90th percentiles are indicated by circles.

exceeding 99.9% confidence intervals determined by bootstrapping (1000 trials).

Results

Evidence of past fires

For this study, we sampled fire scars from a total of 137 trees in riparian plots at Baker and Dugout, most of which were dead when sampled (64% logs, snags or stumps). Most fire-scarred samples derived from ponderosa pine (60%), Douglas fir (15%), western larch (9%) or lodgepole pine (7%) trees, but we also sampled a few grand fir and Engelmann spruce (*Picea engelmannii* Perry ex. Engelmann; 2%) and could not determine the species of 7% of the remnant logs we sampled. We tallied a total of 530 fire-scar dates between the Baker and Dugout sites from 129 of the 160 trees sampled. We were unable to cross-date samples from 10 trees and another 21 lacked scars from during our analysis period (1650–1900). We combined the fire-scar dates we reconstructed for this study with 2103 cross-dated fire scars sampled from 329 trees sampled in mostly upland plots for another study (Heyerdahl *et al.* 2001) and analysed the combined set of 2633 fire scars sampled from 454 trees (Table 1).

Riparian versus upland fire frequency and synchrony

Overall, fire intervals at Dugout were shorter than at Baker when partitioned overall by site (Fig. 2*a*). At the landscape level, fire intervals were shorter in upland than in riparian plots when combined across both sites, but this difference was not significant ($P = 0.15$; Fig. 2*d*). At each site, low-severity fires were also frequent in riparian plots, but less frequent than in upland plots (Fig. 2*b*, *c*). Specifically, the Weibull median interval for riparian versus upland plots was 20 versus 15 years at Baker (Fig. 2*b*) and 17 versus 14 years at Dugout (Fig. 2*c*).

Fires burned synchronously in riparian and upland plots during more than half of the fire years at both Baker and Dugout (55% and 57%, respectively; Fig. 3*a*, *b*). At Baker, fires burned during 65 years of the analysis period (1650–1900); 36 of these years burned in both riparian and upland plots, 7 burned only in riparian plots and 22 burned only in upland plots. At Dugout, fires burned during 74 years of the analysis period; 42 of these years burned in both riparian and upland plots, 3 burned only in riparian plots and 29 burned only in upland plots (Figs 3, S2).

Fires were more extensive (i.e. more plots burned in both riparian and upland forests) during synchronous than non-synchronous years. During synchronous years at Baker, 11 upland and 3 riparian plots burned on average compared with 4 and 2 plots during non-synchronous years. At Dugout, 22 upland and 6 riparian plots burned on average during synchronous years compared with 3 and 2 plots during non-synchronous years (Figs 3, S2). At both Baker and Dugout, during years when high percentages of upland plots burned, high percentages of riparian plots also burned (Fig. 4*a*, *b*), although Baker ($n = 2$; Fig. 4*a*) experienced fewer fire years that burned higher percentages (75–100% range) of riparian and upland plots compared with Dugout ($n = 10$; Fig. 4*b*).

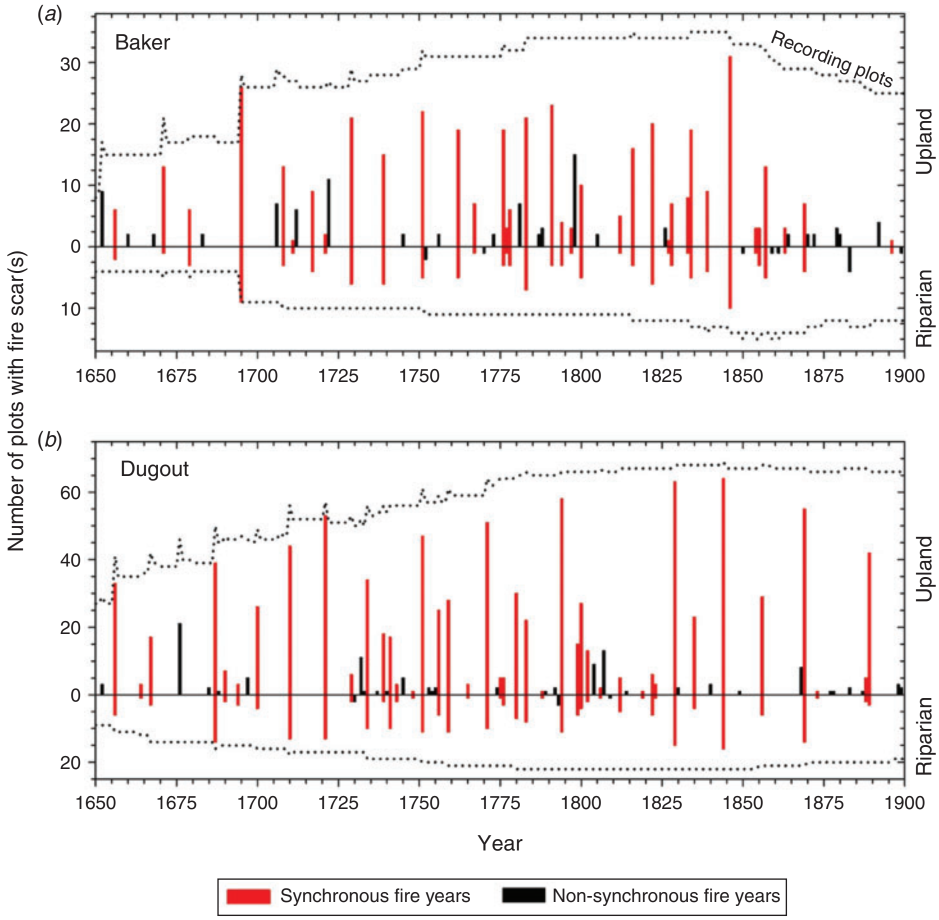

Fig. 3. Synchrony of tree-ring reconstructed fire among riparian and upland plots across two sites, (*a*) Baker and (*b*) Dugout, in the Blue Mountains, eastern Oregon, USA. Recording plots have trees that had been scarred at least once and thus were more likely to record subsequent fires than plots lacking such trees (Lentile *et al.* 2005). Fires burned in both riparian and upland plots during over half of the fire years at each site (55% at Baker, 57% at Dugout) during the period 1650–1900 CE.

At both sites, average PDSI was significantly warm–dry during synchronous fire years, which suggests climate synchronised historical fire in riparian and upland plots at both Baker and Dugout. However, climate was not significantly cool–wet during non-synchronous fire years at either site (Fig. 5).

Discussion

Riparian versus upland fire regimes

In the two study sites in the Blue Mountains of eastern Oregon during the period 1650–1900, historical fires burned more frequently in upland forests compared with adjacent, downslope riparian forests. However, the difference between riparian and upland fire intervals at both Baker (5 years) and Dugout (3 years) was not statistically significant ($P > 0.10$) and likely not ecologically relevant. The lack of statistical significance does not appear to be a function of our model choice. We used a wide variety of simple and mixed linear model specifications, as well as several different non-parametric permutation-based tests, but no models we tested showed a statistical difference between fire frequency in riparian and upland forests.

Dugout and Baker historically sustained frequent landscape-scale fires that burned synchronously across both riparian and upland forests. Riparian forests within these dry forests (i.e. dry plant association types; Table S1) burned at similar frequency as upslope forests. The dry forest types and subsequent low-severity fire regime are likely due to the gentle topography and dry climatic conditions present throughout the entire Dugout study area (only two riparian plots, out of all the riparian and upslope plots, were mesic forest types) and the lower elevations of the Baker study area (Olson 2000). Fire frequency at Dugout did not vary with topography (neither aspect nor elevation), whereas fire frequency at Baker varied only with elevation (Heyerdahl *et al.* 2001). The similarity in fire frequency between riparian and upland areas that we found at Dugout and Baker supports previous assertions about the influence of elevation and topography on fire activity (Heyerdahl *et al.* 2001).

As elevation increases and terrain becomes more dissected at Baker, longer and more variable fire intervals also occurred. This is likely a result of forest composition changes related to both topography and elevational changes in temperature, as well as aspect controls on varying insolation levels (Olson 2000;

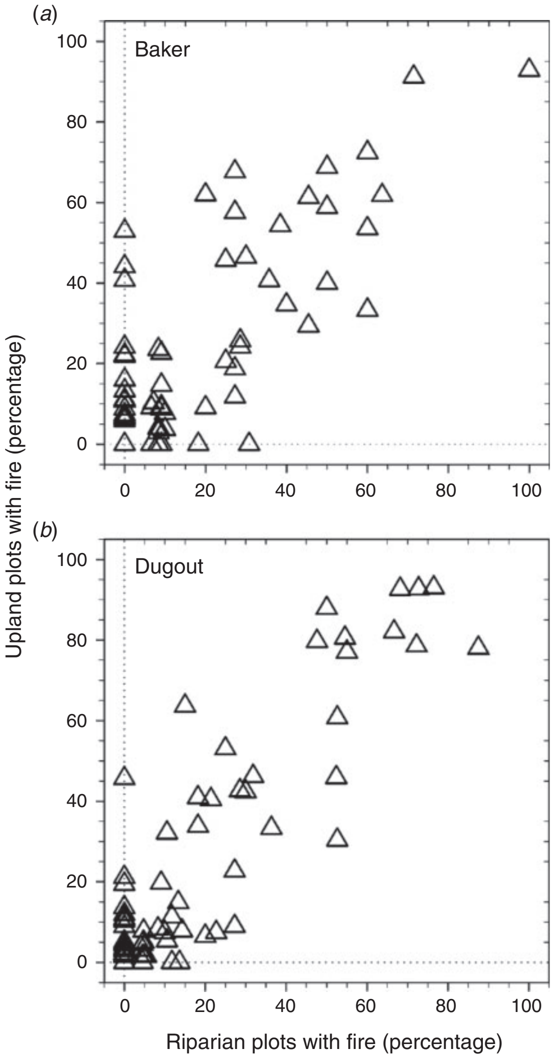

Fig. 4. Relative extent of riparian and upland plots that burned during fire years (triangles) at two sites, (*a*) Baker and (*b*) Dugout, in the Blue Mountains, eastern Oregon, USA during the period 1650–1900 CE.

Heyerdahl *et al.* 2001). When forests occur within interaction zones of climate and topography, such that riparian forests contain greater variety in vegetation composition relative to upslope forests, then fire intervals differ, suggesting that forest composition is important as landscape dissection increases. Compared with Dugout, riparian valleys at Baker are more incised and therefore receive less insolation, resulting in a north-facing slope and riparian forest composition that is more mesic compared with adjacent south-facing upslope forests. Although we did not analyse it here, fire frequency did not vary strongly with stream size at either site (Olson 2000).

At both Dugout and Baker, the fire characteristics within the various vegetation classes may be representative of the overall fuel moisture conditions within each study area during the fire year. If we expect correspondence between large-fire years and the supply of continuously dry fuels, our findings suggest that moisture levels during those years were not high enough to inhibit fire spread from the upslope forests to the riparian forests at either Dugout or the lower portions of Baker. Additionally, given the relative spatial extent of historical fires, streams did not appear to act as fire barriers during large-fire years. Smaller fires were likely characterised by a mosaic of varied fuel dryness across the study area. Hence, fuel moisture levels may have varied enough within and between riparian forests and upslope forests, resulting in smaller fires and greater variations in burn severity.

The riparian plots were installed and sampled at lower elevations compared with the upland plots and fire intervals in upland plots varied with elevation at Baker, but not at Dugout, consistent with the differences in frequency we found. The slightly shorter fire frequencies noted in upland forests could possibly be a result of the relative size and characteristics of the different areas where we collected samples. Riparian forests are confined linear features that make up just 10% and 15% (Dugout and Baker, respectively) of the total area that we searched for fire scars. Upland areas are open and relatively easy to search and we often had many fire-scarred trees available to be sampled within any particular area. Upland forests at Baker have a higher proportion of early seral, shade-intolerant trees (i.e. ponderosa pine) that readily record fire compared with riparian forests. These forests are often dominated by less fire tolerant species such as grand fir that are apt to develop rot in response to fire wounds that cannot be easily sampled with a chainsaw or cross-dated. This is not the case, however, at Dugout, further supporting the notion that riparian forests have more landscape heterogeneity than previously thought, such that the structure, composition and fire regimes of riparian forests likely vary with landscape context. Trees in upland forests are potentially also more likely to be found on a slope where fire intensities are greater and scar formation on the upslope portion of a tree bole is more likely.

The fire history reconstructions from both the Dugout and Baker sites only reconstructed low-severity fires. The riparian and upland forests at each site were similar in vegetation composition and structure and given that low-severity fire was shown to dominate upland forests (Heyerdahl *et al.* 2001), we expected the same for riparian forests. Yet we did not attempt to reconstruct higher-severity fires in riparian forests. If such fires occurred, they would increase fire frequency in the riparian forests at Dugout and Baker. Fire conditions in riparian forests can be heterogeneous depending on topography, forest structure and continuity, fuel loading and condition and thus we would expect a mix of fire regimes, from low to high severity (Pettit and Naiman 2007). Much variation has been found in the relative severity of modern fires in riparian versus adjacent upland forests. Following the 2002 Biscuit fire and 2003 Bear Butte and Booth Complex fire in Oregon, although understory fire severity was significantly lower for riparian areas compared with adjacent uplands, overstory fire severity was similar for each fire event (Halofsky and Hibbs 2008). Some studies provide empirical evidence that riparian areas burn less severely, such as in the eastern Cascades (Agee 1994) and the Klamath Mountains of northern California (Skinner 2003). Others have found that, in turn, riparian areas burned more severely than adjacent uplands in central Mexico (Segura and Snook 1992), Wyoming (Romme and Knight 1981), the Washington Cascades (Camp *et al.* 1997; Everett *et al.* 2003); Oregon (Williamson 1999; Tollefson *et al.* 2004) and across many areas of the western USA (Agee 1998).

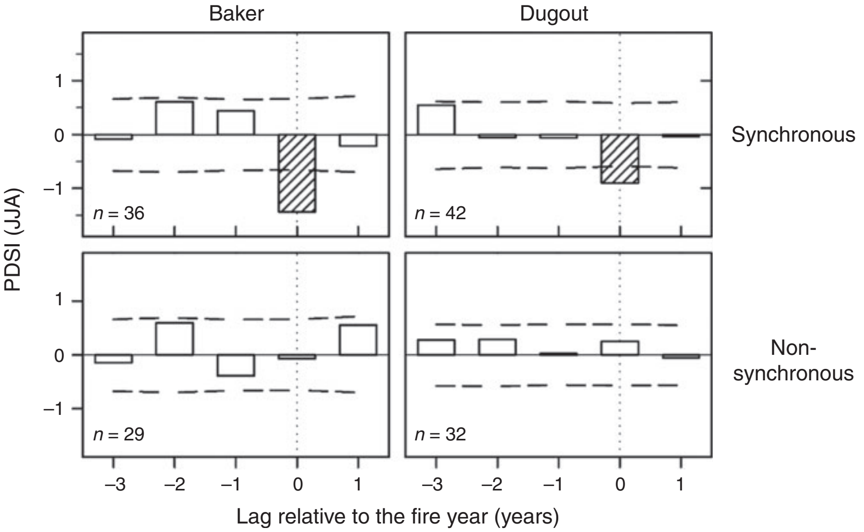

Fig. 5. Lagged interannual relationship of tree-ring reconstructed synchronous (fire in both riparian and upland plots) and non-synchronous fire years (fire in either riparian or uplands plots, but not both) and summer (Jun–Aug, JJA) drought during the period 1650–1900 CE (Palmer Drought Severity Index, PDSI; Cook *et al.* 1997). Departures exceeding the 99.9% confidence intervals (dashed lines) are hatched and the fire year (lag 0) is denoted with a vertical dotted line. The number of fire events is shown (n) in each panel. PDSI is negative during relatively warm–dry conditions and positive during relatively cool–wet conditions.

Climate drivers of synchronous fire

The influence of hydroclimate on fire occurrence in the western USA is well established. In the inland North-west, previous studies demonstrate the strong, positive relationship that exists between aridity (e.g. PDSI) and historical fires (e.g. Heyerdahl *et al.* 2002; Hessl *et al.* 2004; Kitzberger *et al.* 2007; Heyerdahl *et al.* 2008; Littell *et al.* 2009; Johnston *et al.* 2017). In the Blue Mountains, we show a strong relationship between aridity and pre-1900 fires that burned upslope forests and carried across into adjacent riparian forests. In addition to finding that historical fires burned synchronously across riparian-upslope forests during dry years, we suggest that widespread fire events are influenced by topography (Olson 2000) and, hence, forest composition.

We did not find significant antecedent effects of climate on fire events at either Dugout or Baker. SEA results indicated that wetter conditions occurred 1–2 years and 3 years before synchronous fire at Baker and Dugout, respectively, although the relationship was not significant at the $\alpha = 0.01$ level. The relationship between non-synchronous fire years and aridity was not significant, further bolstering the importance of aridity and drought in creating vegetative conditions conducive for carrying fire between riparian and upslope forests.

Management implications and conclusions

Current management direction for riparian forests within national forests in the Blue Mountains generally prohibits actions unless designed to protect, maintain or enhance water quality and the ecological health of aquatic and riparian ecosystems and associated resources. We show that during the period 1650–1900 CE, fire was common in riparian forests in two study sites of the Blue Mountains during dry years and it follows that the historical range of variability in water quality and aquatic health is consistent with frequent fire. If the management objective of riparian forests includes a restoration to conditions before European settlement, then the reintroduction of riparian forest fire is necessary. If the goal is to maintain and conserve the forest in its current state, we must recognise the importance of fire in determining the structure and vegetation composition within these forests. The persistent suppression of fire will continue to alter the structure and vegetation composition of riparian forests and allow the accumulation of fuels that could result in fire intensities and subsequently higher fire severities that were not present in the system historically and are thus unprecedented since at least 1650 CE (Williamson 1999; Bendix and Cowell 2010*b*; Van de Water and North 2011; de Almeida Souza *et al.* 2019). However, if the management goal is to restore historical disturbance regimes to riparian forests of the Blue Mountains, our results indicate that these forests should be managed according to the historical fire regime of the forest type and plant association. At both the Dugout and Baker study sites, drier forest conditions similar to adjacent upslope forests can occur well within the current managerial definition of a riparian zone.

We show the possibility that entire riparian zones may have burned historically in the Dugout and Baker areas during dry years, which suggests that if fuel conditions are dry enough, these forests may be susceptible to ignition even from a low-intensity fire. Nearly 95% of the riparian forests sampled in the vicinity of Dugout were currently at risk for crown fire ignition under 90th percentile weather conditions (Williamson 1999). Therefore, if management goals include protecting riparian forests similar to those in this study from crown fire ignition and maintaining low-severity fire regimes, management plans may need to include reduction of current fuel loads.

Conflicts of interest

The authors declare no conflicts of interest.

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Supplementary Material

Riparian and adjacent upland forests burned synchronously during dry years in eastern Oregon (1650-1900 CE), USA

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Table S1. Potential vegetation groups for riparian and upland vegetation plots at the Dugout and Baker study areas, Blue Mountains, Oregon (Powell et al. 2007).

Plant association	**Riparian**		**Upland**	
	Baker	**Dugout**	**Baker**	**Dugout**
Mesic plant associations (total)	13	4	4	0
Abies grandis/Acer glabrum	9			
Abies grandis/Clintonia uniflora	1			
Abies grandis/Linnaea borealis	1		3	
Abies grandis/Symphoricarpos albus	2	2		
Abies grandis/Vaccinium membranaceum			1	
Abies grandis/Vaccinium scoparium		1		
Pinus contorta (Abies grandis)/Vaccinium scoparium/Calamagrostis rubescens		1		
Dry plant associations (total)	3	18	31	69
Abies grandis/Carex geyeri	2		1	3
Abies grandis/Calamagrostis rubescens		1	4	10
Pinus ponderosa/Carex geyeri			1	2
Pinus ponderosa/Calamagrostis rubescens		1		6
Pinus ponderosa/Festuca idahoensis			1	
Pinus ponderosa/Symphoricarpos albus		8		
Pseudotsuga menziesii/Carex geyeri	1	2	3	8
Pseudotsuga menziesii/Calamagrostis rubescens			19	40
Pseudotsuga menziesii/Cercocarpus ledifolius/Carex geyeri			2	
Pseudotsuga menziesii/Symphoricarpos albus		6		
Total	**16**	**22**	**35**	**69**

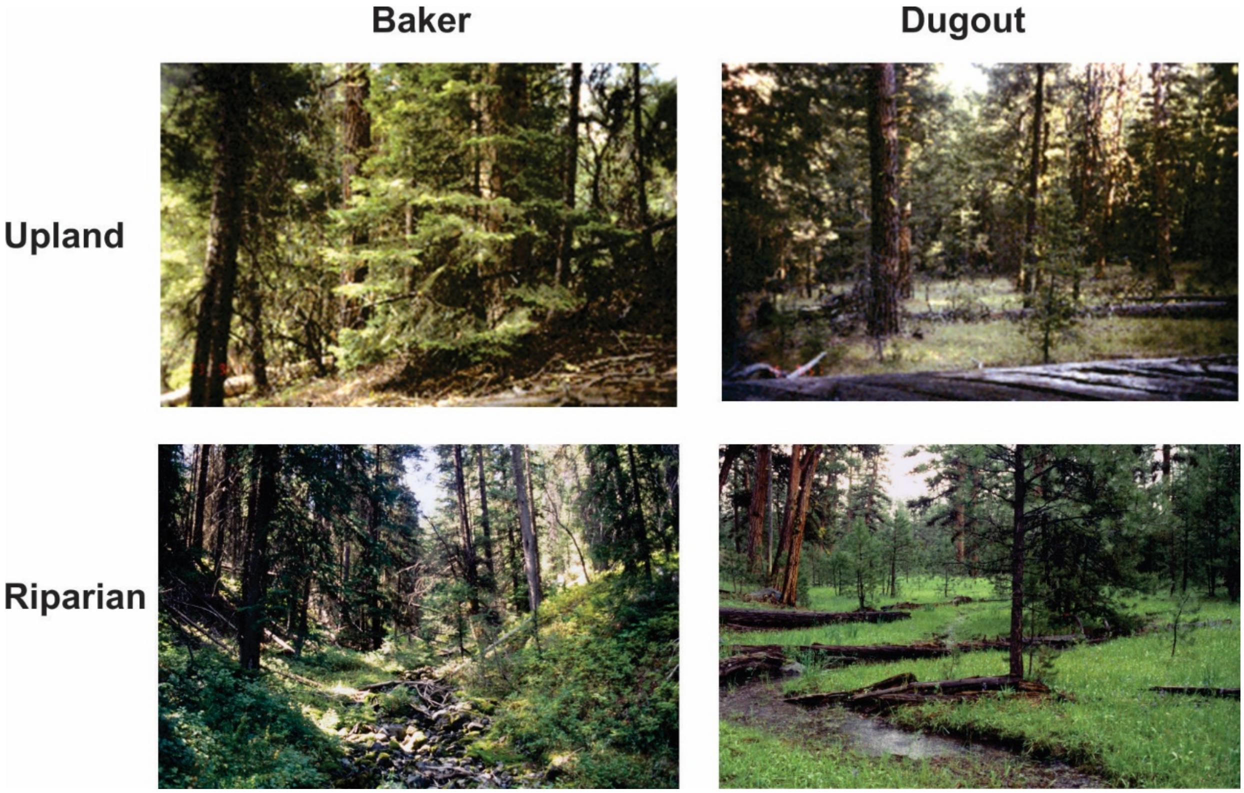

Figure S1. Photographs of riparian plots we sampled for this study, paired with a photograph of the corresponding upland plot that was sampled for another study (Heyerdahl et al. 2001). All photographs were digitized from slides taken in the mid to late 1990s. Fire was historically frequent in all four of these plots but was largely excluded by the late 1800s. As a consequence, it is likely that the understory vegetation in the late 1800s was different than it is today.

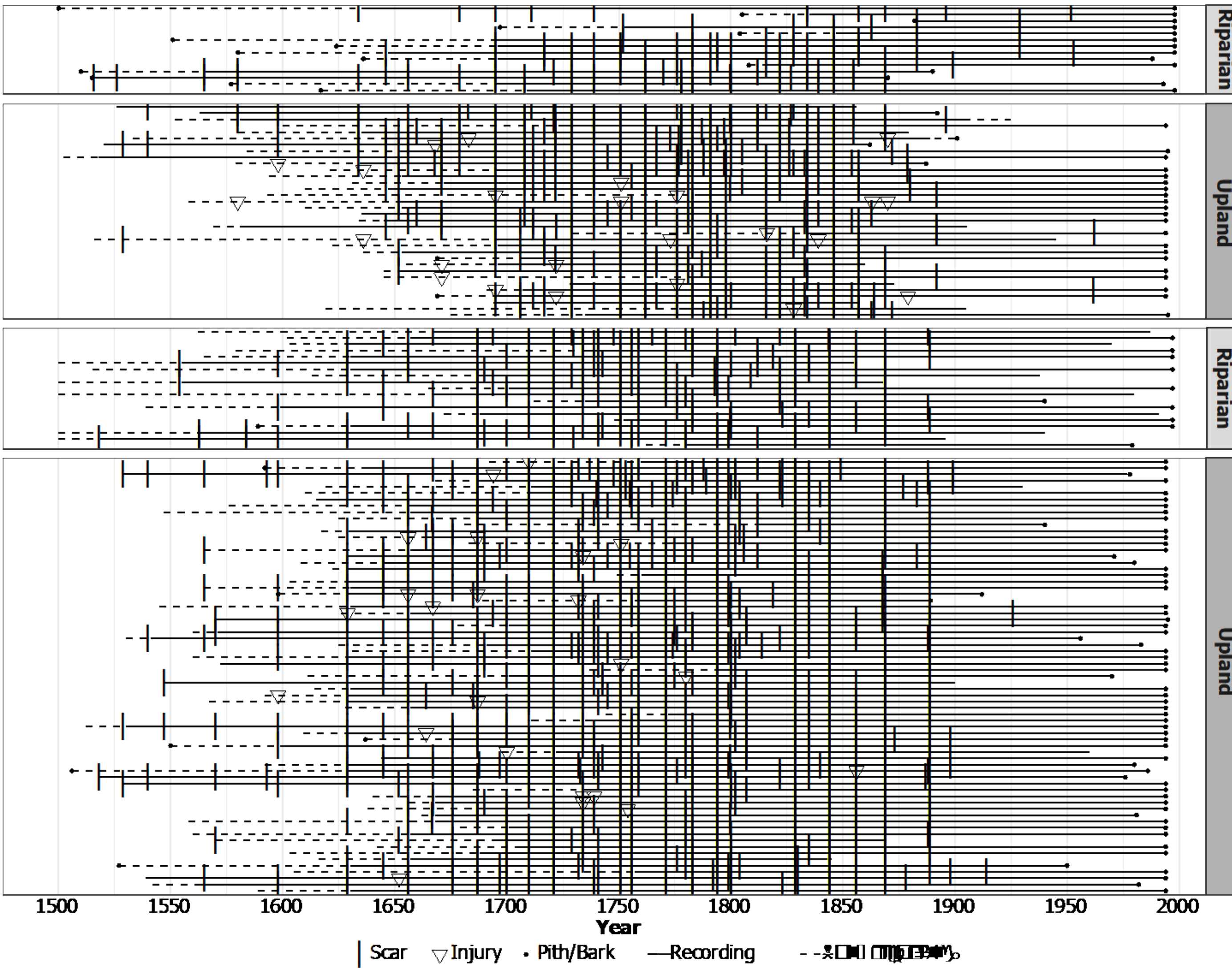

Figure S2. Fire history data for riparian (light grey) and upland (dark grey) plots at Dugout and Baker, respectively. Vertical black tick marks represent individual fire events. Upland plot data derived from Heyerdahl et al. (2001).

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