Historical fire regimes in the dry conifer forests of the southern Sangre de Cristo Mountains, New Mexico

Final progress report for the USGS-USFS IAA

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Abstract

Wildfires in forests and woodlands of the southwestern United States are increasing in size and severity due to fuel accumulation from over a century of fire exclusion combined with an increasingly warm and dry climate. Watershed resources and ecosystem services, like surface water supplies, are increasingly valuable and vulnerable due to climate change and the growing risk of landscape-scale high-severity fire. We used dendrochronological methods to reconstruct the history of fire in ponderosa pine and mixed-conifer (dry conifer) forests at the southern end of the Rocky Mountains. The study area includes the Santa Fe watershed, which provides up to 40% of the water for the City of Santa Fe, as well as multiple adjacent watersheds. We synthesized existing and new collections of fire-scarred trees from throughout the 27,500 acre dry conifer study area to characterize local to landscape fire history. We analyzed 1,298 crossdated fire scars from 272 fire-scarred trees in 33 plots (mean plot elevation = 8,900 ft). An additional 104 fire-scarred trees located outside of the plots were used for mapping historical fire extents. We found fire scars dating back to the early 1300's and the last recorded fire burned in 1902. The positions of the scars within the annual growth rings suggest that most fires historically burned in the early summer. The median fire interval for the full study area was 2 years; the minimum interval was 1 year; and the maximum was 10 years (1600 – 1902 CE). This indicates that a fire burned somewhere within the dry conifer forests at this range of frequencies, not necessarily burning the entire study area. Local, plot-level median fire intervals ranged from 7 to 32 years, and some plots burned in consecutive years. The median fire interval for large fires that burned at least half of the plots was 20 years. The majority (64%) of the fires that burned in the Santa Fe Watershed also burned in the adjacent watersheds, demonstrating the strong potential for fire spread among multiple watersheds. Fire-related mortality (mixed- or high-severity fire) was rare, although it occurred at 24% of the plots over the last four centuries, primarily in mixed-conifer forest. In all cases these plots burned with multiple low-severity fires either before or after the higher-severity event. In addition, the higher-severity events were rarely synchronous among plots in different watersheds, that is, they were localized, and most followed anomalous multi-decadal fire-free periods possibly related to early livestock grazing. Overall, the historical fire regime in the dry conifer forest was dominated by frequent, low-severity fire, with some variable severity over time and space. Fires were associated with drought during the fire year. Widespread fires occurred during severe droughts, preceded by wet years. The drought-fire relationship suggests increased occurrence of widespread fire under projected hotter, drier conditions. This fire-climate relationship combined with the increased fuels from over 115 years of fire exclusion suggests that there is an increasingly high probability of uncharacteristically large and severe fire.

Introduction

Increased fuel loads from over a century of fire exclusion, combined with increasing temperatures and drought, are driving increased fire sizes and severity in the western United States (Westerling et al., 2006; Mallek et al., 2013) and the southwestern U.S. (Singleton et al. 2019; Mueller et al. 2020). The Sangre de Cristo Mountains in New Mexico are the southern extent of the Rocky Mountains and contain a unique combination of wildland urban interface and municipal water supplies superimposed on a gradient of fire-adapted vegetation types and corresponding fire regimes. Fire history case studies in the area suggest that the historical fire regime in the dry conifer forests was historically dominated by low-severity fire (Margolis and Balmat, 2009) and that large patches of high-severity fire historically occurred in the higher elevation subalpine and aspen forests of the Sangre de Cristos (Margolis et al., 2007).

Recent fires in the region (e.g., 2011 Pacheco and Las Conchas, and 2013 Jaroso Fires) have burned with uncharacteristic large patches of high severity across the elevation and forest type gradient, including in the Pecos Wilderness just northeast of Santa Fe. A similar fire in the Santa Fe watershed and adjacent watersheds (hereafter the Santa Fe Fireshed) would result in post-fire flooding and debris flows that would jeopardize the municipal water supply, risk life and property in the wildland urban interface, and likely catalyze conversion of forests to non-forested shrub or grasslands in the dry conifer forests (Guiterman et al. 2018).

Fuels reduction treatments that include mechanical thinning or mastication, followed by prescribed or managed fire reduce the probability of severe fire in dry conifer forests (Safford et al., 2012; Stephens et al., 2012). Multi-party collaborative efforts in the Santa Fe municipal watershed have initiated treatments in much of the dry conifer forests outside of the wilderness area. Some areas have even been re-burned over the last two decades, which is beginning to restore the historically frequent fire regime. The treatments have primarily been focused on the Santa Fe watershed. Hight fuel loads in the adjacent watersheds combined with the large size and spread of recent wildfires (e.g., the Las Conchas Fire burning 40,000 acres in 14 hours) has recently increased the focus of fuels and fire management in the watersheds adjacent to the Santa Fe watershed. However, there is little information on the potential for wildfire connectivity across adjacent watersheds and vegetation types with different fire regimes to inform fire hazard reduction and protection of the municipal watersheds,

The goal of this study was to use tree rings to reconstruct the historical fire regime (fire frequency, season, severity, and relative extent) in the ponderosa pine and mixed conifer forests in the southern Sangre de Cristo Mountains. The sampled fire-scarred trees spanned multiple watersheds to the north and the south of the Santa Fe Municipal watershed. This allowed us to assess the relative extent of historical fires and inform the likelihood of fire spread among watersheds within the study area.

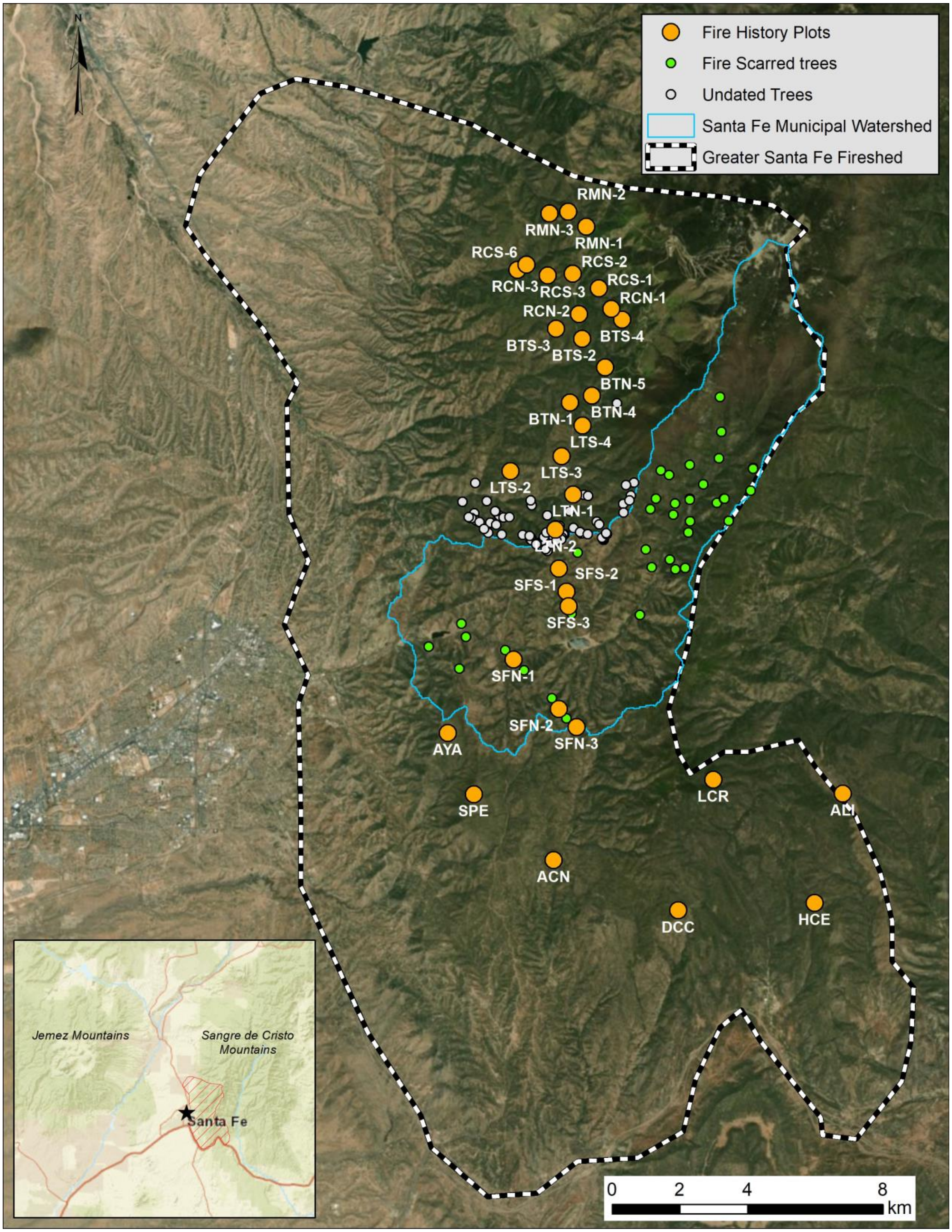

Figure 1. Map of tree-ring fire-scar plots and trees in the Santa Fe Fireshed, located at the southern-most extent of the Rocky Mountains. Plots were located throughout the dry conifer (ponderosa pine and mixed conifer) forests of the Santa Fe Municipal watershed and adjacent watersheds.

Table 1. Fire history group and plot information. Plots are listed in three groups, northwest to southeast, pertaining to geographic location within the southern Sangre de Cristo range.

Group	Plot Name	Site code	Dated Trees	Mean plot elev. (m)
West-slope Watersheds	Rio en Medio North - 1	RMN - 1	12	2832
	Rio en Medio North - 2	RMN - 2	8	2793
	Rio en Medio North - 3	RMN - 3	10	2750
	Rio Chupadero South - 1	RCS - 1	8	2796
	Rio Chupadero South - 2	RCS - 2	8	2748
	Rio Chupadero South - 3	RCS - 3	3	2640
	Rio Chupadero South - 6	RCS - 6	7	2579
	Rio Chupadero North - 1	RCN - 1	7	2863
	Rio Chupadero North - 2	RCN - 2	8	2744
	Rio Chupadero North - 3	RCN - 3	4	2588
	Big Tesuque South - 2	BTS - 2	7	2716
	Big Tesuque South - 3	BTS - 3	5	2858
	Big Tesuque South - 4	BTS - 4	5	2918
	Big Tesuque North - 1	BTN - 1	7	2657
	Big Tesuque North - 4	BTN - 4	6	2797
	Big Tesuque North - 5	BTN - 5	8	2839
	Little Tesuque South - 2	LTS - 3	8	2689
	Little Tesuque South - 3	LTS - 4	9	2756
	Little Tesuque North - 1	LTN - 1	9	2638
	Little Tesuque North - 2	LTN - 2	11	2731
Santa Fe Watershed	Santa Fe North - 1	SFN - 1	10	2457
	Santa Fe North - 2	SFN - 2	8	2710
	Santa Fe North - 3	SFN - 3	12	2771
	Santa Fe South - 1	SFS - 1	6	2830
	Santa Fe South - 2	SFS - 2	5	2743
	Santa Fe South - 3	SFS - 3	7	2685
Southern Watersheds	Atalaya Mountain	AYA	11	2678
	Sierra Pelada East	SPE	10	2659
	Apache Canyon	ACN	12	2452
	La Cueva Ridge	LCR	12	2925
	Deer Creek Canyon	DCC	11	2537
	Hagen Canyon East	HCE	10	2588
	Alamitos	ALI	8	2547
All plots	--------	All	272	2713

Methods

We synthesized tree-ring fire-scar data from three different parts of the Santa Fe Fireshed, including: 1) published collections in the Santa Fe Watershed (Margolis and Balmat, 2009), 2) unpublished collections north of the Santa Fe Watershed – hereafter the "west-slope watersheds" (Marshall and Falk, unpublished data; Margolis, unpublished data), and 3) new collections south of the Santa Fe Watershed – hereafter the "southern watersheds" (Figure 1, Table 1). This sample design allowed us to assess variability in historical fire regimes across the study area and compare fire synchrony, and likely fire spread between watersheds.

To make analyses comparable across the different collections, we used a plot-based design (Table 1, Figure 1). We combined records from multiple fire-scarred trees within small plots because individual trees rarely record all fires (Stephens et al., 2010) and fires-scar plot composites reliably record known fire events (Farris et al. 2010). The Margolis (unpublished) west-slope watersheds and the new southern watersheds samples were collected in one-hectare (56.4-m radius) plots. Clusters of trees from the Margolis and Balmat (2009) and the Marshall and Falk (unpublished) collections were grouped into similar-sized plots, where possible. Trees located outside of plots were not analyzed for fire frequency or season, but were used for mapping fire years.

Figure 2. Ponderosa pine cross-section with 12 fire scars (1522 – 1729) and a fire-scarred southwestern white pine snag from the Santa Fe Fireshed.

Seven new plots were sampled in the southern watersheds, south of the Santa Fe watershed in 2017 (Figure 1). Plots were spatially distributed at approximately 3-4 km spacing to represent the dry conifer forest. Final plot locations were determined by scouting the pre-determined zone for a site with abundant fire scars. In each plot we collected full or partial cross-sections with a chainsaw from up to 12 remnant fire-scarred trees, stumps, and logs to obtain the longest, most-complete record of fires (Figure 2). All tree-ring samples were prepared using standard dendrochronological procedures (Stokes and Smiley, 1968). Fire-scarred samples were crossdated and the year and season of fires were determined based on the position of the fire scar within the annual ring (Baisan and Swetnam, 1990).

Analysis

We displayed the fire scar data using fire charts containing individual trees and plot- or study-area fire composites to assess the fire history at different spatial scales, from tree to plot to study area. Fire frequency statistics (e.g., mean and median fire intervals) were calculated at multiple spatial scales and varying relative fire sizes (i.e., using % of recording trees or plots scarred) using the 'burnr' dendroecology package in R (Malevich et al. 2018). Fire synchrony among the watersheds was quantified using percent of trees and plots recording fire and by mapping the locations of fire-scarred trees for each fire year. Fire synchrony between the Santa Fe watershed and the adjacent watersheds was quantified and represented with fire history charts and Venn diagrams to assess the potential for fire spread among the Santa Fe watershed, the west-slope watersheds, and the southern watersheds. A concave hull with a 500 m buffer around the plots was used as a conservative measure of sampled forest area.

Fire severity was qualitatively assessed from the age structure of the sampled fire-scarred trees at each plot. Plots were assessed for having the following evidence possibly associated with mixed- or high-severity fire: 1) multiple trees with similar death or outer-rings dates associated with a fire recorded at the plot or at adjacent plots, 2) the lack of trees that survived a fire recorded at the plot or adjacent plots, and 3) pulses of tree regeneration following a fire. The last line of evidence, on its own, occurred widely following the collapse of frequent fire regimes in the late 1800s and is most indicative of the lack of fire, therefore it was only considered evidence of mixed- or high-severity fire when combined with clustered death dates or the lack of trees that survived a given fire.

Fire-climate relationships among fires with small to large relative extents (all fires and fires recorded at $\geq$ 25% of plots) were analyzed using superposed epoch analysis (SEA; Swetnam, 1993). SEA is a compositing procedure that tests for relationships between tree-ring reconstructed drought (Palmer drought severity index, PDSI) with historical fire occurrence. Antecedent conditions were also evaluated, since relationships between prior-year climate and fire in subsequent years may provide the potential for fire forecasting (e.g., Westerling and Swetnam, 2003), and has been linked to fine fuel dynamics (Swetnam and Baisan, 1996). Results are discussed in the context of local and regional watershed and fire management in the face of increasing fire activity and severity.

Results

We analyzed 385 fire-scarred trees, most of which were ponderosa pine, but also including southwestern white pine and Douglas-fir (Figures 3 – 5 and S1 - S9). Most of the fire-scarred trees were located in 33 plots (n = 272 trees), but an additional 104 dated trees were located outside of plots and used for the fire mapping. The plot-based tree-ring record spanned 722 years (1296 to 2017 CE) and contained 1,298 fire scars that burned during 571 unique fire years (1331 – 1902 CE). Most fire scars occurred in the spring dormant or early-summer (early earlywood scar positions; Figure 6). The median fire interval for all fires over the common period (1600 – 1902) was 2 years (mean fire interval = 2.6 years). The minimum and maximum intervals were 1 and 10 years, respectively (Table 2, Figures 7 - 8). The median fire intervals of the individual plots ranged from 8 to 32 years, with each having multi-decadal fire-free periods (20 – 69 years, Table 2, Figures 8 and 9). Most of the long fire-free intervals occurred in the late 1700s and early 1800s. Some plots with low sample depth, or that had periods without recording trees possibly related to higher-severity fire, had unreliable estimates of fire intervals that likely did not reflect the actual history of fire (e.g., RMN1, Table 2, Figure S1).

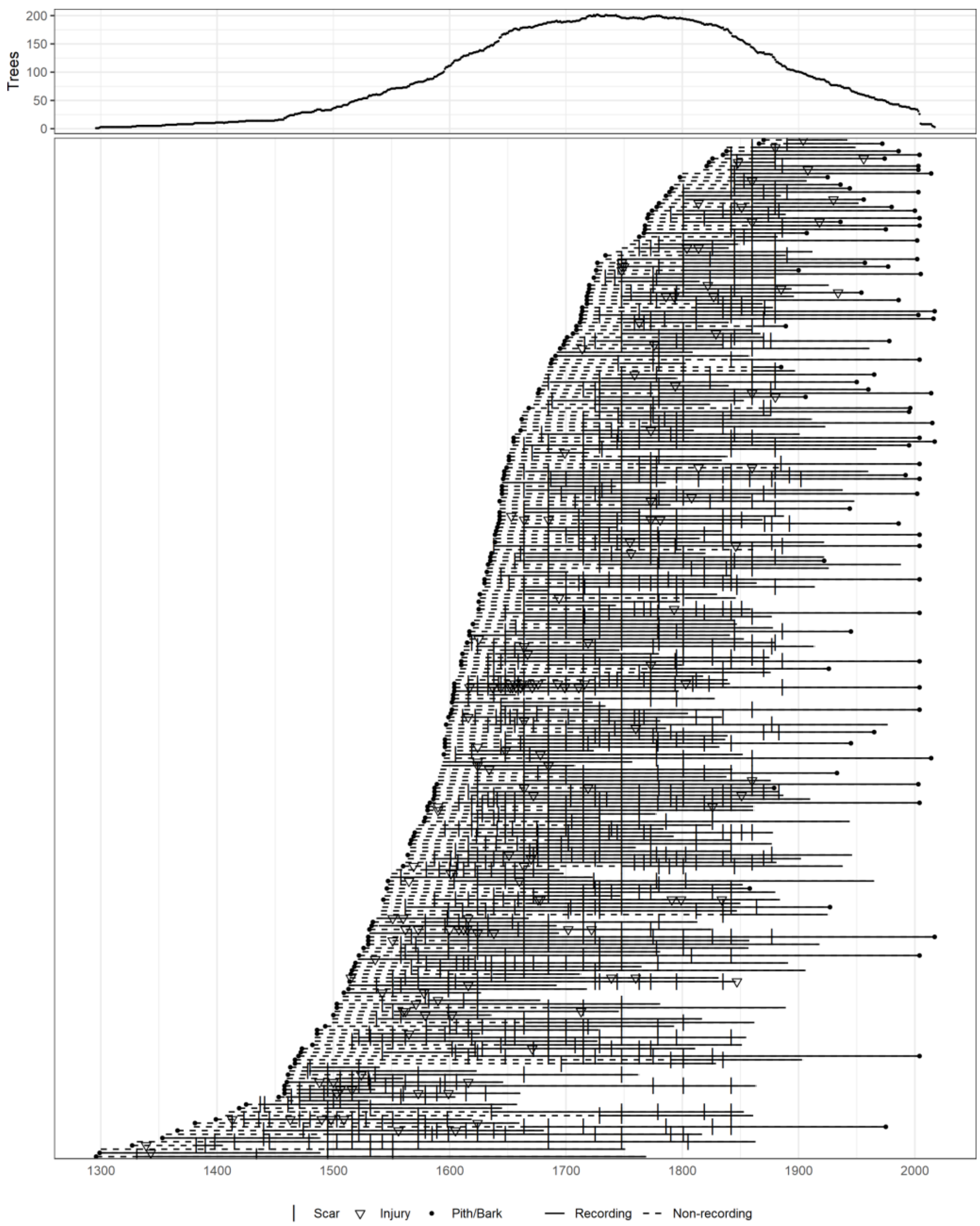

Figure 3. Fire chart for trees in plots in the Santa Fe Fireshed (n = 272 trees, 1296 – 2017 CE). Horizontal lines are trees and vertical ticks are fire scars. Top plot is sample depth. Note the lack of fire since 1880.

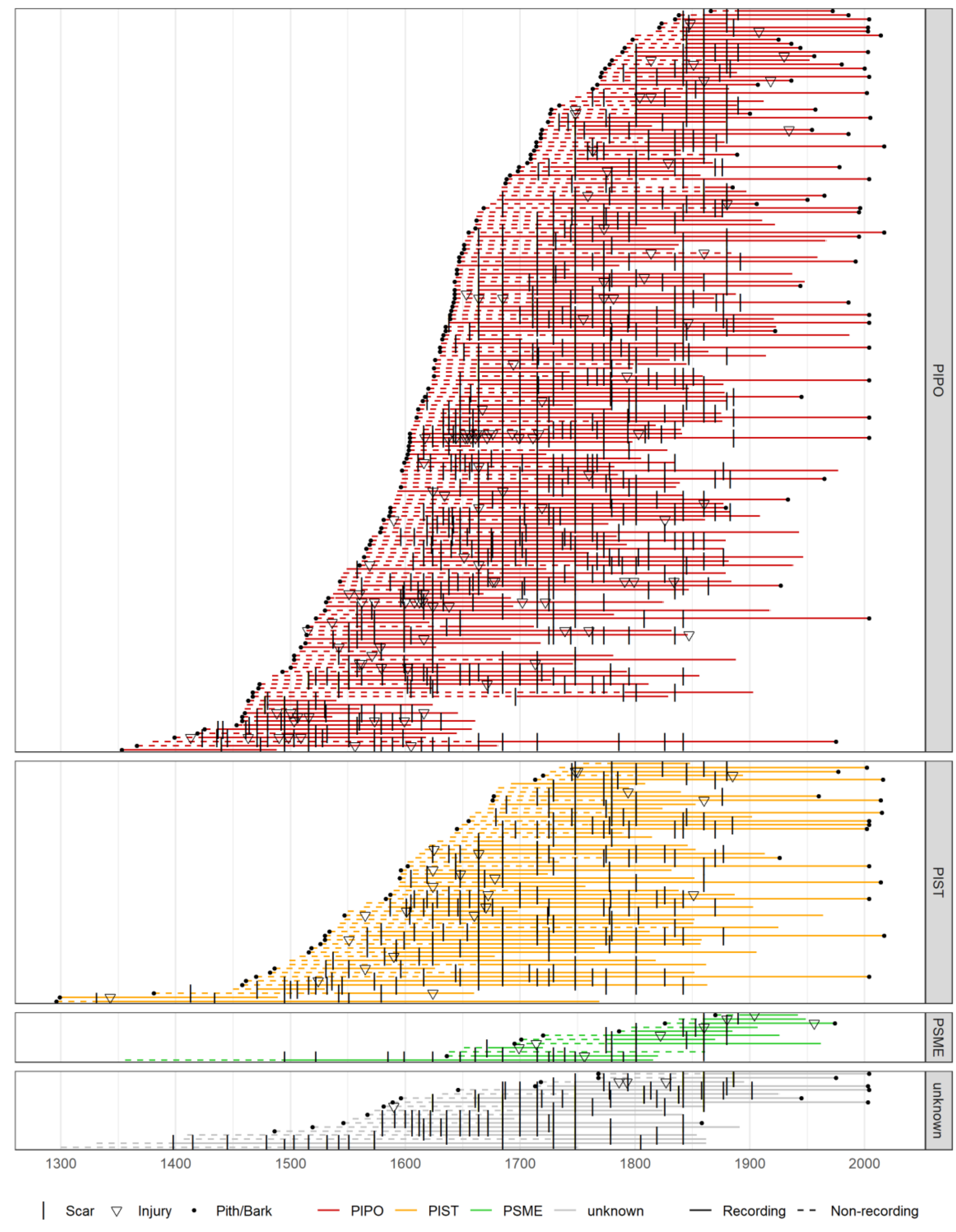

Figure 4. Firechart for all trees in plots in the southern Sangre de Cristo Mountains grouped by species. PIPO = *Pinus ponderosa*, PIST = *P. strobiformus*, and PSME = *Pseudotsuga menziesii.*

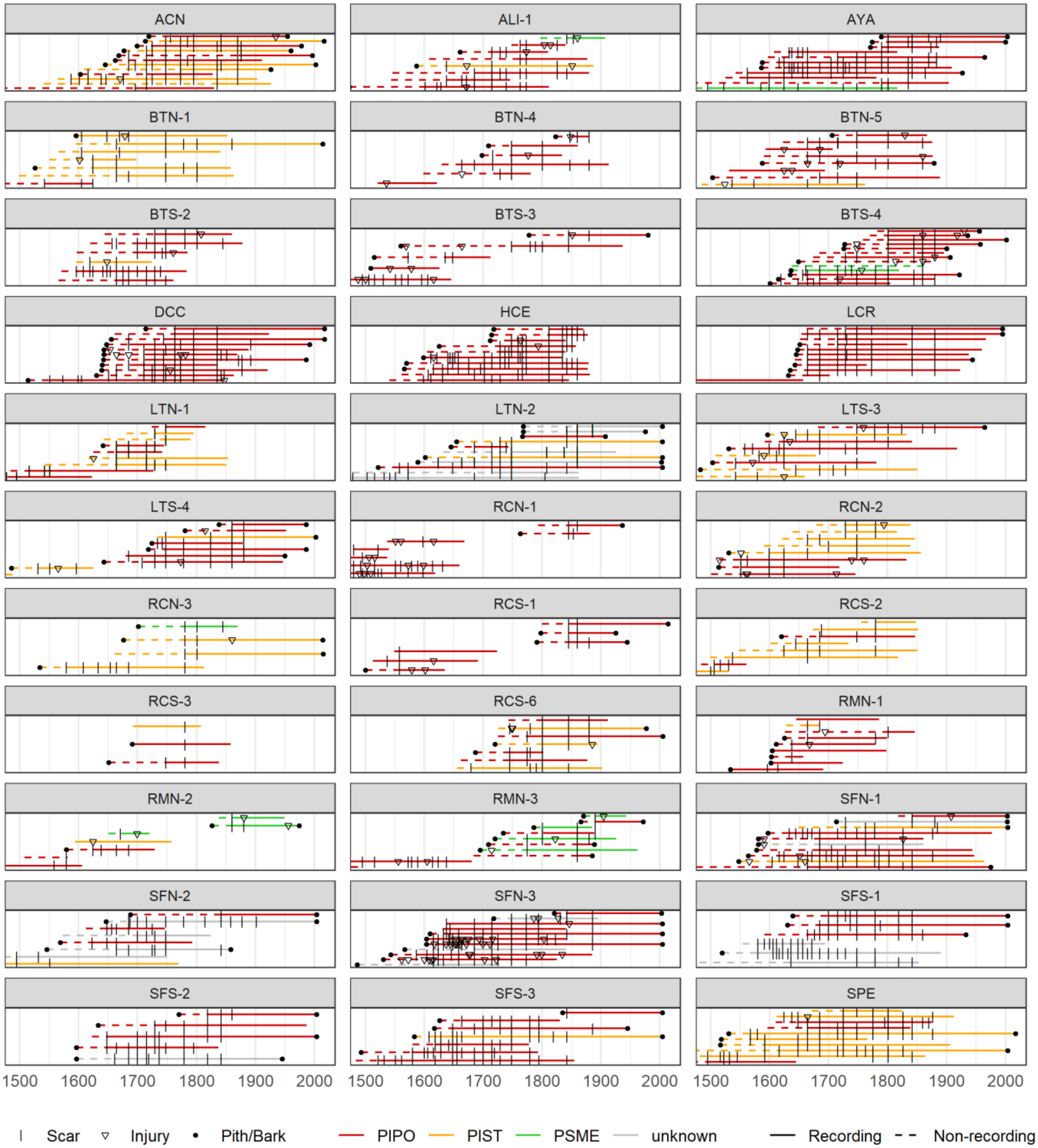

Figure 5. Fire charts for 33 plots in the southern Sangre de Cristo Mountains (1480 - 2010). PIPO = *Pinus ponderosa*, PIST = *P. strobiformus*, and PSME = *Pseudotsuga menziesii*

Table 2. Fire interval statistics for individual plots over the common period (1600 - 1902).

		Fire interval (years)			
Plot	Fires (#)	Mean	Median	Min	Max
RMN1	6	37.4	24	21	*
RMN2	7	42.7	17	7	*
RMN3	8	39.4	20	10	*
RCS1	3	17.5	17.5	15	20
RCS2	7	26	20.5	3	60
RCS3	2	32	32	32	32
RCS6	8	28.7	30	5	66
RCN1	5	61.5	12.5	7	*
RCN2	7	26	25	15	40
RCN3	8	33.9	21	10	*
BTS2	19	13.2	10.5	3	44
BTS3	9	34.2	31	9	*
BTS4	16	17.4	14	3	44
BTN1	10	28.3	23	5	63
BTN4	9	27	20.5	13	53
BTN5	8	28	30	1	59
LTS3	14	20.6	21	4	36
LTS4	10	21.7	21	5	46
LTN1	5	21	20	14	30
LTN2	14	20.2	18	3	57
SFN1	25	11.7	9.5	3	35
SFN2	17	17.4	16	2	36
SFN3	23	12.8	11	2	44
SFS1	23	11.8	9	4	31
SFS2	15	15.1	15	3	31
SFS3	21	14.3	12	2	44
AYA	25	11.4	8.5	3	34
SPE	18	15.4	15	6	30
ACN	18	16.2	12	6	40
LCR	9	27	23	2	69
DCC	19	15.9	14	4	46
HCE	29	9.4	7.5	4	39
ALI	15	17.9	13.5	6	53
All plots	117	2.6	2	1	10

* denotes plots with low sample depth resulting in unreliable maximum interval calculations.

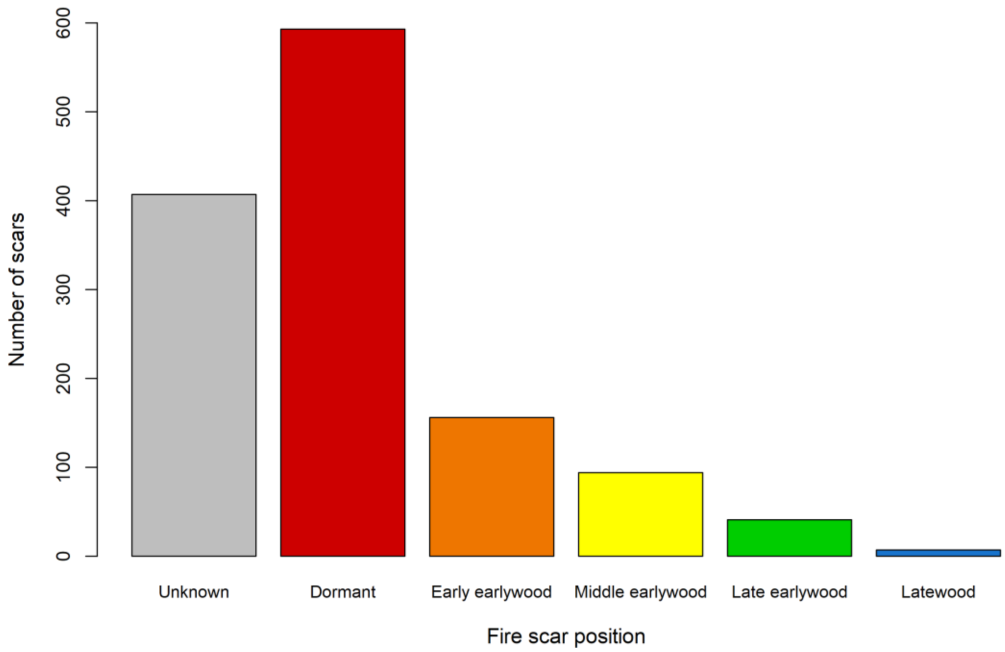

Figure 6. Seasonality of historical fires in the southern Sangre de Cristo Mountains derived from the position of the scar within the tree ring (1,298 fire scars from 272 fire-scarred trees). The most common fire scar positions, dormant and early earlywood, likely correspond to May and June, early growing-season fires.

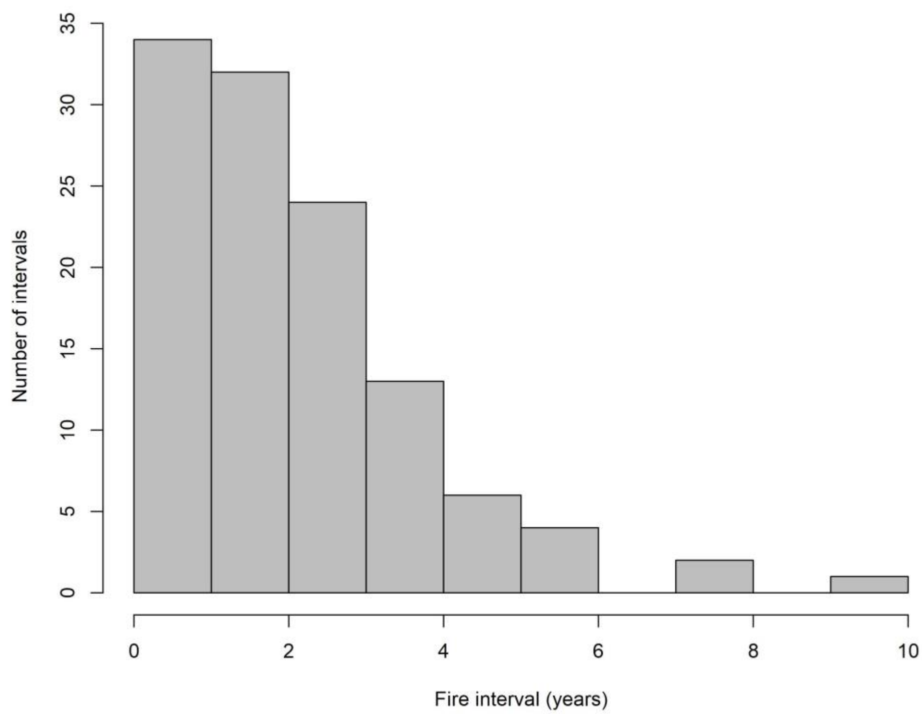

Figure 7. Distribution of fire intervals for all trees at all plots in the Santa Fe Fireshed (n = 117 fire years, 1600 - 1902). The right-skewed distribution of the fire intervals - more short intervals and few long intervals - is common to frequent fire regimes and indicates that the median interval is more useful than the mean interval.

The relative extent of fires – approximated by fire synchrony and fire mapping - varied in space and time (Figures 8 – 11 and S10 - S17). Widespread fires burning across all watersheds (e.g., 1685 and 1748, Figure 10) were relatively common from the mid-1600s to the mid-1700s. Fires that burned at least half of the sampled plots (17 or more plots, n = 5 fires) occurred at a 20-year median interval (Table 3). Small fires burning in one to three plots were most common circa 1600 (Figure 8), but occurred throughout the record (e.g., 1778 and 1779, Figure 10).

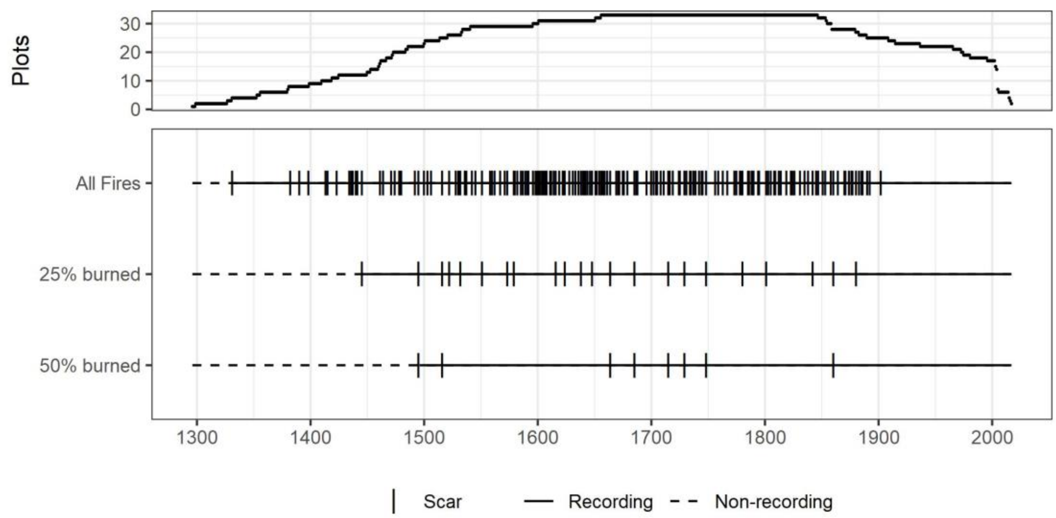

Figure 8. Fire composites illustrating fires that burned differing percentages of plots in the Santa Fe Fireshed (33 plots, 1296 – 2017 CE). The horizontal lines indicate the frequency of fires with different relative extents, including: 1) all fires, 2) fires that burned 25% of the recording plots and a minimum of two plots, and 3) fires that scarred 50% of the recording plots and a minimum of two plots. The top curve shows the number of recording plots through time. The data suggest that there were many small fires circa 1600 and a peak in widespread fires circa 1700.

Table 3. Fire interval statistics for fires that burned at different spatial scales during the common period (1600 – 1902). We sampled 33 plots, so 9 and 17 plots burned represents 25% and 50% of total recording plots burned.

		Fire interval (years)			
Number of plots burned (≥)	Fires (#)	Mean	Median	Min	Max
2	66	4.5	3	1	18
9	13	22	20.5	8	41
17	5	21	20	14	30

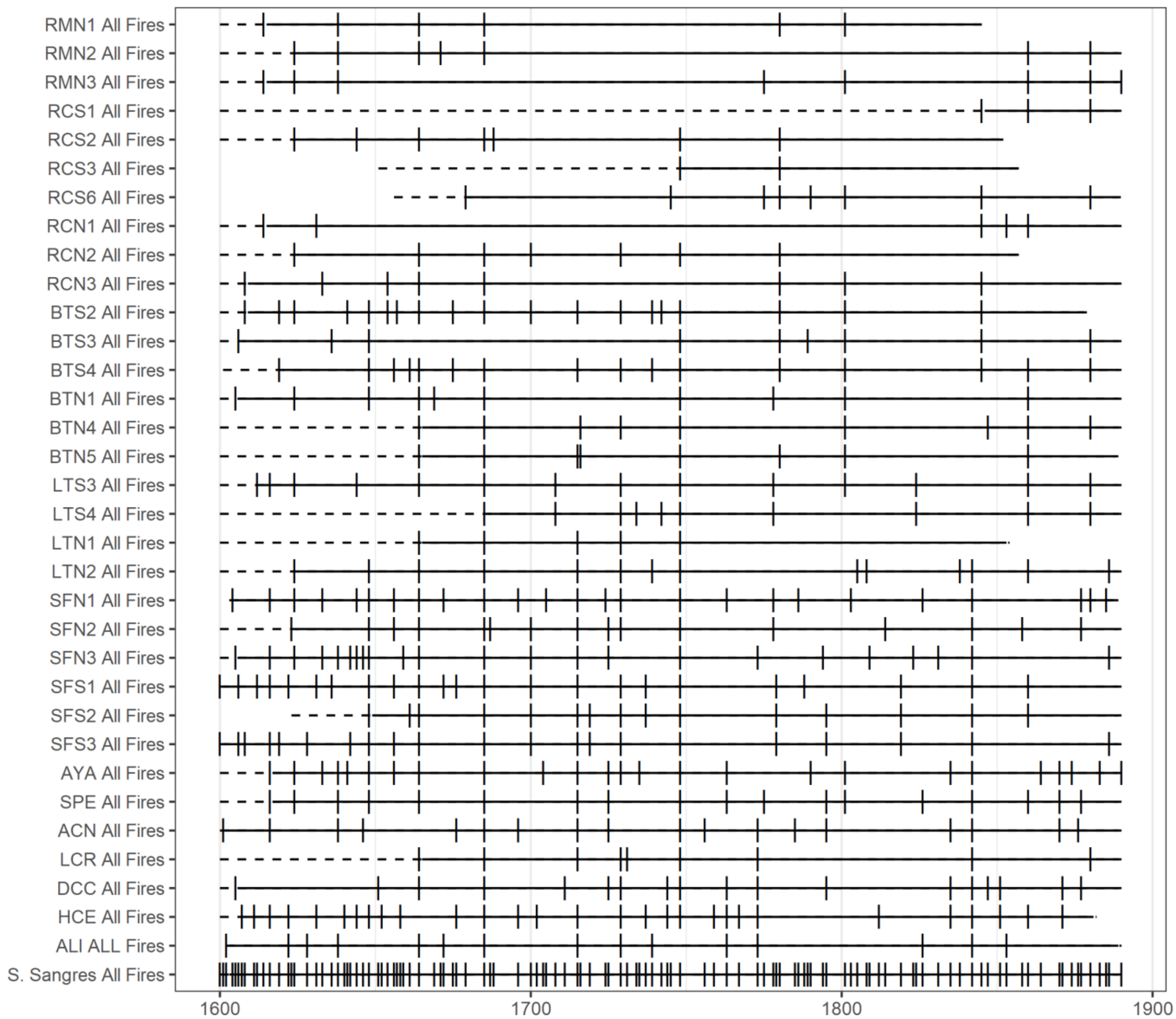

Figure 9. Composite fire histories for the 33 individual fire history plots (e.g., RMN1) and all fires (S. Sangres All Fires - bottom) in the Santa Fe Fireshed. Plots are arranged geographically from northwest to the southeast (top to bottom). See Table 1 for site names.

Fire was commonly burning synchronously in the Santa Fe watershed and the adjacent watersheds (Figure 11). There were 17 fires that burned synchronously in all watersheds (1600 – 1902). These widespread multi-watershed fires occurred every 18 years, on average. Fires burning between the Santa Fe Watershed and only one of the adjacent watersheds burned even more frequently. Almost half (48%) of recorded fires in the West-slope Watersheds were also recorded in the Santa Fe Watershed. Similarly, 45% of recorded fires in the Southern Watersheds were also recorded in the Santa Fe Watershed.

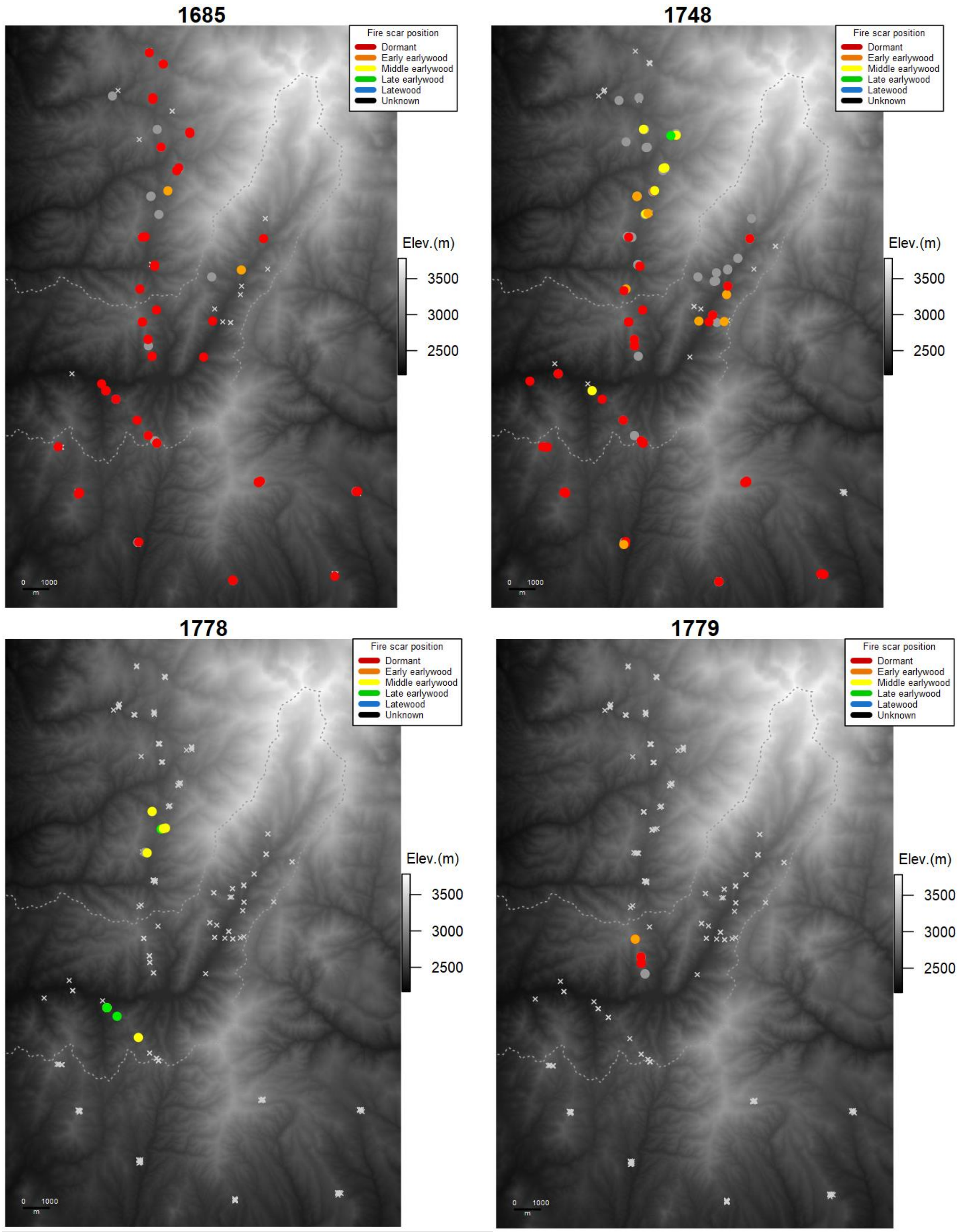

Figure 10. Trees recording widespread fires in 1685 and 1748 and localized fires in 1778 and 1779. Colors correspond to fire scar position, or seasonality. Grey x's indicate recording trees not scarred. The grey dotted line is the Santa Fe Watershed boundary.

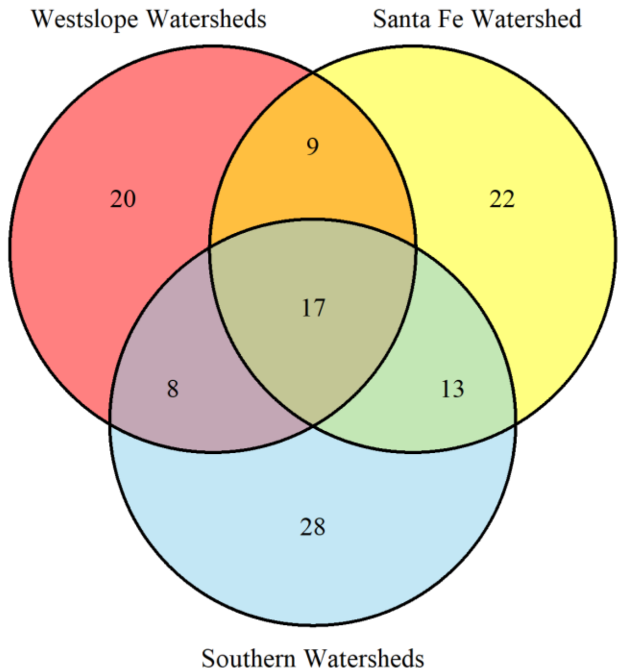

Figure 11. A venn diagram illustrating fire synchrony between the Westslope Watersheds, the Santa Fe Watershed, and the Southern Watersheds (1600 – 1902). Numbers indicate the number of fire years. Seventeen fires burned synchronously in all three watersheds over the 303-year period of anlysis.

Fire-related mortality (a mixed- or high-severity fire) likely occurred at 8 of 33 (24%) of the plots at some point over the last four centuries (e.g., RCN1 and RCN2, and RCS1-3, Figures 5, S2, and S3). The plots with evidence of higher-severity fire were primarily in mixed-conifer forest. In addition, these higher-severity fires were concentrated in the Rio Chupadero watershed in the north end of the study area (five RCN and RCS plots, Figures 1 and 5). Although complete mortality at the plot-level (1 ha) occurred during a few fires (e.g., 1860), the mortality was not synchronous across watersheds (Figure 5). In all cases, these same plots burned with multiple low-severity fires either before or after the mixed- or high-severity fire, indicating a historical fire regime in the mixed-conifer forest dominated by low-severity fire, with occasional, patchy mixed- or high-severity fire.

Fires were significantly related to drought (negative PDSI departures, 1600 – 1902, Figure 12). All fires, which included both small and large fires, occurred during moderate drought conditions, with no relationships with climate during prior years. Widespread fires that burned at least 25% of the plots, occurred during severe droughts that were preceded by wet conditions in prior years.

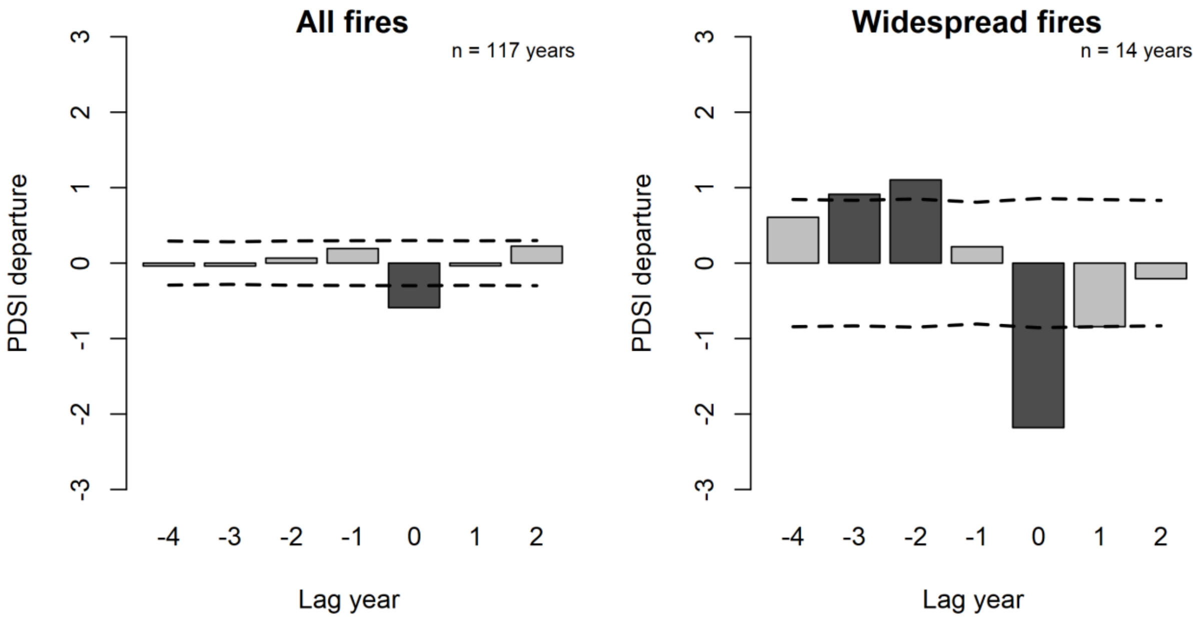

Figure 12. Superposed epoch analysis used to test for fire-climate relationships of all fires and widespread fires (1600 – 1902). Widespread fires burned 25% or more of the plots in the study area. PDSI is Palmer Drought Severity Index; negative PDSI departures are dry and positive PDSI departures are wet. Shaded bars indicate significant departures from mean PDSI ($p < 0.05$). Confidence intervals were determined using a bootstrap procedure with 1,000 iterations.

Discussion

Fire frequency

The fire regime in the dry conifer forests at the southern extent of the Rocky Mountains historically burned frequently and was dominated by low-severity fire. This is similar to other dry conifer forests of the region (Swetnam and Baisan, 1996) and across the West (Taylor and Skinner, 2003; Brown et al., 2008). Fires occurred in consecutive years on multiple occasions, but usually in different locations, suggesting a fuel limitation immediately following fire that prevents re-burning. Individual plots burned less frequently, on average (7 – 32 year median intervals). Widespread fires that burned at least half of the plots and crossed watersheds occurred relatively frequently (e.g., 20-year intervals). These fire frequency estimates at different spatial scales are useful for planning fire treatments and fire frequency for fire regime restoration and maintenance burning. For three hundred years (1600 – 1902), the longest period without a fire in the study area was 10 years (1892 – 1902; Figures 8 and 9). The current fire-free interval (119 years) is over 11 times the historical maximum fire-free interval. These fire frequency estimates are similar to other studies across the region (Swetnam and Baisan, 1996).

Fire synchrony between the Santa Fe Watershed and adjacent areas

The majority (64%) of the fires the burned in the Santa Fe watershed also burned in adjacent watersheds. The last synchronous fire was > 135 years ago (1886). The degree of reconstructed historical synchrony, combined with observations of modern fires commonly burning across watershed boundaries, suggests that fire spread between the Santa Fe watershed and adjacent watersheds was likely common. Currently, the prevailing winds are generally from the south to the west during the fire season (May and June), which suggests that fires in adjacent watersheds have the high potential to spread into the Santa Fe watershed, particularly the upper Santa Fe watershed. This indicates that a landscape-scale perspective to forest, fire, and watershed management is necessary.

Fire seasonality – management implications

Similar to other fire history studies in the Southwest, the predominant fire season was in the spring and early summer (dormant or early earlywood scars -- early growing season), with few fall fires recorded. This contrasts with the current primary season for prescribed fire across the region, which is the fall. However, it is important to note that prescribed fire in previously treated areas in the Santa Fe Watershed are increasingly occurring in spring, which was historically more common. Burning during the historical fire season is more ecologically beneficial, but in many cases this is not feasible until fuel levels are reduced by initial mechanical or late-season fire treatments. Mid-summer, monsoon-season, fires did occcur in the past and can be an intermediary goal, or another alternative to burning in the windy and dry spring and early summer.

Potential early human alteration of the fire regime in the Rio Chupadero drainage

There is some evidence to suggest a possible early human interuption in the fire regime beginning in the late 1700s in the Rio Chupadero. The three plots that surround a large meadow (Vigil Grant) along the Rio Chupadero (RCN-2, RCS-2, and RCS-3, see Figure 1) experienced an 80-year fire-free period beginning in 1780 (Figure 5). Meanwhile, the surrounding plots were buring in widespread fires (e.g., 1801 and 1845 fires). This anomalous fire free period at the three plots surrounding the Rio Chupadero meadow was followed by high-severity fire that killed all sampled trees at these plots (e.g., Figures 5, S1, and S2). Prior to this 80-year fire free interval, these three plots were burning repeatedly at low severity, with some individual trees surviving up to ten fires (e.g., plot RNC-2). The meadow in the Rio Chupadero is at the junction of the drainage and the Borrego (goat or sheep) Trail. The Borrego Trail was used historically to move sheep north and south, to and from Santa Fe from the villages to the north. The Rio Chupadero was possibly also an early travel route from Tesuque Pueblo east into the Sangre de Cristo mountains. It is possible that early grazing in and around the meadow at the intersection of the Rio Chupadero and the Borrego Trail eliminated surface fuels (grass) neessary to facilitate fire spread in this area, as well as created animal trails that would have further fragmented surface fuels. The long fire-free intervals likely increased fuels loads and generated ladder fuels (young trees), so that when the area finally burned again, the fire killed the forest that had survived many prior fires. Culturally modified (bark-peeled) ponderosa pine have been observed in the study area, particularly along the Borrego Trail, and dating the years of the modifications may be one way of dating human presence and testing this localized grazing hypothesis, in conjunction with written historical records.

Conclusions

The dry conifer forests of the southern Sangre de Cristo Mountains burned frequently, primarily at low severity, for centuries up until the late 1800s. This pattern has been documented in dry conifer forests across the Western U.S. Lack of fire for over a century, especially in these relatively productive, high-elevation forests allows fuel to accumulate, which increases the risk of fires with uncharacteristically large patches of high-severity fires like those occurring in other parts of the Sangre de Cristo Mountains, regionally, and across the West. In one case, a multi-decadal period of fire exclusion in the late 1700s/early 1800s, possibly related to early sheep grazing, was followed by high-severity fire at multiple plots, which had previously burned repeatedly at low-severity in prior centuries. This historical example of localized surface fire removal, paired with the large, contiguous high-severity fire patches just north of the study area (e.g., Pacheco fire) highlights the processes that have lead to the current increased risk of high-severity fire in the dry conifer forests. The drought-fire association of past centuries indicates that with increased drought severity in a warmer climate, combined with the increased fuels, fire occurrence and size are likely to cointinue to increase in coming decades. These combined factors underscore the value of strategic, proactive restoration of fire-resilient forest compositions and structures that facilitate restoration of the lost keystone ecological process of low-severity fire in the ecologically, economically, and culturally important watersheds of the greater Santa Fe area.

Acknowledgements

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Supplementary Materials

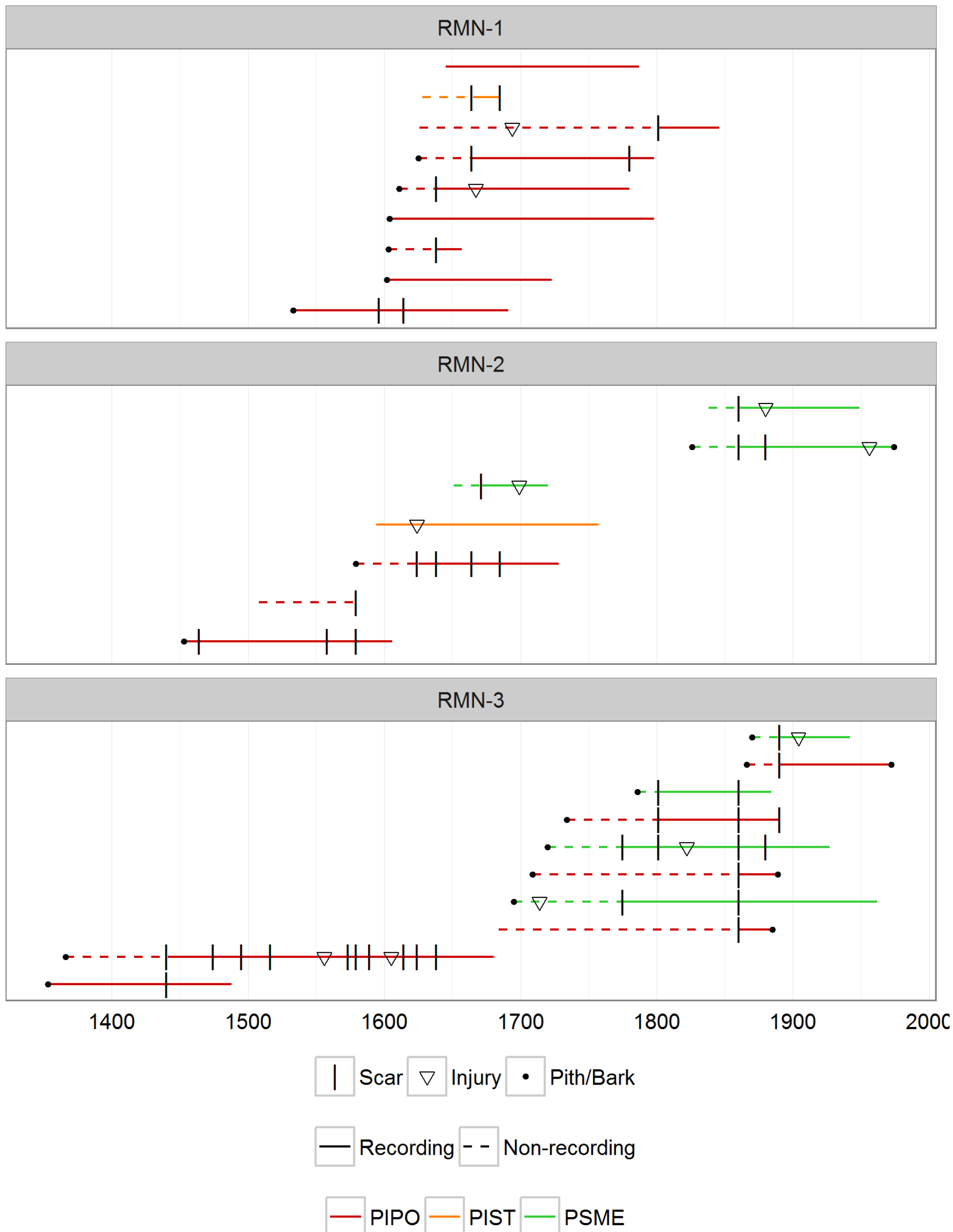

Figure S1. Fire chart for Rio en Medio drainage north-facing aspect (RMN), individual plots.

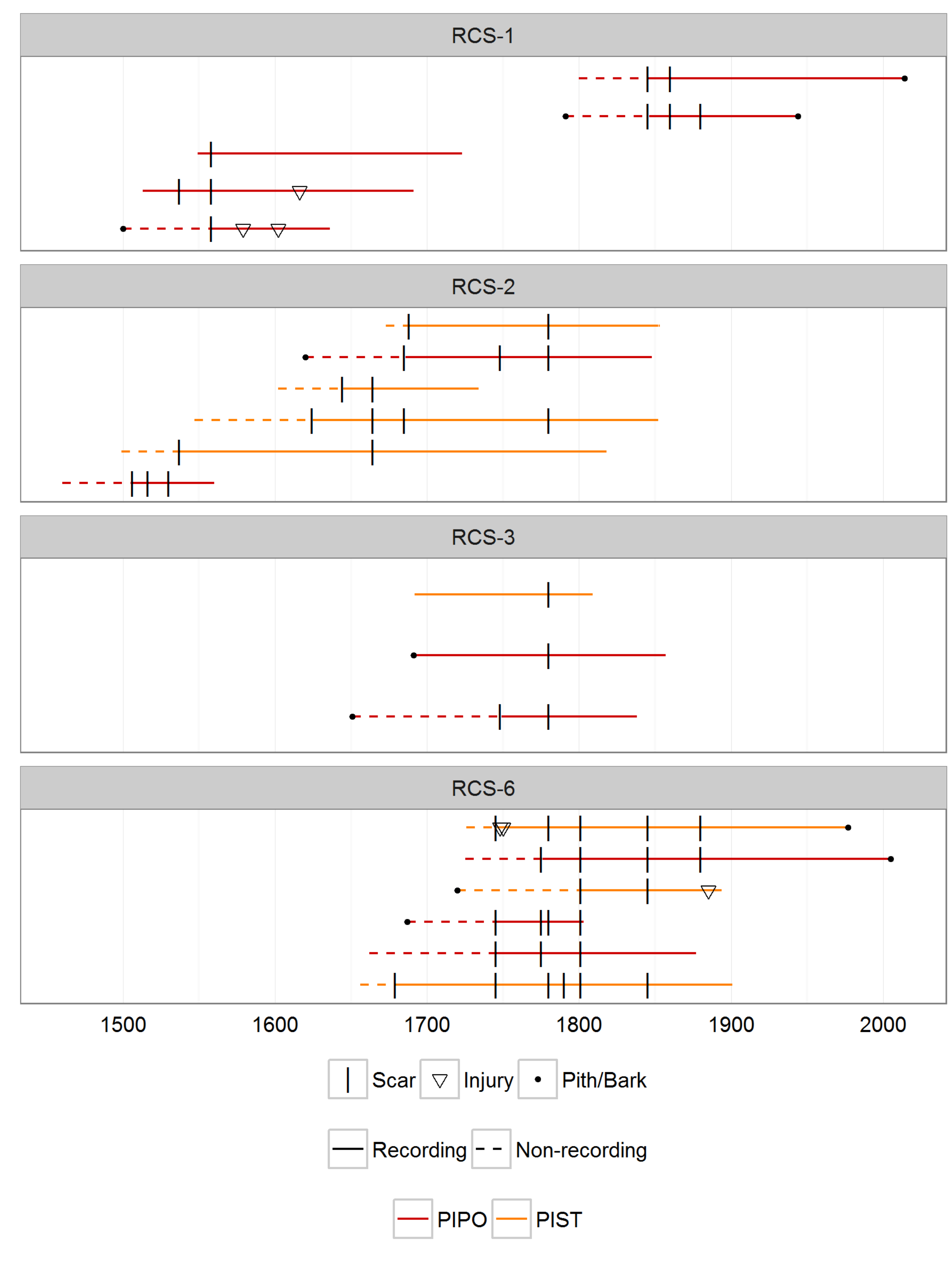

Figure S2. Fire chart for Rio Chupadero drainage south-facing aspect (RCS), individual plots.

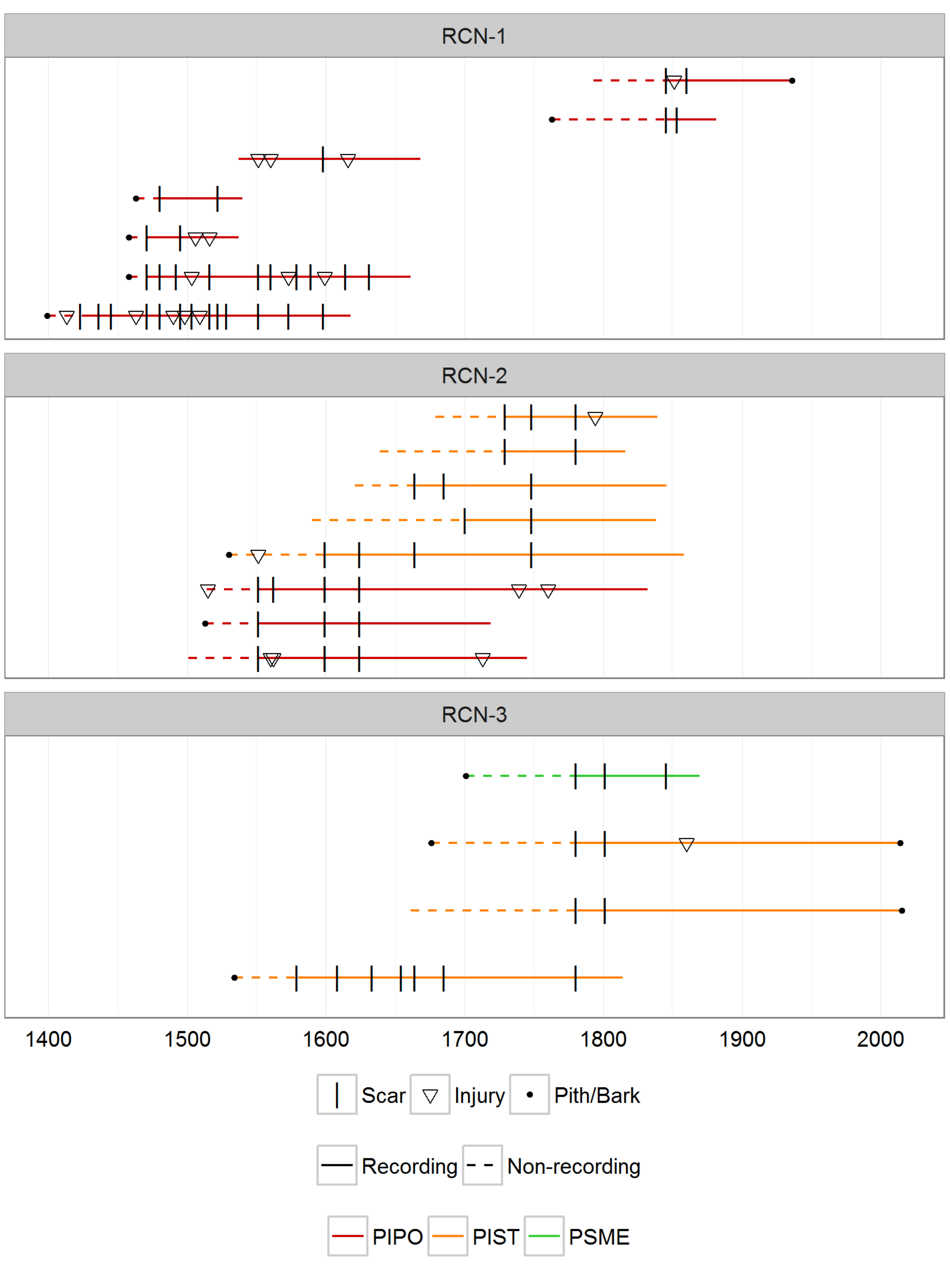

Figure S3. Fire chart for Rio Chupadero drainage north-facing aspect (RCN), individual plots.

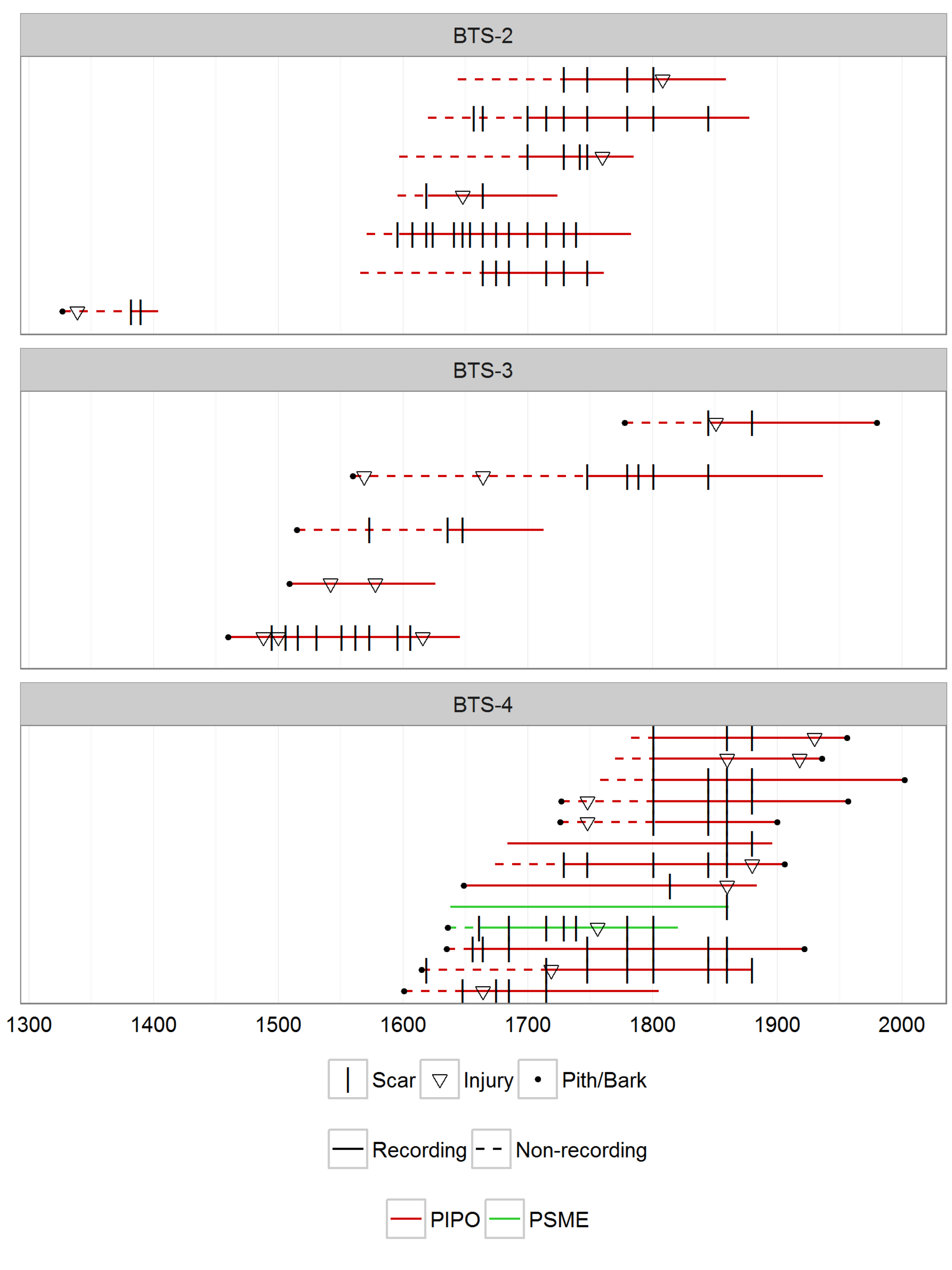

Figure S4. Fire chart for Big Tesuque drainage south-facing aspect (BTS), individual plots.

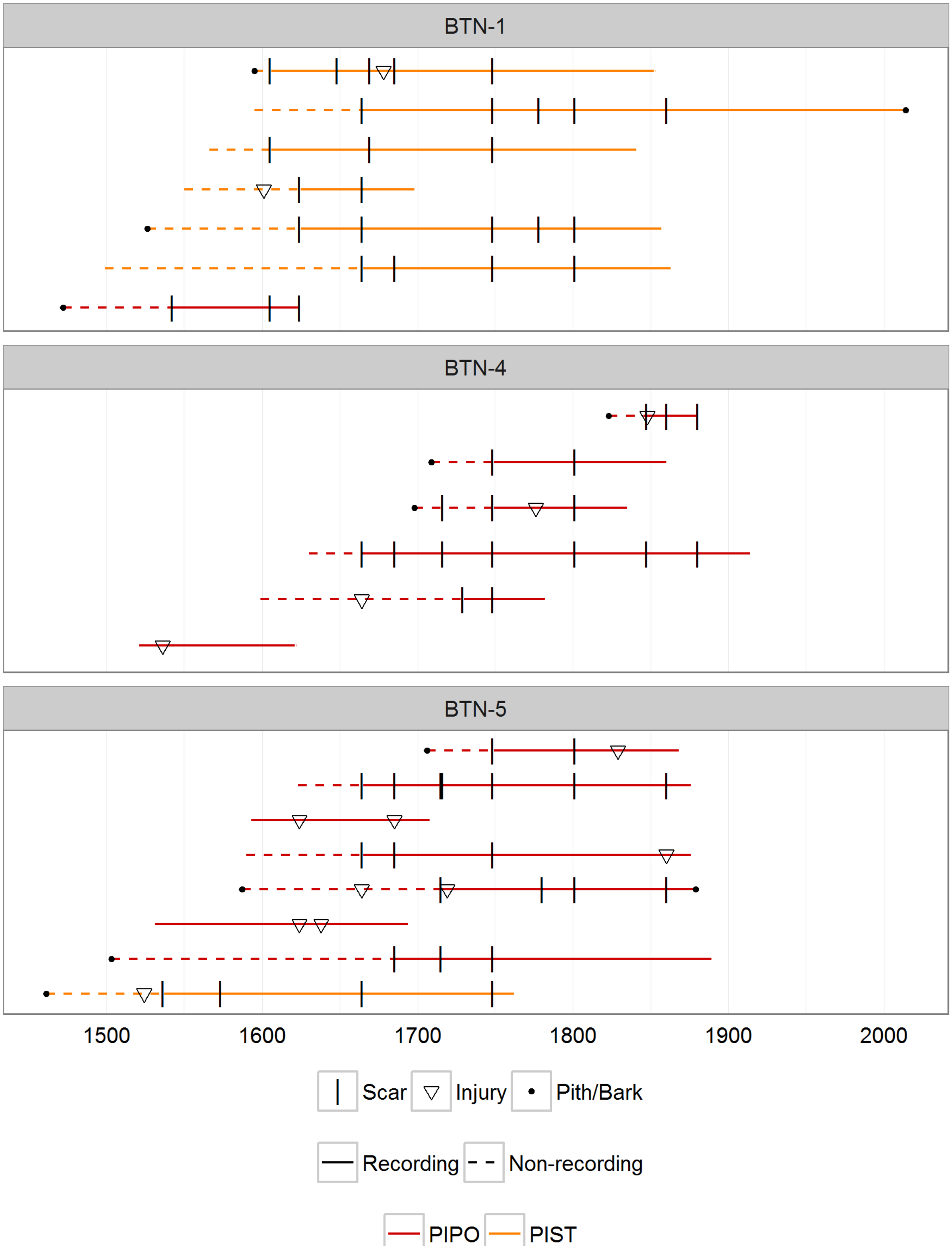

Figure S5. Fire chart for Big Tesuque drainage north-facing aspect (BTN), individual plots.

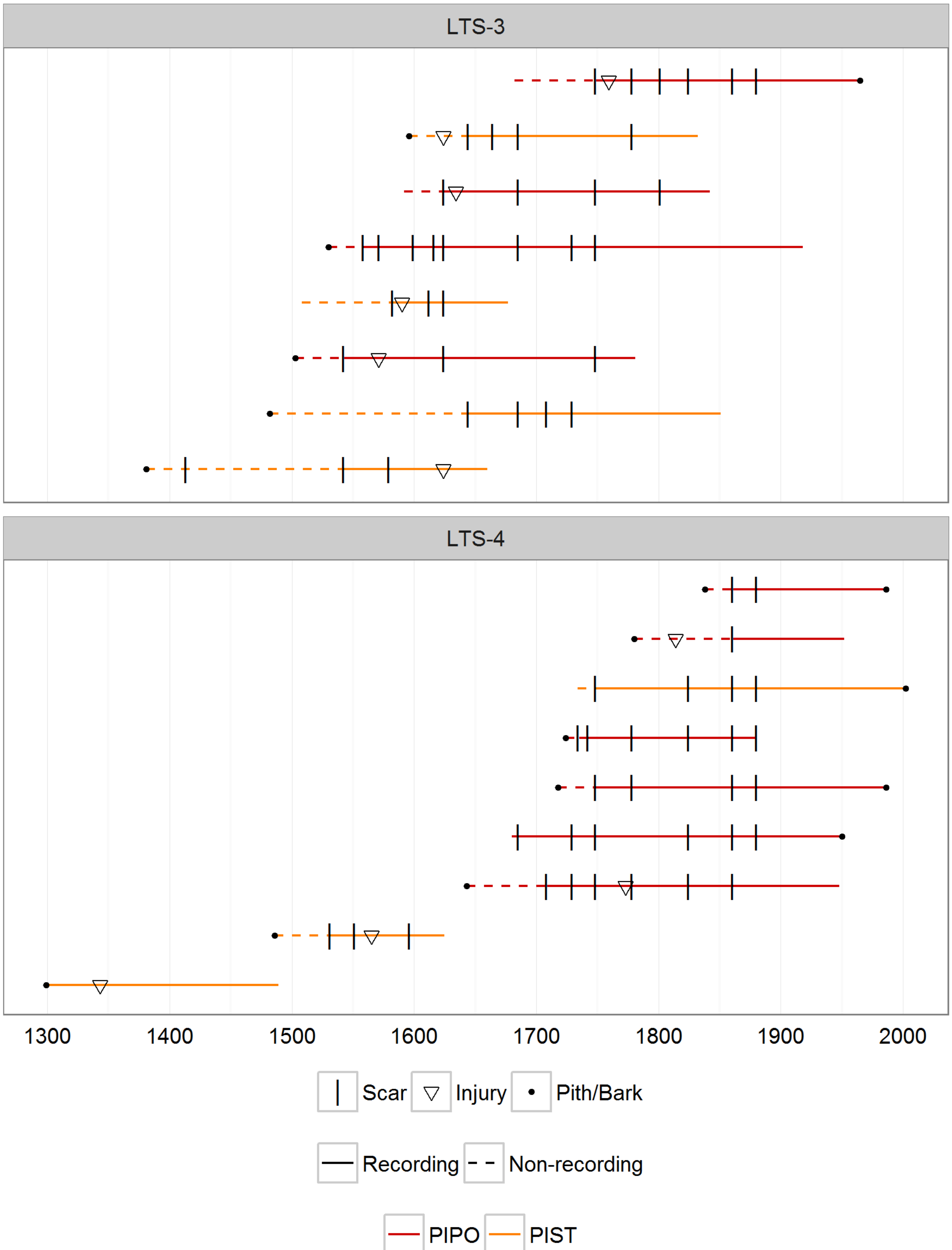

Figure S6. Fire chart for Little Tesuque drainage south-facing aspect (LTS), individual plots.

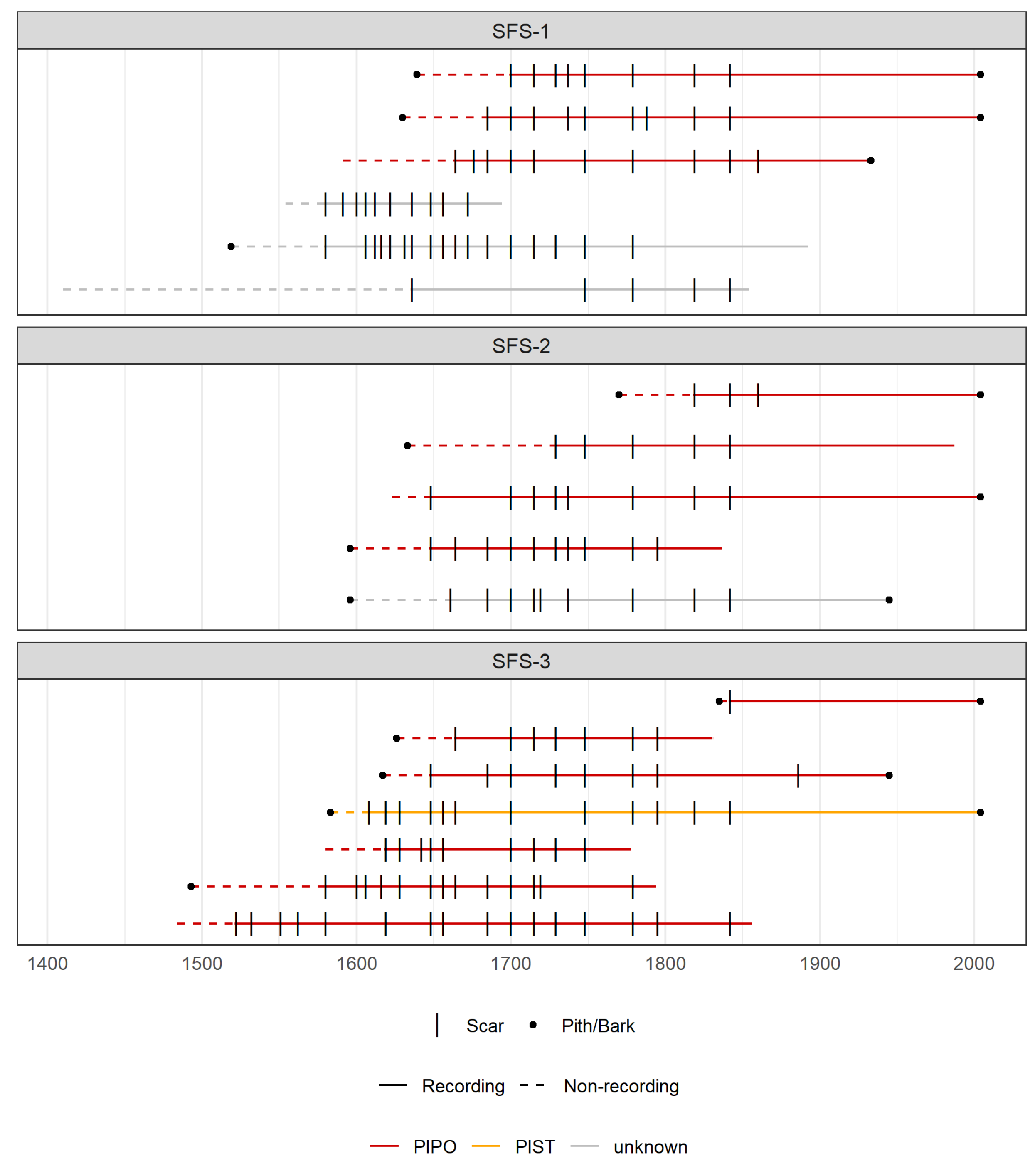

Figure S7. Fire chart for the Santa Fe Watershed south-facing aspect plots (SFS).

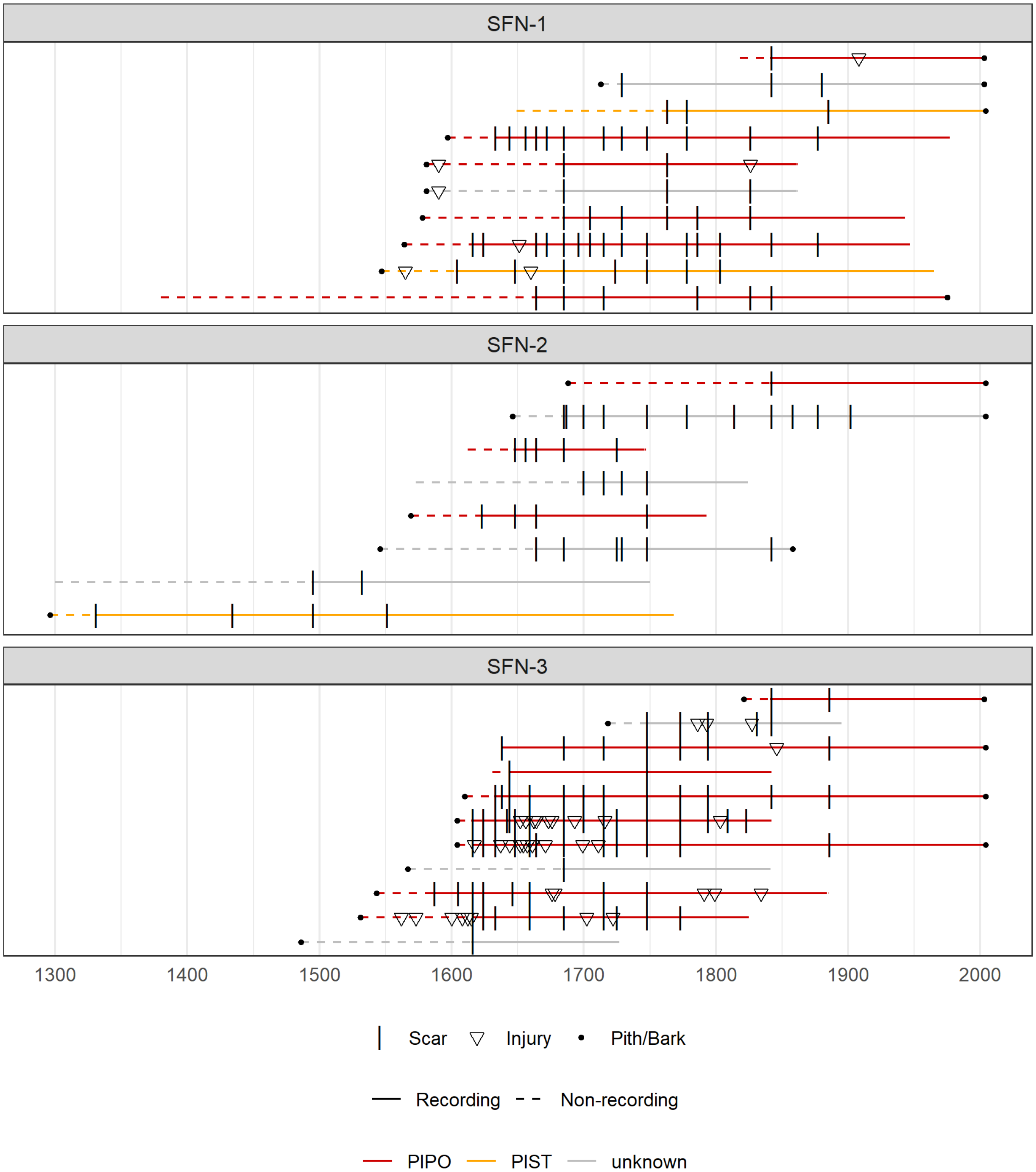

Figure S8. Fire chart for the Santa Fe Watershed north-facing aspect plots (SFN).

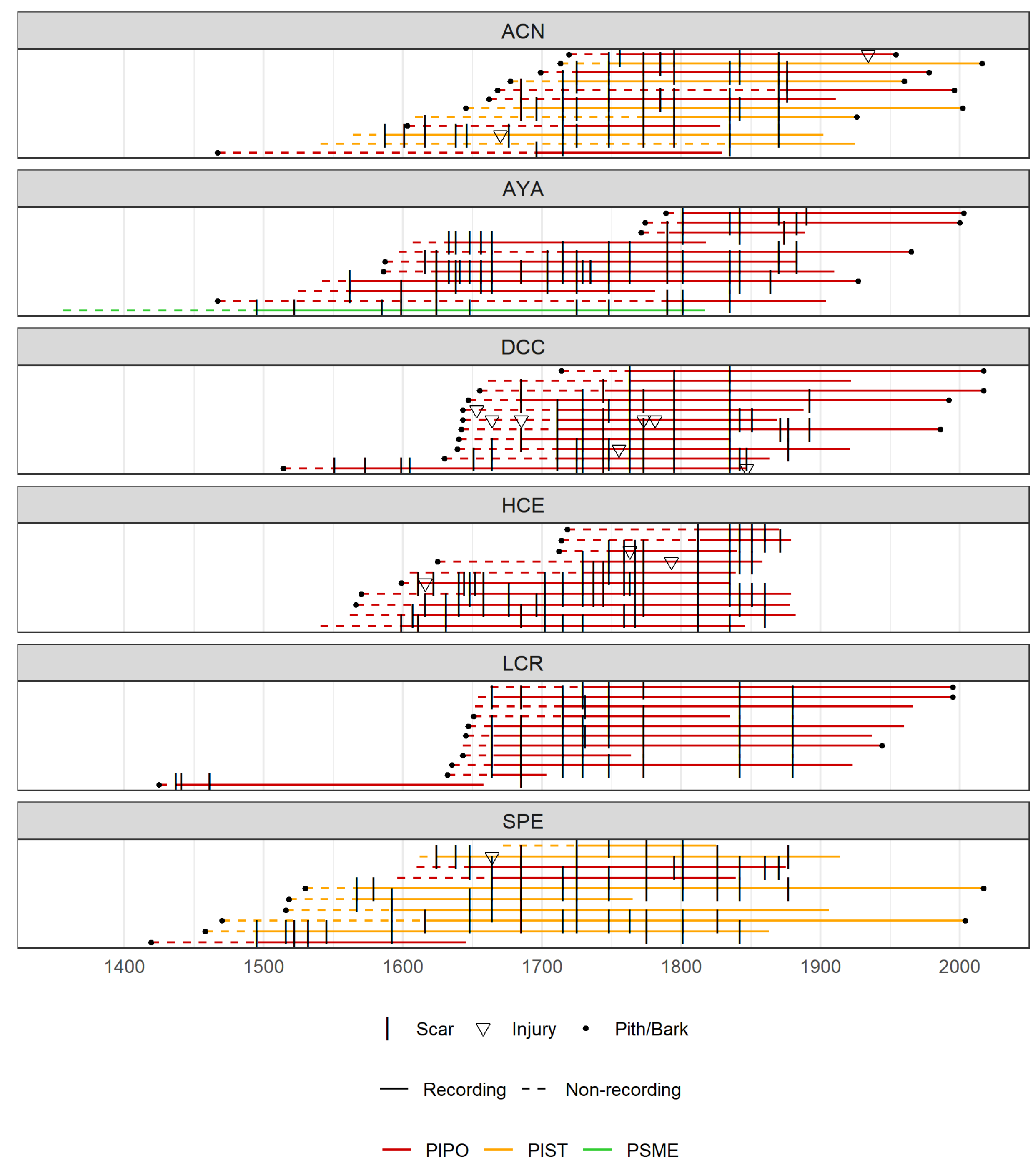

Figure S9. Fire chart for plots in the Southern Watersheds group.

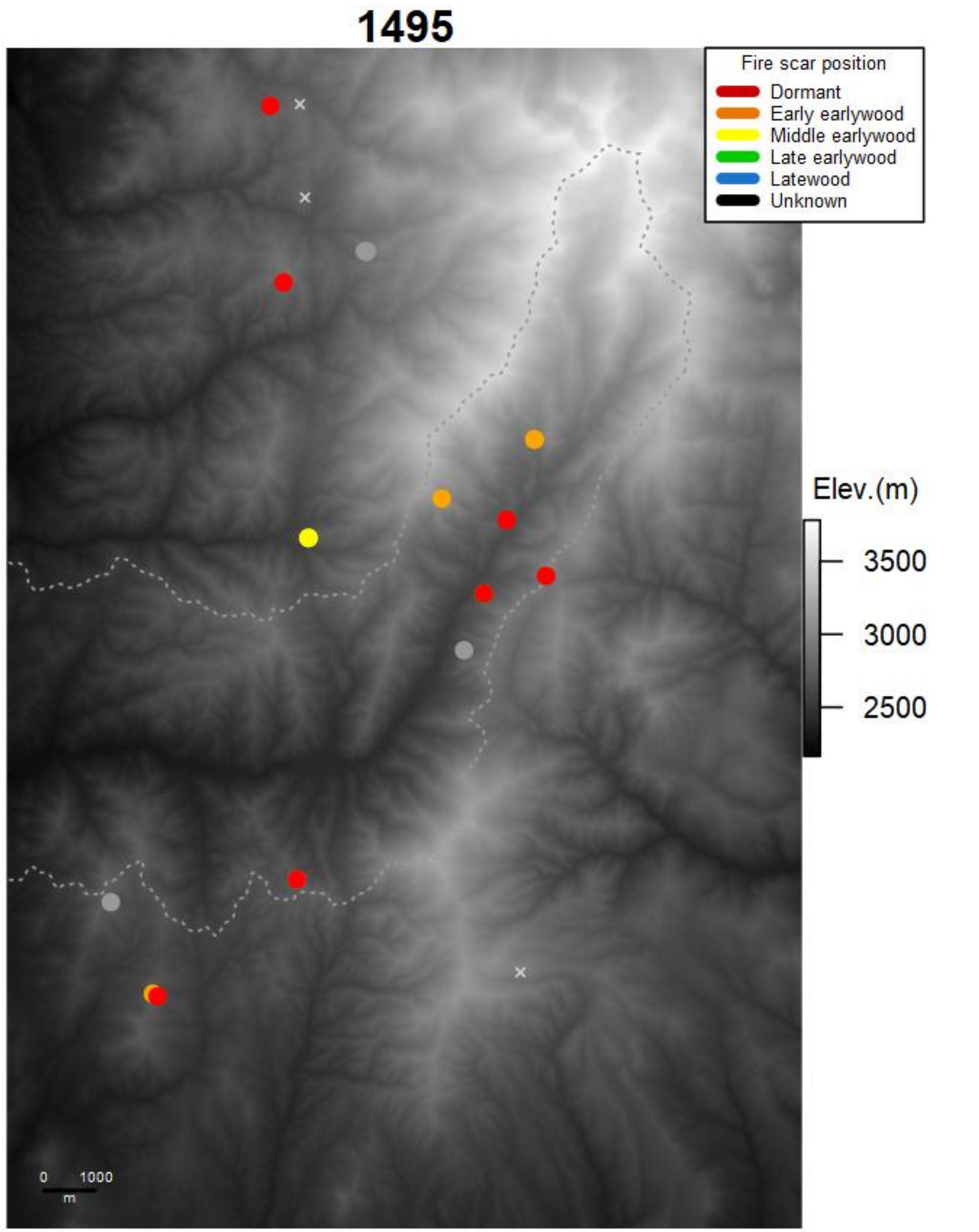

Figure S10. All trees recording 1495 fire within the study area. Colors correspond to fire scar position, or seasonality. Grey x's indicate recording trees not scarred.

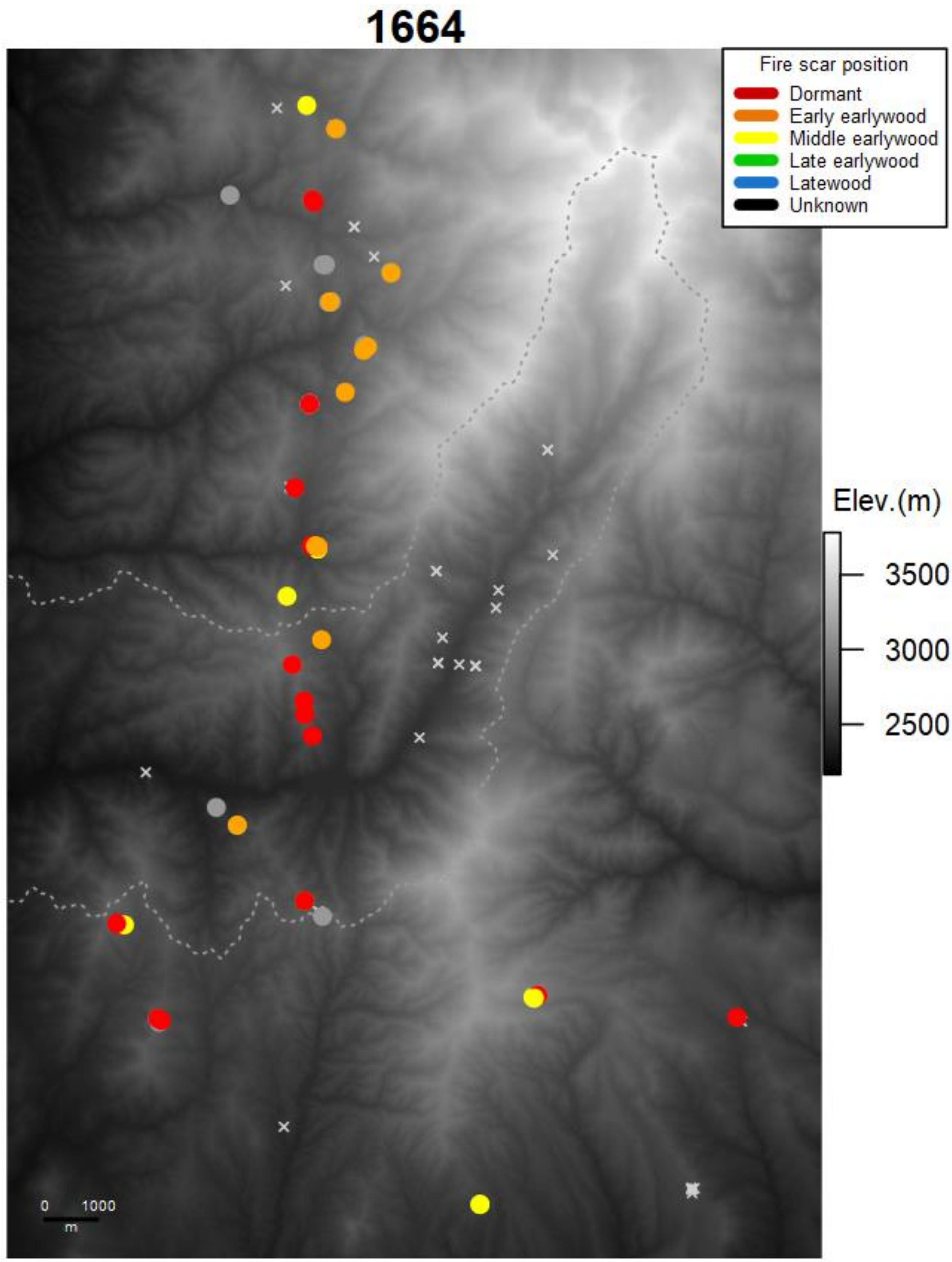

Figure S11. All trees recording 1664 fire within the study area. Colors correspond to fire scar position, or seasonality. Grey x's indicate recording trees not scarred.

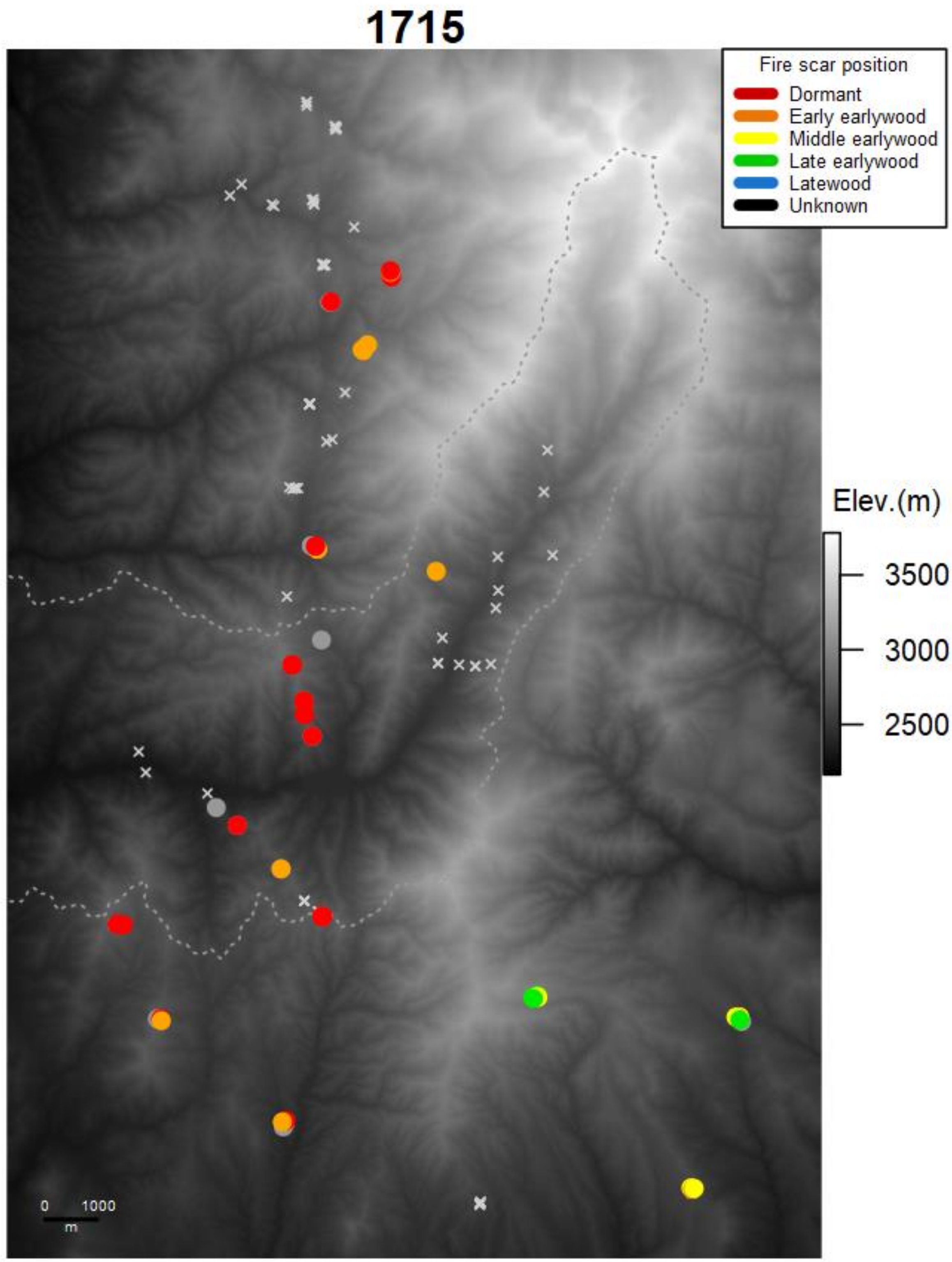

Figure S12. All trees recording 1715 fire within the study area. Colors correspond to fire scar position, or seasonality. Grey x's indicate recording trees not scarred.

1716

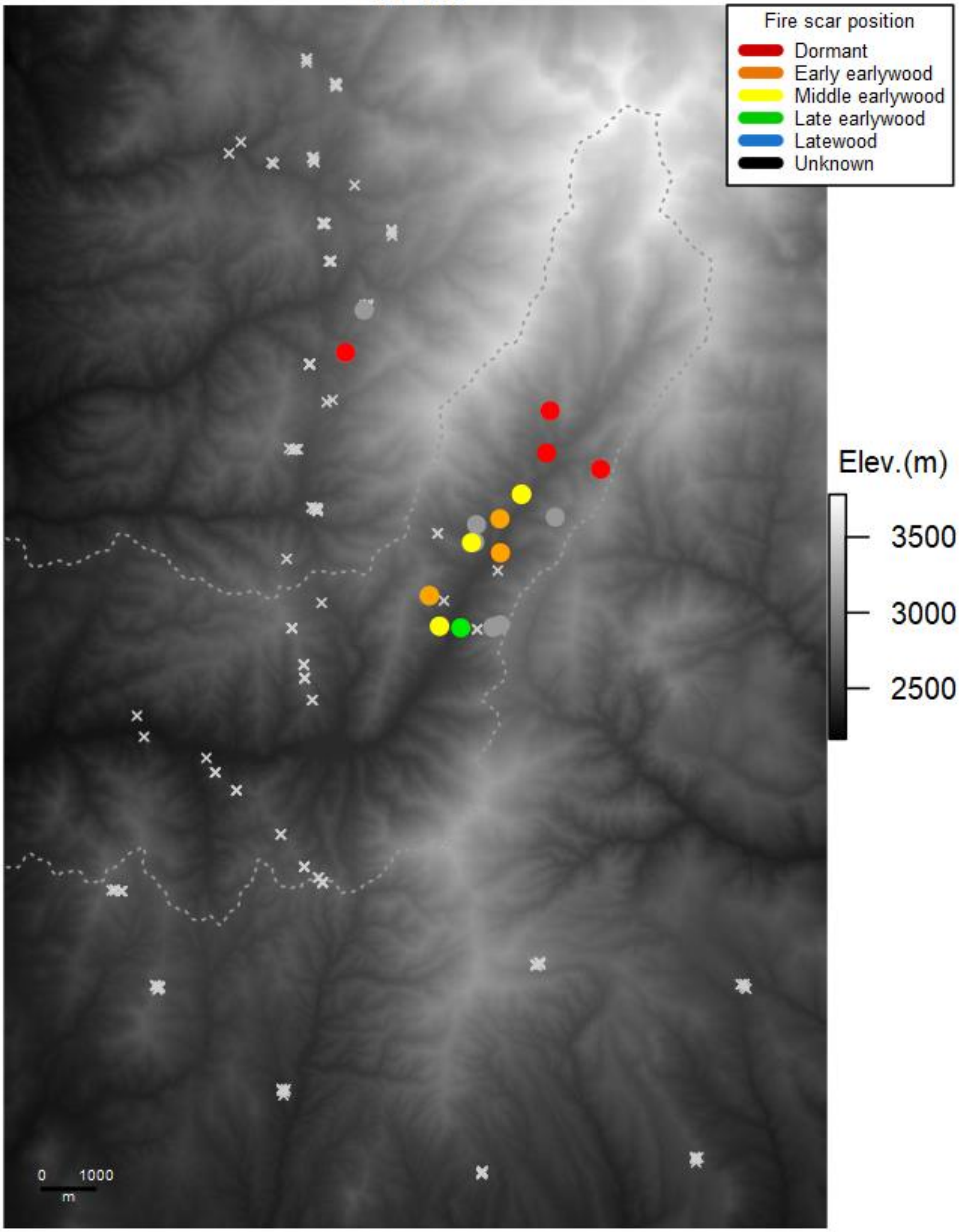

Figure S13. All trees recording 1716 fire within the study area. Colors correspond to fire scar position, or seasonality. Grey x's indicate recording trees not scarred.

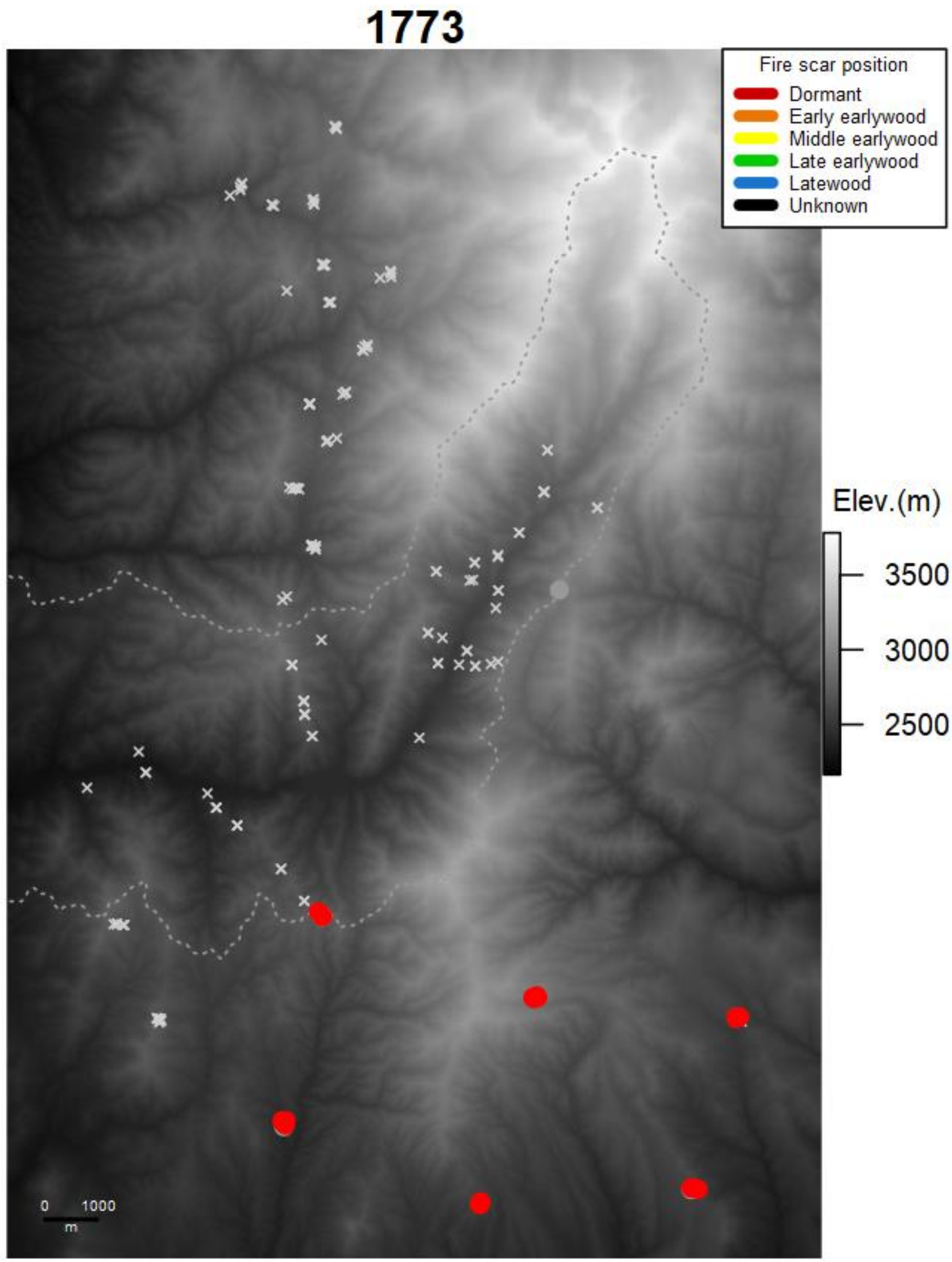

Figure S14. All trees recording 1773 fire within the study area. Colors correspond to fire scar position, or seasonality. Grey x's indicate recording trees not scarred.

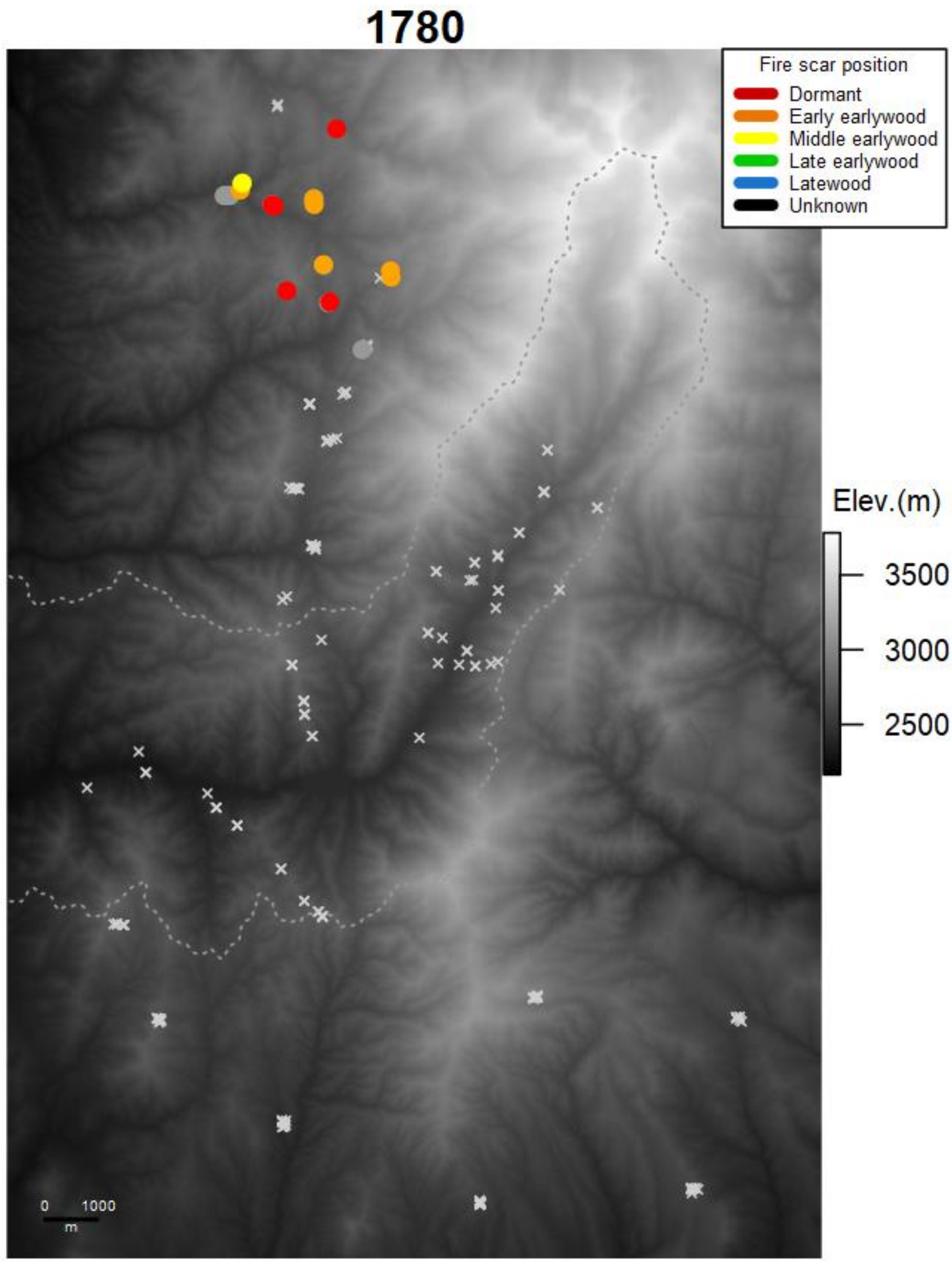

Figure S15. All trees recording 1780 fire within the study area. Colors correspond to fire scar position, or seasonality. Grey x's indicate recording trees not scarred.

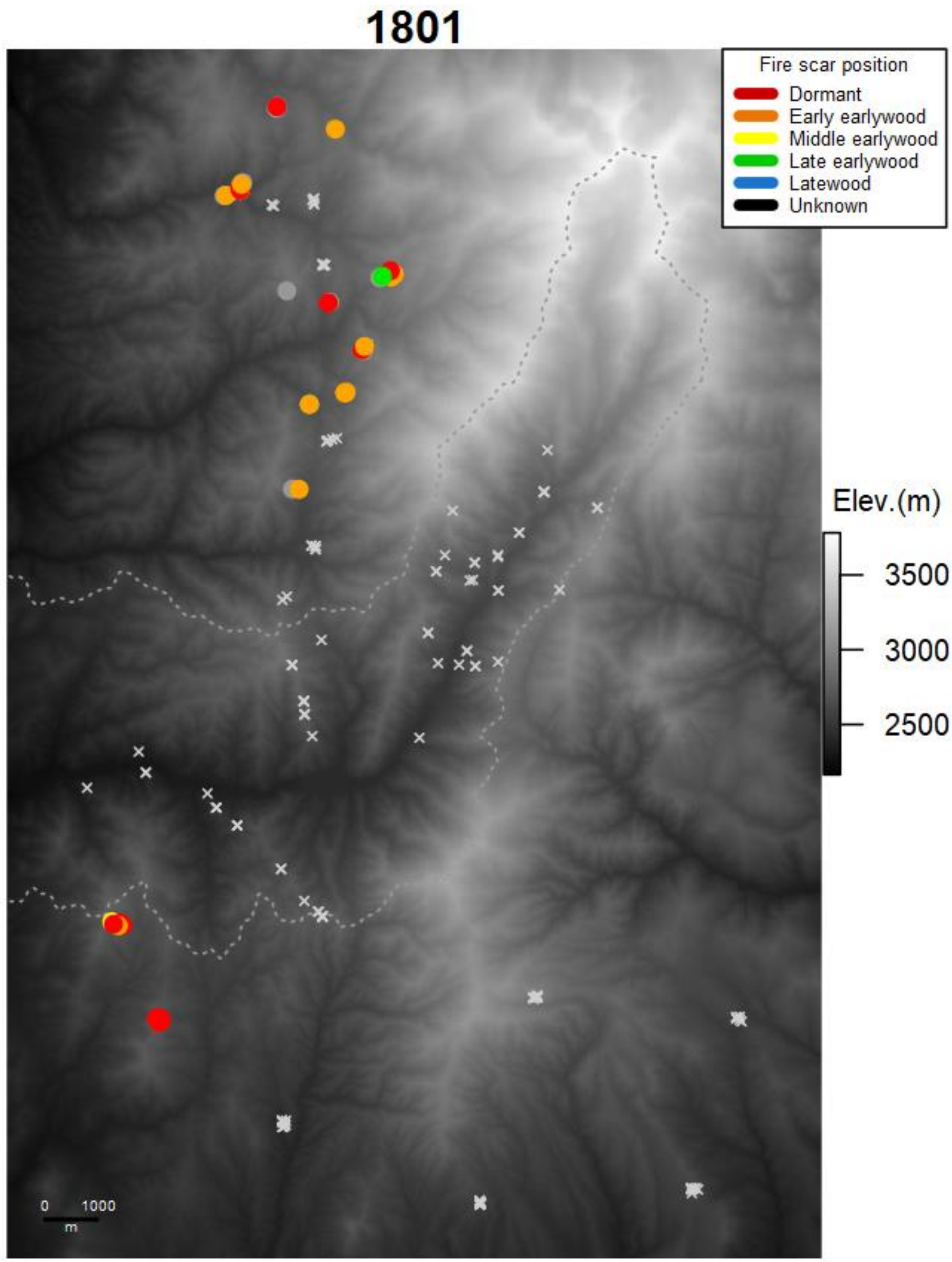

Figure S16. All trees recording 1801 fire within the study area. Colors correspond to fire scar position, or seasonality. Grey x's indicate recording trees not scarred.

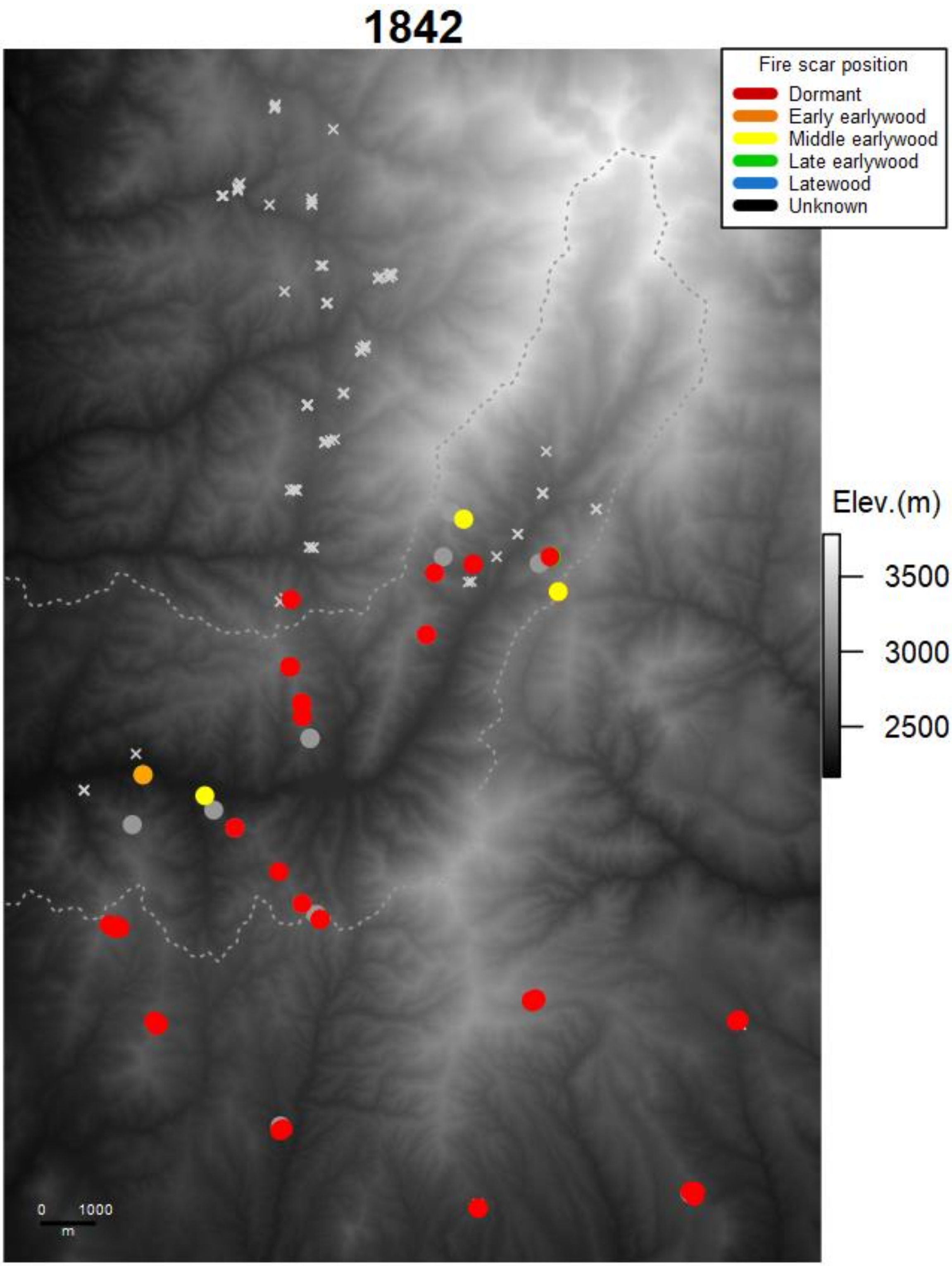

Figure S17. All trees recording 1842 fire within the study area. Colors correspond to fire scar position, or seasonality. Grey x's indicate recording trees not scarred.

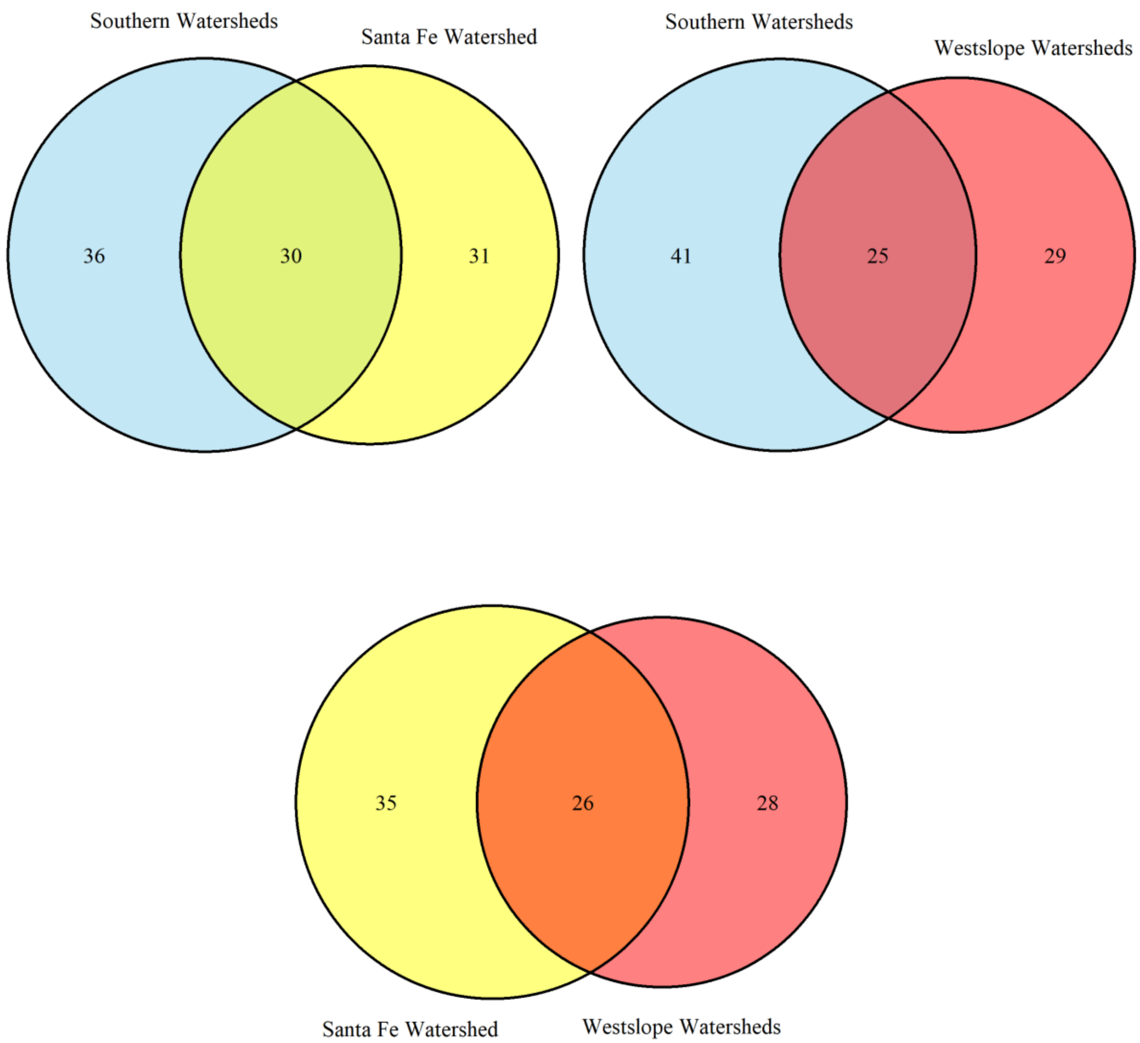

Figure S18. Venn diagrams illustrating the number of synchronous fires between paired watershed groups.