NRC Research Press

NOTE

Variation in fire scar phenology from mixed conifer trees in the Sierra Nevada

Scott L. Stephens, Liam Maier, Lilah Gonen, Jennifer D. York, Brandon M. Collins, and Danny L. Fry

Abstract: Fire scar based studies have provided robust reconstructions of past fire regimes. The season in which a fire occurs can have considerable impacts to ecosystems but inference on seasonality from fire scars is relatively uncertain. This study examined patterns in the phenology of cambium formation and wounding responses in the five common mixed conifer tree species of the Sierra Nevada. The outer bark was shaved on 35 trees and individual locations within the shaved portions were wounded systematically by applying direct heat using a handheld torch. Most of the trees had not commenced annual ring development by the first burning treatment in late May. By the second treatment, scars were identified mostly within the early or middle earlywood, although variation was high compared with other treatment periods. By late October, all scars were recorded at the ring boundary. Although intra-ring scar positions generally followed a logical temporal pattern, there was high tree to tree variation such as Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) burned on 26 June induced scars in the early, mid, and late earlywood depending on the individual tree. This high variation makes it somewhat challenging to precisely assign past fire season to published fire history studies.

Key words: cambium phenology, dendrochronology, fire regime, fire scar, fire seasonality.

Résumé : Les études basées sur les cicatrices de feu ont fourni des reconstitutions robustes des régimes des feux passés. La saison durant laquelle un feu survient peut avoir des impacts considérables sur les écosystèmes mais les déductions fondées sur la saisonnalité des cicatrices de feu sont relativement incertaines. Cette étude examine les patrons dans la phénologie de la formation du cambium et les réactions aux blessures chez cinq espèces communes de conifères mélangés de la Sierra Nevada. L'écorce externe a été enlevée sur 35 arbres et plusieurs endroits distincts à l'intérieur de la zone sans écorce ont été systématiquement blessés en y appliquant directement une source de chaleur à l'aide d'un chalumeau. Le développement du cerne annuel n'avait pas débuté chez la plupart des arbres lors du premier traitement à la fin du mois de mai. Lors du deuxième traitement, des cicatrices ont été identifiées surtout au début ou au milieu de la zone de bois initial, mais il y avait beaucoup de variation comparativement aux autres périodes de traitement. Vers la fin du mois d'octobre, toutes les cicatrices ont été observées à la limite du cerne annuel. Même si la position à l'intérieur du cerne annuel suivait généralement un patron temporel logique, il y avait une grande variation d'un arbre à l'autre de telle sorte que des cicatrices ont été observées au début, au milieu et à la fin de la zone de bois initial chez des douglas de Menzies brûlés le 26 juin. Cette grande variation constitue un défi de taille pour déterminer précisément durant quelle saison dans le passé des feux sont survenus dans le cas d'études publiées au sujet de l'historique des feux. [Traduit par la Rédaction]

Mots-clés : phénologie du cambium, dendrochronologie, régime des feux, cicatrice de feu, saisonnalité des feux.

Introduction

Using dendrochronological techniques, tree-ring fire scars are dated with annual resolution and, with multiple fire-scarred samples collected across a given area, fire regime attributes such as frequency and spatial extent can be estimated (Farris et al. 2010; Krasnow et al. 2017). The network of fire scar based studies in conifer forests across western North America has provided robust reconstructions of past fire regimes and insights on multi-scale patterns of fire synchronicity and fire–climate relationships (Kitzberger et al. 2007; Falk et al. 2011).

The intra-annual position of the scar should allow for a more precise assignment of the seasonal timing of fire occurrence. Scar position is usually assigned to being in the earlywood, latewood, or the dormant period between annual rings. Extending the observed intra-annual position of the scar to the assignment of calendrical season requires greater understanding of the timing of wood production and differentiation. The seasonal timing of cambial growth varies by several factors including the differential response of species to the environmental parameters that control their growth (Fritts 1976; Schmidt and Lotan 1980).

The season in which a fire occurs can have considerable impact on ecosystem structure and function, independent of fire intensity. Knapp et al. (2009) conducted a comprehensive review which identified ecologically relevant differences in fire effects between early and late season prescribed fires. These differences included not only a range of impacts to flora and fauna, but also a range in fuel consumption. Given contemporary record keeping practices, calendar dates for prescribed fires are mostly known; however, the same is not necessarily true for historical fires identified within tree rings. This study seeks to identify patterns in the

Received 7 August 2017. Accepted 26 October 2017.

S.L. Stephens, L. Maier, L. Gonen, and D.L. Fry. Department of Environmental Science, Policy, and Management, 130 Mulford Hall, University of California, Berkeley, CA 94720-3114, USA.
J.D. York. Center for Forestry, University of California, Berkeley, Georgetown, CA 95634, USA.
B.M. Collins. Center for Fire Research and Outreach, University of California, Berkeley, CA 94720-3114, USA.
Corresponding author: Scott L. Stephens (email: sstephens@berkeley.edu).

 Published at www.nrcresearchpress.com/cjfr on 8 November 2017.

Fig. 1. Tree samples at different stages of the study: (A) treatment application via handheld blowtorch on the bole of a sugar pine where the bark was shaved; (B) bole of a white fir showing the five treatment applications, with a nail marking each location; (C) partial cross section of a white fir with an early earlywood scar; (D) ponderosa pine with a late earlywood scar. [Colour online.]

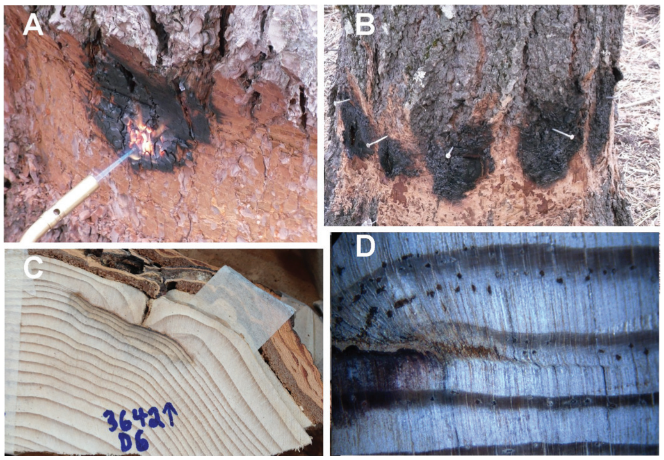


Table 1. Mean diameter at breast height (DBH, 1.3 m) and age of trees used in the fire scar study.

Species	DBH (cm)	Tree age (years)
Douglas-fir	70.4 (5.2)	93.3 (2.6)
Incense-cedar	48.7 (2.6)	101.3 (7.1)
Ponderosa pine	73.3 (4.1)	93.6 (3.9)
Sugar pine	90.4 (8.7)	89.6 (3.1)
White fir	64.3 (3.9)	90.0 (1.6)

Note: Data format is mean (one standard error). The age of trees was measured at stump height (*n* = 7 for each species).

Table 2. Summary of intra-ring scar position and calendar date for fire injuries applied to mixed conifer trees at BFRS in 2010.

	Amount of sample scarred (%)				
Date	EE	ME	LE	L	RB
20 May	6	6	—	—	88
26 June	30	57	9	4	—
26 July	—	14	76	10	—
7 September	—	—	9	91	—
30 September	—	—	5	45	50
29 October	—	—	—	—	100

Note: Intra-ring locations: early earlywood (EE), middle earlywood (ME), late earlywood (LE), latewood (L), and ring boundary (RB).

phenology of cambium formation and wounding response in the five common mixed conifer species of the Sierra Nevada. The specific objectives were to (*i*) identify the intra-ring location of thermally induced scars applied to tree boles and (*ii*) assess individual species responses to different timing of thermal injuries.

Methods

Study area

The study was conducted at the University of California Blodgett Forest Research Station (BFRS; 38°54′N, 120°39′W), an experimental research forest on the western slopes of the northern Sierra Nevada, approximately 21 km east of Georgetown, California. BFRS (1174 ha) is a mixed conifer forest with an overstory composed of sugar pine (*Pinus lambertiana* Douglas), ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson), white fir (*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.), incense-cedar (*Calocedrus decurrens* (Torr.) Florin), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and California black oak (*Quercus kelloggii* Newberry). Elevation ranges from 1100 to 1410 m and total annual precipitation averages 1600 mm, falling mainly between September and May. The mean minimum daily temperature in January is 0.6 °C and the mean maximum daily temperature in July is 28.3 °C. Wildfires are suppressed at BFRS; prior to the policy of fire suppression that began early in the 20th century, the median composite fire interval at the 9–15 ha spatial scale was 4.7 years with a range of 4–28 years (Stephens and Collins 2004).

Treatment

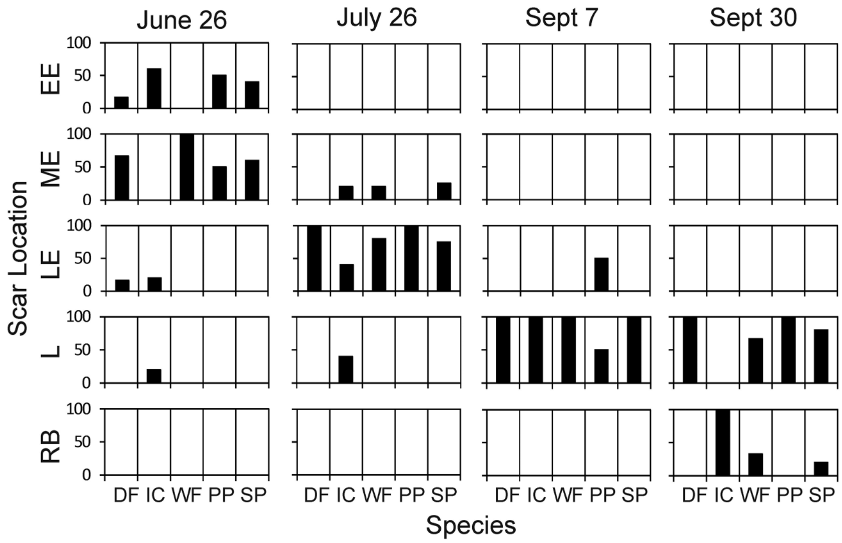
Three healthy overstory trees from of each of the five conifer species were selected from two separate management units (plots) for this study. In one plot, one tree from each species was selected to serve as a control (*n* = 35 trees total). Age at base height and diameter at breast height (DBH, 1.3 m) were collected for each tree. Thirty trees received six identical burn treatments administered over a 6-month period that extended from May to October in 2010. Every control and treatment tree had all but a thin layer of bark removed (approximately 2.5 cm of bark remained after shaving) from its main stem using a hatchet, approximately 30 cm × 90 cm along the circumference of the bole and approximately 25 cm above the forest floor (Fig. 1). This was done in an effort to reduce intra- and inter-tree variations in bark thickness that may have induced differential responses to identical treatments. We realize that the thermal bark properties for each species vary, which could influence the degree of cambial injury from heating. That said, Martin (1963) reported little variation in thermal diffusivity over wide ranges of bark density, moisture content, and temperature. The six within-tree bark burn treatments were positioned approximately 15–30 cm apart and horizontally arranged along one side of each tree's stem (Fig. 1).

Bark-stripped sites were wounded systematically, at roughly 1-month intervals, by applying direct heat to tree bark surfaces using a handheld propane torch for approximately 15 min; 15 min was estimated to be sufficient based on the study by Peterson and Ryan (1986, eq. 10) that derived the relationship between bark thickness and the amount of time needed to kill the cambium given a fire with a constant temperature. The upper edge of the area of shaved bark was marked with an aluminum nail driven into the stem, which remained in place through the course of the study (Fig. 1). Control trees were shaved but received no heat treatment.

After all treatments had been applied, trees continued to grow for 3 years before being hand-felled in 2014. Half-rounds, containing the six temporally (and spatially) separated treatments, were then taken from each tree. Sample extractions were completed using, first, a chainsaw to cut out the centers out of the half-rounds and segment the remaining scar-containing round into smaller pieces, most of which contained 1–2 treatment loci. Multiple horizontal cross-sections were then taken from each scar by passing the samples through a bandsaw. To prepare scar cross sections for analysis, samples were sanded until the cellular structure was visible (Fig. 1). The within annual ring position of each scar was evaluated by three independent viewers using a dissecting microscope and recorded as EE (early earlywood), ME (middle earlywood), LE (late earlywood), L (latewood), and RB (ring boundary, identified as pre- or post-growth of the annual ring). The multiple observers were trained together to increase consistency and some scars were sent to a senior dendrochronologist (Peter Brown) to verify recorded scar positions.

To describe the climate preceding the treatment application, we summarized temperature and precipitation collected from the Bald Mountain Remote Automated Weather Station (38°54′N, 120°42′W; 1427 m elevation), 3–5 km from the BFRS study areas. We used analysis of variance (ANOVA) to determine if significant

Fig. 2. Percentage of observed trees (within species and date) with an intra-annual position or ring boundary fire scar in treated trees at Blodgett Forest Research Station, Georgetown, California. Positions included early earlywood (EE), middle earlywood (ME), late earlywood (LE), latewood (L), or ring boundary (RB). Tree species included Douglas-fir (DF), incense-cedar (IC), ponderosa pine (PP), sugar pine (SP), and white fir (WF).



differences (p < 0.05) existed in tree age and tree size between plots and species. If a significant difference was detected, pairwise multiple comparisons using the Tukey–Kramer HSD test identified which species were statistically different.

Results

For the 6 months preceding the treatment, the monthly mean of the daily maximum temperature approximated the long-term mean (data not shown). Only in December was the mean temperature less than 90% of the long-term mean. Total precipitation from October 2009 through March 2010 was 94.7 cm, compared with the long-term mean of 99 cm. Monthly precipitation totals in the 2009–2010 wet season were higher in four of the six months and 11% higher in February and March compared with the long-term means.

The mixed conifer tree species that was most difficult to remove the bark from was Douglas-fir. It took approximately twice as long to shave this species with a hatchet compared with the other mixed conifer species. Ponderosa pines had relatively thick bark under their plates, but bark thickness beneath their bark furrows was much thinner. When Douglas-fir was treated with the hand-held propane torch, its bark expanded outward by several centimetres during combustion; no other species did this when the torch was applied. Small segments of burning sugar pine bark (approximately 1–2 cm in diameter) were ejected up to 50 cm away from the tree when burned by the torch.

The mean DBH for all trees was 69.4 cm (standard error (SE) = 3.2 cm) and individual tree sizes ranged from 40.2 cm to 78 cm (Table 1). There was no difference in tree sizes between plots (t test = −0.824; p = 0.414). Across species, there were significant differences in tree sizes (F value = 8.232; p value = 0.000). Mean DBH for incense-cedar was significantly lower than for Douglas-fir (p = 0.047), ponderosa pine (p = 0.019), and sugar pine (p = 0.000). White fir had a significantly smaller DBH than sugar pine (p = 0.012). The mean age of the trees was 93.6 years (SE = 1.9 years), and individual ages ranged from 78 to 128 years. Most tree ages ranged from 80 to 90 years except for two incense-cedars (125 and 128 years old), which persisted through timber harvesting that took place in the early 20th century (Stephens and Collins 2004). There was no difference in tree age between plots (t test = 1.290; p = 0.118) or species (F value = 1.30; p = 0.293).

There was no observable impact of bark shaving on tree-ring development in the control trees. The proportion of trees that formed visible fire scars across the six treatment applications was relatively low despite having bark shaved down to approximately 2.5 cm thick (Supplementary data[1]). Douglas-fir and white fir had the lowest incidence of scar formation. Most of the trees (88%) had not commenced annual ring development by the first treatment on 20 May (Table 2). By the second treatment, most of the scars were identified within the EE (30%) or ME (56%) portion of the annual ring (Fig. 2). Incense-cedar had the largest range in scar location (EE to L), whereas all of the white firs were in the ME. In the third and fourth treatment applications, the observed scar location was focused in the LE (76%) and L (91%), respectively. Half the recording trees stopped ring development by 30 September, including all of the incense-cedars. With the exception of two ponderosa pine trees and one sugar pine, all scars resulting from 7 September or later were in the L or RB. By the last burning treatment date (29 October), all of the scars were recorded at the RB.

Although intra-ring scar positions generally followed a logical temporal pattern (Table 2), there was high tree to tree variation in the stage of annual xylem increment formation (Supplementary Table S1[1]). As an example of this variation, Douglas-fir burned on 26 June resulted in visible scar formation in the EE, ME, and LE, whereas incense-cedar burned on 26 July resulted in visible scar formation in ME and LE and in latewood depending on the individual tree (Fig. 2).

Discussion

Despite our efforts to meticulously shave bark from the treatment area, few trees possessed a complete series of burn scars. Nonscarred samples were common and often displayed a great deal of bark scorch but no sign of vascular damage or healed wounds (Fig. 1). Tree bark provides critical protection from radiant and convective heat, and our study demonstrated that even bark thicknesses of 2.5 cm could retard injury.

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2017-0297.

California mixed conifer forest species exhibit a variety of bark structures. Incense-cedar has a dense fibrous wooden sheath, and ponderosa pine has thick bark that falls away from their stems in jigsaw-puzzle shaped pieces. White fir has a corky bark that tends to be thinner than that of Douglas-fir but similar in density (van Mantgem and Schwartz 2003); both of these species had the lowest proportion of scar formation likely due to their higher heat tolerances, at least for Douglas-fir (Peterson and Ryan 1986; van Mantgem and Schwartz 2003). Intra-species variation in bark properties can often be attributed to differences in age, plot history, and (or) genetic potentials (cited in Ryan and Reinhardt (1988)).

Heyerdahl et al. (2007) found variation in fire scar position among species and topographic position in ponderosa pine and mixed conifer forests in British Columbia, Canada. The majority of scars on Douglas-fir trees were located on the ring boundary regardless of aspect. Ponderosa pine fire scars tended to occur within the annual ring (i.e., growing season) on north aspects and within the annual ring and at the ring boundary on south aspects.

The percentage of Douglas-fir trees that received fire scars from the hand held torch was the lowest of all species (Supplementary Table S1[1]). Our observation of how Douglas-fir bark expanded during burning could have contributed to this by providing additional cambium insulation to retard injury and others have found high stem heat tolerance of this species (Peterson and Ryan 1986). Other mixed conifer tree species also had relatively low amounts of scarring in this study (Supplementary data[1]), possibly shaving the bark even more before the torch was applied could have enhance scarring. Even with our study limitations, the sequence of fire scar locations from BFRS revealed a logical temporal pattern that began at the dormant position, followed by different percentages of earlywood and latewood scars and ending with the dormant position at the end of the season (Table 2). This pattern generally supports the continued use of intra-ring scar positions to capture distinct periods within a given growing season. However, high tree to tree variation within individual species in annual xylem increment formation, especially early in the growing season, makes it somewhat challenging to precisely assign past fire season to published fire history studies.

Acknowledgements

We thank Rob York, Jana Nisbet, Zev Balsen, and BFRS staff for logistical support in applying the treatments and transport of samples; we also thank the loggers that harvested the trees while preserving our fire scars. We appreciate Peter Brown's assistance in interpreting our fire-scarred samples.

References

Falk, D.A., Heyerdahl, E.K., Brown, P.M., Farris, C., Fulé, P.Z., McKenzie, D., Swetnam, T.W., Taylor, A.H., and Van Horne, M.L. 2011. Multi-scale controls of historical forest-fire regimes: new insights from fire-scar networks. Front. Ecol. Environ. **9**: 446–454. doi:10.1890/100052.

Farris, C.A., Baisan, C.H., Falk, D.A., Yool, S.R., and Swetnam, T.W. 2010. Spatial and temporal corroboration of a fire-scar-based fire history in a frequently burned ponderosa pine forest. Ecol. Appl. **20**: 1598–1614. doi:10.1890/09-1535.1. PMID:20945762.

Fritts, H.C. 1976. Tree rings and climate. Academic Press, New York.

Heyerdahl, E.K., Lertzman, K., and Karpuk, S. 2007. Local-scale controls of a low-severity fire regime (1750–1950), southern British Columbia, Canada. Ecoscience, **14**: 40–47. doi:10.2980/1195-6860(2007)14[40:LCOALF]2.0.CO;2.

Kitzberger, T., Brown, P.M., Heyerdahl, E.K., Swetnam, T.W., and Veblen, T.T. 2007. Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proc. Natl. Acad. Sci. U.S.A. **104**: 543–548. doi:10.1073/pnas.0606078104. PMID:17197425.

Knapp, E.E., Estes, B.L., and Skinner, C.N. 2009. Ecological effects of prescribed fire season: a literature review and synthesis for managers. USDA For. Serv. Gen. Tech. Rep. PSW-GTR-224. USDA Forest Service, Pacific Southwest Research Station, Albany, Calif.

Krasnow, K.D., Fry, D.L., and Stephens, S.L. 2017. Spatial, temporal and latitudinal components of historical fire regimes in mixed conifer forests, California. J. Biogeogr. **44**: 1239–1253. doi:10.1111/jbi.12914.

Martin, R.E. 1963. Thermal properties of bark. For. Prod. J. **8**: 419–426.

Peterson, D.L., and Ryan, K.C. 1986. Modeling postfire conifer mortality for long-range planning. Environ. Manage. **10**: 797–808. doi:10.1007/BF01867732.

Ryan, K.C., and Reinhardt, E.D. 1988. Predicting postfire mortality of seven western conifers. Can. J. For. Res. **18**: 1291–1297. doi:10.1139/x88-199.

Schmidt, W.C., and Lotan, J.E. 1980. Phenology of common forest flora of the northern Rockies, 1928 to 1937. USDA For. Serv. Res. Pap. INT-RP-259. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah. doi:10.5962/bhl.title.68874.

Stephens, S.L., and 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.

van Mantgem, P., and Schwartz, M. 2003. Bark heat resistance of small trees in Californian mixed conifer forests: testing some model assumptions. For. Ecol. Manage. **178**: 341–352. doi:10.1016/S0378-1127(02)00554-6.