



burnr: Fire history analysis and graphics in R

Steven B. Malevich^{a,b,*}, Christopher H. Guiterman^b, Ellis Q. Margolis^{b,c}

^a Department of Geosciences, University of Arizona, 1040 E. 4th Street, Tucson, AZ 85721, USA

^b Laboratory of Tree-Ring Research, University of Arizona, 1215 E. Lowell Street, Tucson, AZ 85721, USA

^c US Geological Survey, Fort Collins Science Center, New Mexico Landscapes Field Station, Santa Fe, NM 87508, USA

ARTICLE INFO

Keywords:

Fire ecology
Statistical software
Event
Visualization
Tree ring
SEA

ABSTRACT

We developed a new software package, `burnr`, for fire history analysis and plotting in the R statistical programming environment. It was developed for tree-ring fire-scar analysis, but is broadly applicable to other event analyses (e.g., avalanches, frost rings, or culturally modified trees). Our new package can read, write, and manipulate standard tree-ring fire history FHX files, produce fire—demography charts, calculate fire frequency and seasonality statistics, and run superposed epoch analysis (SEA). A key benefit of `burnr` is that it enables automation of analyses and plotting, especially for large data sets. The package also facilitates creative plotting, mapping, and analyses when combined with the thousands of packages available in R. In this paper, we describe the basic functionality of `burnr` and introduce users to fire history analyses in R.

1. Introduction

Faced with complicated environmental challenges such as climate change, dendrochronologists are tackling increasingly sophisticated research questions. The dendroecological fire history community has grown rapidly in recent decades, driven by the need to put increases in fire size and severity in a long-term context. Novel insights can often be gained with analyses of large tree-ring data networks (e.g., Cook, 2004) and the proliferation of publicly available data facilitates such efforts. Across the western United States, for example, researchers have built an extensive network of over 1,000 tree-ring fire history sites (Falk et al., 2011), hosted on the International Multi-Proxy Paleofire Database (IMPD). However, performing network-scale analyses is challenging without the ability to read existing data formats (e.g., FHX files) into statistical computer software, such as the popular R language environment (R Development Core Team, 2017). Performing fire-history research in R would facilitate coarse-scale, complex analyses by allowing for automated workflows, easy sharing of data and methods with collaborators or in publications, and the ability to link and analyze metadata associated with fire history data. To facilitate future growth, efficiency, and creativity in dendroecological fire history analyses, we developed `burnr`.

`burnr` is a new Open Source package for R, written for users and projects with advanced needs while being accessible for basic use. Specifically, `burnr` was designed to provide a variety of functions that are simple and flexible, and to bring fire history data to the rich analysis and plotting tools in the R environment. Dendrochronologists are

increasingly using R, in part due to the number of powerful packages that have been developed (e.g., Bunn, 2008; Altman et al., 2014; Zang and Biondi, 2015). With flexible base functionality and exposure to R, `burnr` can act as a foundation from which users can develop their own advanced tools for fire history, or any event-based research – such as frost rings, culturally modified trees, insect outbreaks, flood scarring, or avalanche reconstructions.

The `burnr` package grew out of methods established by fire history studies that capitalized on the ability of tree rings to record events with annual to sub-annual precision over long time periods (e.g., Dieterich and Swetnam, 1984). Existing tree-ring fire history analysis programs, including FHX2 (Grissino-Mayer, 2001) and FHAES (Brewer et al., 2016), are widely used. We based the `burnr` functions on these software systems, but by facilitating analyses in R, we hope that users will develop new research and analytical approaches.

In this paper we describe how to install `burnr`, and we demonstrate its basic use for manipulating and summarizing FHX files, fire—demography plotting, fire interval analysis, and superposed epoch analysis (SEA). In many of these sections we showcase some of the exciting ways that users can benefit by analyzing fire-history data in R. Each section of this paper explains code and analysis, assuming that the user has installed R and loaded the `burnr` package (see Section 2). Text in `fixed-width font` indicates code that is typed or output to an interactive R shell. Lines prefixed with “>” denote code entered by the user. Finally, note that source code to recreate this paper's figures is available online (https://github.com/brews/burnr_2018_manuscript_figures). Output presented in this paper is from `burnr` v0.2.2.

* Corresponding author at: Department of Geosciences, University of Arizona, 1040 E. 4th Street, Tucson, AZ 85721, USA.
E-mail address: malevich@email.arizona.edu (S.B. Malevich).

2. Availability and installation of burnr

The `burnr` package is freely available as Open Source software through the Comprehensive R Archive Network (CRAN). R can be downloaded and installed directly from the CRAN homepage (<https://cran.r-project.org/>) or through an alternative R distribution. Users can install `burnr` from within an R session like any other R package:

```
> install.packages("burnr")
```

The library is then loaded with:

```
> library(burnr)
```

With the package loaded, `burnr` functionality becomes available to the user. Development releases and source code for the project are available online (<https://github.com/ltrr-arizona-edu/burnr>). In addition to this paper, support documentation is distributed with the package, including an introduction (<https://cran.r-project.org/web/packages/burnr/vignettes/introduction.html>).

3. Reading, manipulating, and summarizing FHX files in R

With `burnr`, fire-history data can be read into R from FHX files. From there, R has the capability to edit, sort, merge, and write data back to FHX files. For example:

```
> library(burnr)
> url <- paste0("https://ww1.ncdc.noaa.gov/",
  "pub/data/paleo/firehistory/",
  "firescar/northamerica/")
> pmr <- read_fhx(paste0(url, "uspmr001.fhx"))
> pme <- read_fhx(paste0(url, "uspme001.fhx"))
> pmw <- read_fhx(paste0(url, "uspmw001.fhx"))
> pm_all <- pmr+pme+pmw
> write_fhx(pm_all, "pajarito_mountain.fhx")
```

Here we are reading in three FHX files directly from URLs linking to the online IMPD file server. These data sets are assigned to variables named `pmr`, `pme`, and `pmw`. We then concatenate—or combine—the data with the `+` operator, producing a single `fhx` object. Concatenation also checks for duplicate series names before combining the data. The `pm_all` object is then written into a new FHX file in the current working directory.

Within R, fire history data is stored as a special `fhx` object, which is similar to a simple R dataframe with three columns: `year`, `series`, and `rec_type`. The first column, `year` is the datum to the year in which it is recorded; `series` is the tree or series identifier; `rec_type` is the tree-derived information stored in FHX files. We found this structure to be relatively efficient for data storage and analysis in R. The `fhx` object structure is especially effective when combined with tools utilizing a “split-apply-combine” strategy (e.g., Wickham, 2011).

Once loaded in R, several functions are available to analyze FHX data. A quick summary of the individual series in the combined FHX files, `pm_all`, can be produced with:

```
> series_stats(pm_all)
```

Table 1

Example series statistics, from `series_stats()`, for the first five trees in `pm_all`. The table gives the first, last, and total number of years in the series (“No. yrs”). “Inner” and “Outer” denote how each series starts and ends. Number of scars, injuries (“Inj.”), and recording years (“Rec.”) are given. Additionally, we give the mean fire interval (“Interval”) for each series.

Series	First	Last	No. yrs	Inner	Outer	Scars	Inj.	Rec.	Interval
PMR01	1664	1915	252	pith	outer	19	0	231	10.6
PMR02	1663	1875	213	pith	outer	15	0	190	13.2
PMR03	1676	1979	304	inner	bark	7	9	200	15.8
PMR05	1747	1895	149	inner	outer	2	0	95	40.0
PMR06	1653	1860	208	pith	outer	5	0	176	18.0

The corresponding output from `series_stats()` is shown in Table 1. This gives a tree-level summary of the input data.

4. Plotting fire history and demography

To showcase plotting we included example fire-history data sets within the `burnr` package. We begin with `lgr2`, a fire history and demography data set from Los Griegos Peak, New Mexico that contains 11 fire-scarred or fire-injured trees and 15 non-fire-scarred trees of four species (Margolis and Malevich, 2016). Below, we load the example data set to the `lgr2` variable as an `fhx` object, as though we had read the data from an FHX file:

```
> data(lgr2)
```

We can make a fire—demography plot of `lgr2` with the basic plot function:

```
> plot(lgr2)
```

The default `plot()` graphic is shown in Fig. 1. The output from the default plot function is highly customizable, but visually simple. The function includes many options, such as a customizable composite, or “rug”, of fire events summarizing all fire events recorded by all series, the ability to add or remove series labels, customizable year-axis range, inclusion of tree injuries, and addition of a legend.

Colored fire—demography plots are one of the more novel features of `burnr`. In the example below, we add color to differentiate tree species. Tree species are drawn from metadata that can be loaded into R from a comma or tab-delimited file with `read.csv()` or `read.table()`. Metadata recording the species of all trees in the Los Griegos data set is included in `burnr`, and can be loaded with:

```
> data(lgr2_meta)
```

This metadata can be used with the `plot` function because series names in the fire history `lgr2` object match a column (`TreeID`) in the metadata. Type `head(lgr2_meta)` to see the first few metadata entries and get an idea of how the data set is organized. A custom fire chart that incorporates species metadata is now created with:

```
> plot(lgr2,
  color_group=lgr2_meta$SpeciesID,
  color_id=lgr2_meta$TreeID,
  ylabels=FALSE, composite_rug=TRUE,
  injury_event=TRUE)
```

The new arguments to `plot()` produce a fire—demography chart with colors corresponding to tree species and a fire-composite rug along the bottom of the graphic (Fig. 2a). The species information (`color_group`) is joined with `lgr2` through the series names (`color_id`). We also remove the y-axis labels (`ylabels=FALSE`) to save plotting space, and add a composite rug that includes injuries with the arguments `composite_rug=TRUE` and `injury_event=TRUE`.

Coloring by species in fire—demography charts can be especially helpful to identify successional trends or species transitions related to fire or climate variability. For example, in Fig. 2a, *Pinus ponderosa* (red) was present in the stand but becomes locally absent following a high-severity fire, followed by over a century of fire exclusion that promoted dominance by more mesic species: *Populus tremuloides* and *Pseudotsuga menziesii* (Margolis and Malevich, 2016). Color can be associated with other variables such as tree condition (live or dead) or age classes. It can also represent continuous variables like tree diameter at breast height or elevation.

Advanced edits of fire—demography charts requires a deeper understanding of how `burnr` creates graphics. Internally, `burnr` takes advantage of R’s advanced grid plotting framework and the `ggplot2` package (Wickham, 2016). This helps `burnr` to create more sophisticated graphics (e.g., with coloring and faceting) that are also modular and customizable. To introduce this, we modify the `lgr2` fire—demography chart by adding a legend—with custom placement—and a shaded polygon to highlight the species transition we described previously:

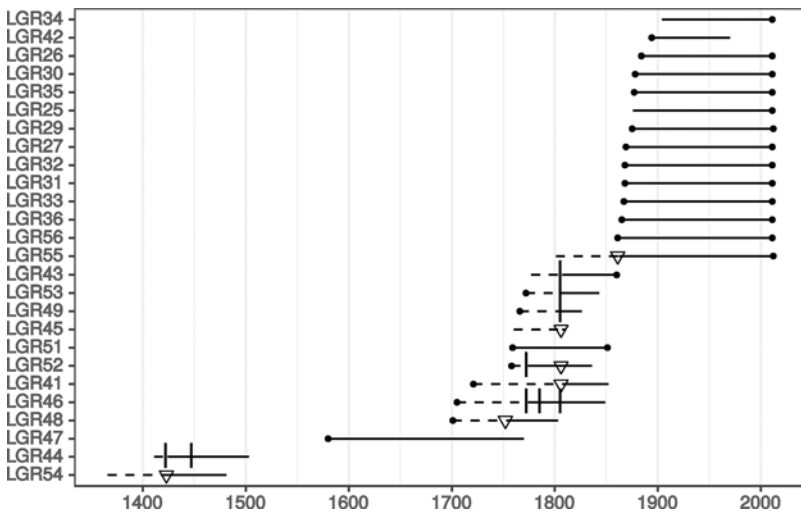


Fig. 1. The default `burnr` fire—demography chart. Dates from pith or bark are shown with a filled circle, segments for “recording” periods are solid, and dashed segments indicate “non-recording” periods. Fire scars are indicated with a single vertical tick. Fire injuries are indicated with an empty triangle. This design emphasizes readability—a characteristic which becomes more important when plotting a larger number of records in a single graphic.

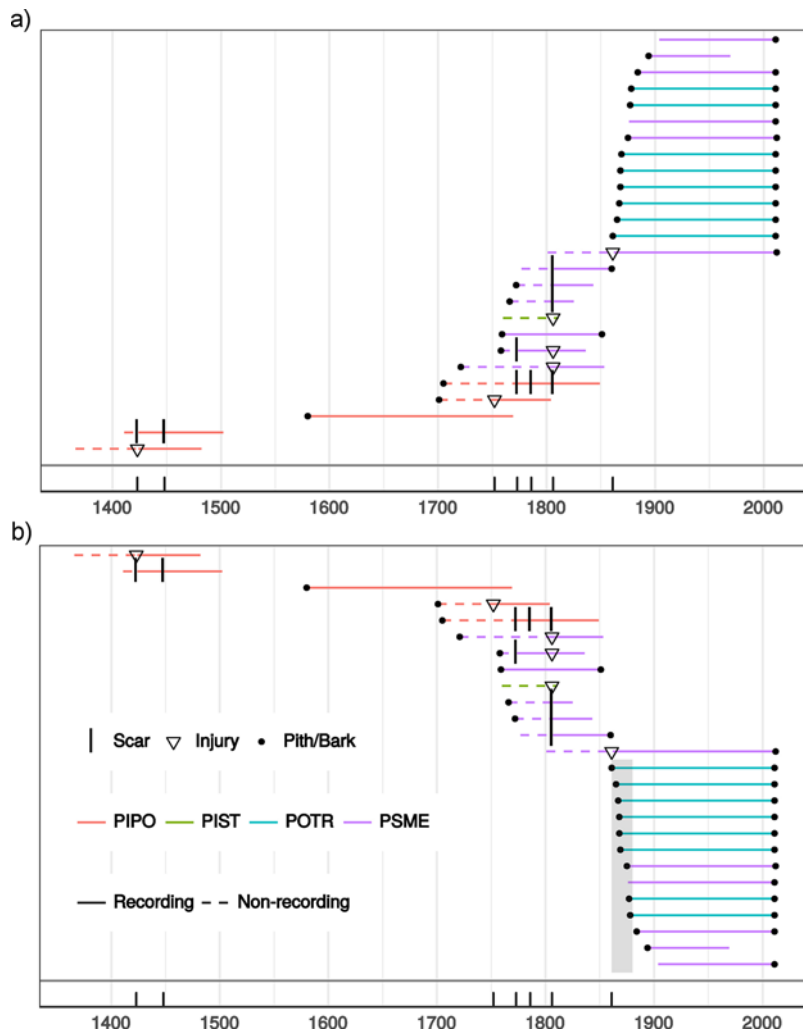


Fig. 2. Custom fire—demography chart with species coloring and simple composite fire record (a). Adding legend and annotation to highlight a post-fire cohort (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

```
> library(ggplot2)
> lgr2_sorted<- sort(lgr2, decreasing=TRUE)
> p<- plot_demograph(lgr2_sorted,
  color_group=lgr2_meta$SpeciesID,
  color_id=lgr2_meta$TreeID,
  composite_rug=TRUE,
```

```
  ylabels=FALSE,
  plot_legend=TRUE)
```

This code sets up our graphic, and assigns it to `p`, but does not yet output the image. The first line imports the `ggplot2` package—this is needed to modify our graphic. The next line sorts the data set by the first ring so the oldest tree series will appear along the top of the

graphic. The following lines of code create a variant of our species-colored fire—demography plot from Fig. 2a. Note that we are using `plot_demograph()` instead of the generic `plot()`. `plot()` passes information and arguments—when used with `fhx` objects—to `plot_demograph()`. We need to explicitly call `plot_demograph()` here because this function returns a `ggplot` object that we can modify to our liking. We can further customize `p` and then `print(p)` to output the graphic:

```
> p <- (p + annotate("rect", alpha=0.2,
  xmin=1861, xmax=1880,
  ymin=2.5, ymax=15.5)
+ theme(legend.position=c(0.25, 0.4),
  legend.direction="horizontal"))
> print(p)
```

Here, we append two simple things to this plot with the `+` operator. First, with `annotate()`, we add a large transparent rectangle to highlight a cohort of trees regenerating after a severe fire in 1861. Next, we change the style of the plot, with `theme()`, by moving the legend within the plot frame, reducing white space in the graphic. The final graphic produced with these changes is shown in Fig. 2b. These modifications can be built upon for more radical changes to `burnr` graphics.

Automated multi-faceted fire—demography plots are another novel feature of `burnr`. Faceting separates the graphic into multiple panels, simultaneously plotting many fire history sites in one graphic, for instance. This helps visual comparisons of fire frequency or age structure across multiple sites. These figures are created with an approach nearly identical to that used for colored plots, as described previously: the `plot()` or `plot_demograph()` arguments `color_group` and `color_id` are simply replaced by the `facet_group` and `facet_id` arguments. Both faceting and coloring can be used simultaneously in the same graphic. An advanced example of this, with faceting based on spatial locations is shown in Fig. 3. This example uses different prescribed fire burn units in Bandelier National Monument, New Mexico (Fig. 3a) to group fire-scarred trees and create fire charts for each burn unit (Fig. 3b). Code to recreate this figure is available online (https://github.com/brews/burnr_2018_manuscript_figures).

Faceting by spatial location also highlights the benefits of combining spatial and cartographic capabilities of `R` with fire-history data in `burnr`. Other useful examples of mapping data from `burnr` include: annual fire year maps can be colored by tree-ring data type (e.g., fire scar, death date, regeneration date); annual fire year maps can be color-coded by fire scar position (seasonality); polygons of recent fire perimeters can be incorporated into tree-ring-derived fire year maps to make comparisons between historical and modern spatial extent of fires; Digital Elevation Models (DEM) can be integrated and points sampled at fire-scar locations to test for relationships among topographic variables and median fire intervals.

5. Composites and fire interval analysis

The `burnr` package includes tools to analyze composite summaries of fire events and fire intervals. To demonstrate this, we use a fire-history data set from Peggy Mesa (Guiterman et al., 2015). The data set (`pgm`) contains 41 tree series dating from 1555 to 2013, of which nine trees are fire-scarred. We create a composite of fire events recorded by 25% of scarred trees with:

```
> data(pgm)
> pgm_comp <- composite(pgm, comp_name="PGM",
  filter_prop=0.25)
```

This code loads the example `pgm` data set and creates a composite, assigning it to the `pgm_comp` variable. The `comp_name` argument lets us give the composite a label in the resulting `fhx` object. By default, this composite is based on fire scars and not fire injuries. We can include injuries in the composite with the `event_injuries=TRUE` argument to `composite()`. Other arguments can filter the composite series by

the minimum number of trees recording, percent of trees scarred, and number of trees scarred. Because `composite()` returns an `fhx` object, we can plot it with `plot(pgm_comp)`, or manipulate it like any other `fhx` object.

With a composite defined, we can analyze the fire intervals with:

```
> pgm_interv <- intervals(pgm_comp)
> print(pgm_interv)
```

```
Interval Analysis
=====
Composite name: PGM
Events range: 1636 to 1871
Total intervals: 20
Mean interval: 11.8
Median interval: 10
Weibull median: 10.6
Standard deviation: 7.7
Minimum interval: 2
Maximum interval: 30
Theoretical distribution
-----
Fit distribution: weibull
shape scale
1.6565206 13.2125358
(0.2797517) (1.8871133)
Percentiles
-----
lower (12.5%): 19.3 |
weibull median (50.0%): 10.6 |
upper (87.5%): 3.9
One-sample Kolmogorov-Smirnov test
-----
D^- = 0.12776, p = 0.89978
Null hypothesis: The intervals
were sampled from the theoretical
distribution.
Alt. hypothesis: The intervals
were not sampled from the theoretical
distribution.
```

The `intervals()` function returns an `intervals` object. This object prints an analysis similar to `FHX2` and `FHAES` interval analyses. It includes basic summary statistics, the parameters for a theoretical distribution fit to the event intervals, select percentiles of the fire intervals distribution, and the result of a Kolmogorov–Smirnov test to assess the theoretical distribution fit. By default, the intervals are fit to a Weibull distribution (Grissino-Mayer, 1999), though other options are available. This is a good place to use base `R` graphics to plot the interval distribution:

```
> hist(pgm_interv$intervals)
> boxplot(pgm_interv$intervals)
```

These functions produce a histogram and boxplot of the empirical fire intervals distribution (Fig. 4). In this case, the figure shows intervals with positive skew. Simply plotting the intervals object (e.g., `plot(pgm_interv)`) is also an option.

6. Fire seasonality

Fire seasonality is a key component of a fire regime (Agee, 1993). Seasonality of fires can have important ecological effects (e.g., Knapp et al., 2009) and is important for managers tasked with restoring fire regimes. Reconstructions of fire seasonality are based on the intra-annual position of fire scars within a tree ring (Baisan and Swetnam, 1990). The `burnr` package facilitates summaries of fire scar position, as well as complex analyses, such as testing for climate drivers of variability in fire seasonality (e.g., Margolis et al., 2017). Using the Peggy Mesa (`pgm`) data, we can get a quick summary of fire-scar positions with:

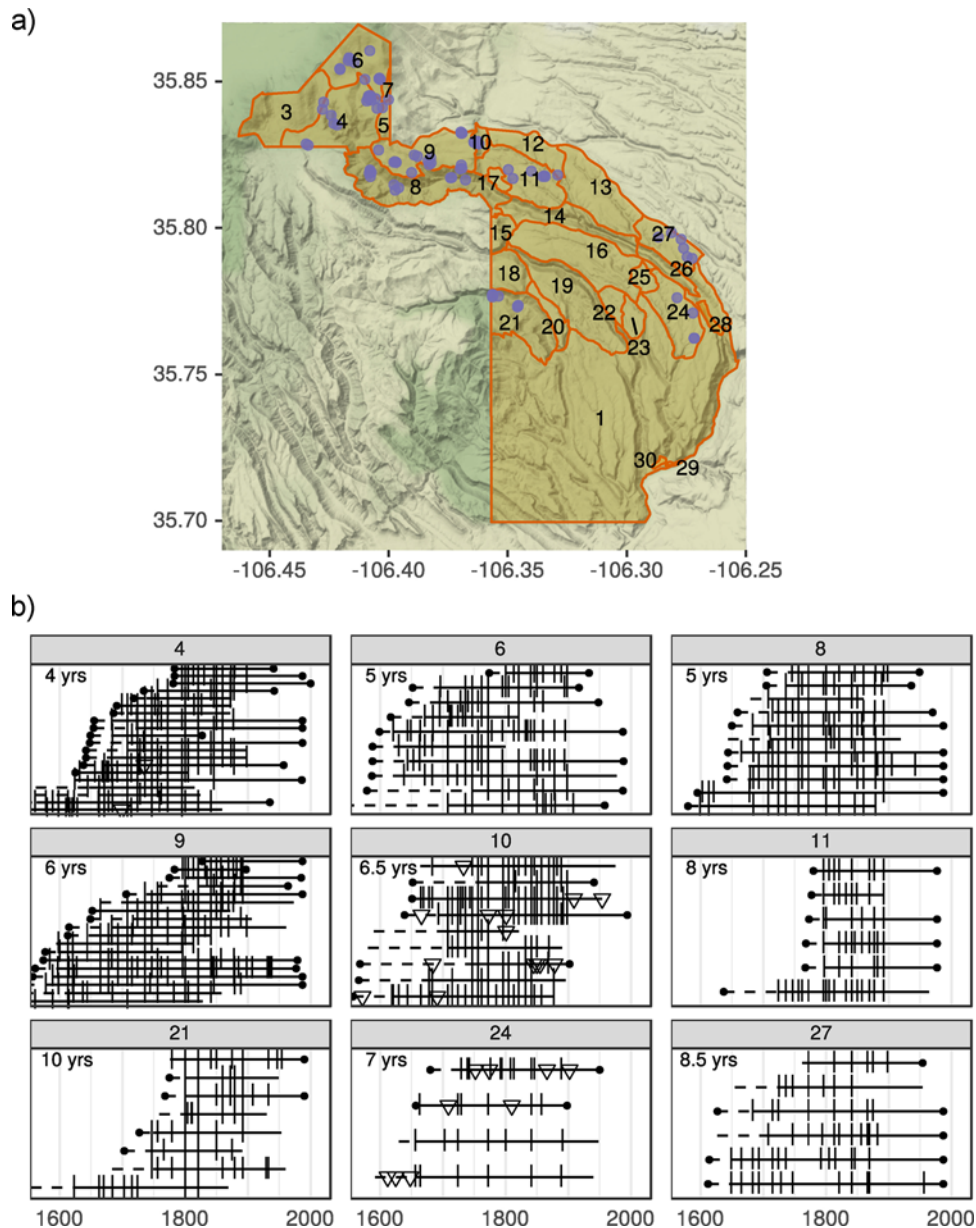


Fig. 3. Map of sampled fire-scarred trees (dots) and prescribed fire units (numbered polygons) in Bandelier National Monument, New Mexico (a). Faceted fire chart of the nine fire units with the most samples (b). Facet titles correspond to burn units in the map. Annotations within each facet note median fire interval.

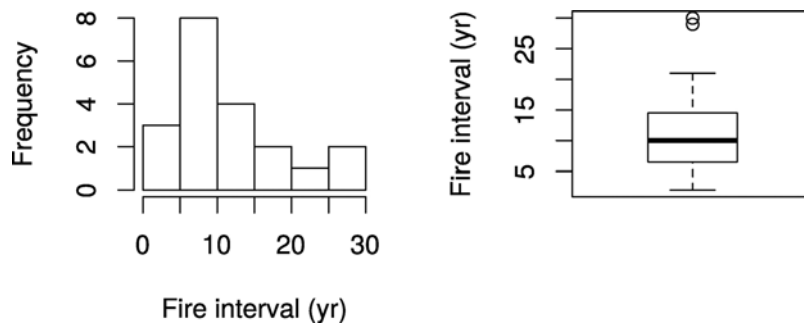


Fig. 4. Histogram and boxplot of the composite fire intervals for Peggy Mesa, New Mexico.

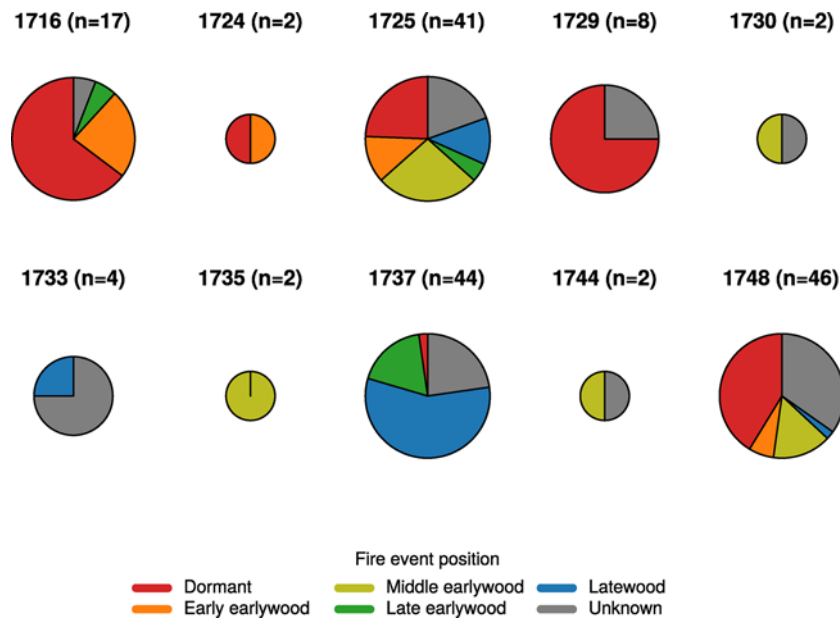


Fig. 5. Pie charts indicating seasonality of fire events for fire years in Bandelier National Monument (1716–1748). The size of the circle is proportional to the number of trees recording fire in that year (n), with pie slices indicating the intra-ring position of those scars.

```
> count_event_position(pgm)
```

	event	count
1	unknown_fs	17
2	dormant_fs	15
3	early_fs	3
4	middle_fs	10
5	late_fs	1

We can plot fire scar position data in a number of ways. For example, Fig. 5 is a custom graphic showing the proportion of fire scar positions for select years at a site, scaled by the number of trees recording fire scars annually. This was created by combining `burnr` functions with R's base plotting system. Plotting all fire years in charts like these can be helpful for quality control when dating and developing fire-history data sets. This graphic is also useful for visualizing changing fire seasonality through time, which may relate to human land-use changes or the influence of climate variability—such as North American monsoon failure (e.g., Margolis et al., 2017). The code to recreate this figure is available online (https://github.com/brews/burnr_2018_manuscript_figures).

7. Superposed epoch analysis

Fire-climate relationships are fundamental to projecting future fire risk (Westerling, 2006; Moritz et al., 2012; Littell et al., 2016). Fire-climate relationships can be quantified in `burnr` using superposed epoch analysis (SEA; Swetnam, 1993). SEA is a compositing tool that tests for inter-annual climate-fire relationships by calculating the departure of a climate time series from average conditions for each year and then using non-parametric bootstrapping to estimate the significance of the departure. Several programs and software packages implement SEA, including but not limited to FHX2 (Grissino-Mayer, 2001), `dplR` (Bunn, 2008), and FHAES (Brewer et al., 2016). The output of `sea()` in `burnr` is similar to the EVENT program (Holmes and Swetnam, 1994) as implemented in FHX2. SEA is an area of continuing development in `burnr` as we add new methods for handling time series data (e.g., Adams et al., 2003).

To demonstrate the basic functionality of SEA in `burnr`, we use the Peggy Mesa fire composites, described previously, and an example tree-ring reconstructed climate time series of summer Palmer Drought Severity Index (PDSI) nearest to Peggy Mesa (Cook and Krusic, 2004, from gridpoint 133). This PSDI time series is included with `burnr`.

```
> data(pgm)
> data(pgm_pdsi)
> pgm_comp <- composite(pgm)
> pgm_sea <- sea(pgm_pdsi, event=pgm_comp)
> print(pgm_sea)
```

```
Superposed Epoch Analysis
=====
```

lag	upper95	lower95	upper99	lower99	departure
-6	1.002	-1.001	1.346	-1.248	-0.289
-5	1.037	-1.012	1.412	-1.336	0.631
-4	0.908	-1.030	1.205	-1.294	-0.122
-3	1.078	-0.959	1.364	-1.380	1.012
-2	1.019	-1.011	1.289	-1.337	1.247.
-1	0.998	-1.021	1.288	-1.229	0.219
0	1.016	-0.997	1.440	-1.389	-2.108 *
1	1.003	-1.035	1.319	-1.317	-0.092
2	0.987	-1.074	1.261	-1.520	-0.512
3	0.979	-1.069	1.295	-1.388	0.272
4	1.006	-0.988	1.307	-1.301	0.278

```
—
Signif. codes: 0.01 '**' 0.05 '.'
```

```
> plot(pgm_sea)
```

After loading the example data set and creating the composite, the function `sea()` returns a `sea` object that we assign to `pgm_sea`. By default, this SEA is conducted with 1,000 bootstrap iterations, though this can be specified with the `n_iter` argument to `sea()`. By default, the SEA includes four lag years following and six lag years prior to the key event year, or the year of fire identified in the PGM composite, in this case. Printing a `sea` object produces a brief summary table giving upper and lower confidence intervals for the lagged years around fire events in the PGM composite. Note that the right-most columns denote the departure of the climate time series from its mean, and significance

of this departure, based on the bootstrapped intervals. Finally, we can plot the `sea` object with the generic `plot()` function, producing a simple bar plot with confidence intervals (figure not included).

8. Conclusion

The new `burnr` package for R is a powerful and flexible set of tools designed to meet the demands of modern fire history and event-based research. This paper introduces `burnr`'s ability to explore, summarize, and visualize tree-ring fire and demography data, analyze fire return intervals, visualize and quantify fire seasonality, and test for fire-climate relationships. We present a few examples of how `burnr` graphics and analyses can be expanded and tailored for complex data sets and research questions, including spatial analyses. A major advancement of `burnr` is to bring fire history data into the R computing environment, facilitating innovation and automation of large data analysis. The package has been used on multiple data sets containing more than 1,000 fire scarred trees and more than 8,000 fire scars (e.g., Margolis et al., 2017). Other non-fire event research may also benefit from `burnr`. The `burnr` package provides researchers with an Open Source tool that enables flexibility and transparency. It is our hope that `burnr` will promote collaboration and inspire creative and sophisticated research projects that advance the fire history field.

Acknowledgements

Development of `burnr` was initiated with support from the Central Oregon Fire Management Service (Deschutes and Ochoco National Forests, Crooked River National Grassland, and Prineville District Bureau of Land Management), Emily Heyerdahl (US Forest Service) and Don Falk (University of Arizona). The authors were supported by an EPA STAR Fellowship (to C.H.G.) and by the U.S. Geological Survey Western Mountains Initiative. Comments and discussion with T.W. Swetnam, C.H. Baisan, C.D. Allen, L.B. Johnson, and P. Brewer improved `burnr`. We thank the many early users and beta testers that helped us to develop and refine this software. This manuscript benefited from the thoughtful feedback of L. D. Daniels, L. B. Johnson, J. Powell and an anonymous reviewer. Background map tiles in Fig. 3a are available from Stamen Design (<http://stamen.com>) under a Creative Commons Attribution 3.0 license. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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