burnr: Fire history analysis and graphics with R

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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.

Keywords: Fire ecology, Statistical software, Event, Visualization, Tree ring, SEA

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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

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

31 The **burnr** package grew out of methods established by fire history studies
32 that capitalized on the ability of tree rings to record events with annual to
33 sub-annual precision over long time periods (e.g. Dieterich and Swetnam,
34 1984). Existing tree-ring fire history analysis programs, including FHX2
35 (Grissino-Mayer, 2001) and FHAES (Brewer et al., 2016), are widely used.
36 We based the **burnr** functions on these software systems, but by facilitating
37 analyses in **R**, we hope that users will develop new research and analytical
38 approaches.

39 In this paper we describe how to install **burnr**, and we demonstrate its ba-
40 sic use for manipulating and summarizing FHX files, fire—demography plot-
41 ting, fire interval analysis, and superposed epoch analysis (SEA). In many of
42 these sections we showcase some of the exciting ways that users can benefit
43 by analyzing fire-history data in **R**. Each section of this paper explains code
44 and analysis, assuming that the user has installed **R** and loaded the **burnr**
45 package (see Section 2). Text in **fixed-width font** indicates code that is
46 typed or output to an interactive **R** shell. Lines prefixed with “>” denote
47 code entered by the user. Finally, note that source code to recreate this pa-
48 per’s figures is available online ([https://github.com/brews/burnr_2018_](https://github.com/brews/burnr_2018_manuscript_figures)
49 [manuscript_figures](https://github.com/brews/burnr_2018_manuscript_figures)). Output presented in this paper is from **burnr** v0.2.2.

50 **2. Availability and installation of burnr**

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

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

57 The library is then loaded with:

```
58 > library(burnr)
```

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

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

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

```
69 > library(burnr)
```

70

```

71 > url <- paste0("https://www1.ncdc.noaa.gov/",
72                "pub/data/paleo/firehistory/",
73                "firescar/northamerica/")
74
75 > pmr <- read_fhx(paste0(url, "uspmr001.fhx"))
76 > pme <- read_fhx(paste0(url, "uspme001.fhx"))
77 > pmw <- read_fhx(paste0(url, "uspmw001.fhx"))
78
79 > pm_all <- pmr + pme + pmw
80
81 > 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).

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

99 `> series_stats(pm_all)`

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

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
				⋮					

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.

102 4. Plotting fire history and demography

103 To showcase plotting we included example fire-history data sets within
 104 the `burnr` package. We begin with `lgr2`, a fire history and demography
 105 data set from Los Griegos Peak, New Mexico that contains 11 fire-scarred or
 106 fire-injured trees and 15 non-fire-scarred trees of four species (Margolis and

107 Malevich, 2016). Below, we load the example data set to the `lgr2` variable
108 as an `fhx` object, as though we had read the data from an FHX file:

```
109 > data(lgr2)
```

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

```
111 > plot(lgr2)
```

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

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

```
124 > data(lgr2_meta)
```

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

Figure 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.

```

130 > plot(lgr2,
131       color_group = lgr2_meta$SpeciesID,
132       color_id = lgr2_meta$TreeID,
133       ylabels = FALSE, composite_rug = TRUE,
134       injury_event = TRUE)

```

135 The new arguments to `plot()` produce a fire—demography chart with colors
 136 corresponding to tree species and a fire-composite rug along the bottom of

137 the graphic (Fig. 2a). The species information (`color_group`) is joined
138 with `lgr2` through the series names (`color_id`). We also remove the y-
139 axis labels (`ylab = FALSE`) to save plotting space, and add a composite
140 rug that includes injuries with the arguments `composite_rug = TRUE` and
141 `injury_event = TRUE`.

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

151 Advanced edits of fire—demography charts requires a deeper understand-
152 ing of how `burnr` creates graphics. Internally, `burnr` takes advantage of
153 R’s advanced `grid` plotting framework and the `ggplot2` package (Wickham,
154 2016). This helps `burnr` to create more sophisticated graphics (e.g., with
155 coloring and faceting) that are also modular and customizable. To introduce
156 this, we modify the `lgr2` fire—demography chart by adding a legend – with
157 custom placement – and a shaded polygon to highlight the species transition
158 we described previously:

```
159 > library(ggplot2)
```

160

```
161 > lgr2_sorted <- sort(lgr2, decreasing=TRUE)
```

162

```
163 > p <- plot_demograph( lgr2_sorted,  
164                        color_group = lgr2_meta$SpeciesID,  
165                        color_id = lgr2_meta$TreeID,  
166                        composite_rug = TRUE,  
167                        ylabels = FALSE,  
168                        plot_legend = TRUE)
```

169 This code sets up our graphic, and assigns it to `p`, but does not yet output the
170 image. The first line imports the `ggplot2` package – this is needed to modify
171 our graphic. The next line sorts the data set by the first ring so the oldest
172 tree series will appear along the top of the graphic. The following lines of
173 code create a variant of our species-colored fire—demography plot from Fig.
174 2a. Note that we are using `plot_demograph()` instead of the generic `plot()`.
175 `plot()` passes information and arguments – when used with `fhx` objects –
176 to `plot_demograph()`. We need to explicitly call `plot_demograph()` here
177 because this function returns a `ggplot` object that we can modify to our
178 liking. We can further customize `p` and then `print(p)` to output the graphic:

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

185 Here, we append two simple things to this plot with the `+` operator. First,

186 with `annotate()`, we add a large transparent rectangle to highlight a cohort
187 of trees regenerating after a severe fire in 1861. Next, we change the style of
188 the plot, with `theme()`, by moving the legend within the plot frame, reducing
189 white space in the graphic. The final graphic produced with these changes
190 is shown in Fig. 2b. These modifications can be built upon for more radical
191 changes to **burnr** graphics.

192 Automated multi-faceted fire—demography plots are another novel fea-
193 ture of **burnr**. Faceting separates the graphic into multiple panels, simultane-
194 ously plotting many fire history sites in one graphic, for instance. This helps
195 visual comparisons of fire frequency or age structure across multiple sites.
196 These figures are created with an approach nearly identical to that used for
197 colored plots, as described previously: the `plot()` or `plot_demograph()` ar-
198 guments `color_group` and `color_id` are simply replaced by the `facet_group`
199 and `facet_id` arguments. Both faceting and coloring can be used simulta-
200 neously in the same graphic. An advanced example of this, with faceting
201 based on spatial locations is shown in Fig. 3. This example uses differ-
202 ent prescribed fire burn units in Bandelier National Monument, New Mexico
203 (Fig. 3a) to group fire-scarred trees and create fire charts for each burn
204 unit (Fig. 3b). Code to recreate this figure is available online ([https://github.com/](https://github.com/brews/burnr_2018_manuscript_figures)
205 [brews/burnr_2018_manuscript_figures](https://github.com/brews/burnr_2018_manuscript_figures)).

206 Faceting by spatial location also highlights the benefits of combining spa-
207 tial and cartographic capabilities of R with fire-history data in **burnr**. Other
208 useful examples of mapping data from **burnr** include: annual fire year maps
209 can be colored by tree-ring data type (e.g., fire scar, death date, regener-
210 ation 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.

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

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

```
237 > print(pgm_interv)
```

238

```
239 Interval Analysis
```

```
240 =====
```

```
241 Composite name: PGM
```

```
242 Events range: 1636 to 1871
```

```
243 Total intervals: 20
```

```
244 Mean interval: 11.8
```

```
245 Median interval: 10
```

```
246 Weibull median: 10.6
```

```
247 Standard deviation: 7.7
```

```
248 Minimum interval: 2
```

```
249 Maximum interval: 30
```

250

```
251 Theoretical distribution
```

```
252 -----
```

```
253 Fit distribution: weibull
```

```
254       shape       scale
```

```
255       1.6565206   13.2125358
```

```
256       ( 0.2797517) ( 1.8871133)
```

257

```
258 Percentiles
```

```
259 -----
```

```

260 lower (12.5%): 19.3 |
261 weibull median (50.0%): 10.6 |
262 upper (87.5%): 3.9
263
264 One-sample Kolmogorov-Smirnov test
265 -----
266
267 D^- = 0.12776, p = 0.89978
268 Null hypothesis: The intervals
269 were sampled from the theoretical
270 distribution.
271 Alt. hypothesis: The intervals
272 were not sampled from the theoretical
273 distribution.

```

274 The `intervals()` function returns an `intervals` object. This object prints
 275 an analysis similar to FHX2 and FHAES interval analyses. It includes basic
 276 summary statistics, the parameters for a theoretical distribution fit to the
 277 event intervals, select percentiles of the fire intervals distribution, and the
 278 result of a Kolmogorov-Smirnov test to assess the theoretical distribution
 279 fit. By default, the intervals are fit to a Weibull distribution (Grissino-Mayer,
 280 1999), though other options are available. This is a good place to use `base`
 281 R graphics to plot the interval distribution:

```

282 > hist(pgm_interv$intervals)
283 > boxplot(pgm_interv$intervals)

```

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

288 6. Fire seasonality

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

```
298 > count_event_position(pgm)
```

299

```
300           event count
301 1 unknown_fs      17
302 2 dormant_fs      15
303 3  early_fs        3
304 4 middle_fs       10
305 5  late_fs         1
```

306 We can plot fire scar position data in a number of ways. For example,
307 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

332 Mesa fire composites, described previously, and an example tree-ring re-
 333 constructed climate time series of summer Palmer Drought Severity Index
 334 (PDSI) nearest to Peggy Mesa (Cook and Krusic, 2004, from gridpoint 133).
 335 This PSDI time series is included with **burnr**.

```
336 > data(pgm)
337 > data(pgm_pdsi)
338
339 > pgm_comp <- composite(pgm)
340
341 > pgm_sea <- sea(pgm_pdsi, event=pgm_comp)
342
343 > print(pgm_sea)
344 Superposed Epoch Analysis
345 =====
346 lag upper95 lower95 upper99 lower99 departure
347 -6 1.002 -1.001 1.346 -1.248 -0.289
348 -5 1.037 -1.012 1.412 -1.336 0.631
349 -4 0.908 -1.030 1.205 -1.294 -0.122
350 -3 1.078 -0.959 1.364 -1.380 1.012
351 -2 1.019 -1.011 1.289 -1.337 1.247 .
352 -1 0.998 -1.021 1.288 -1.229 0.219
353 0 1.016 -0.997 1.440 -1.389 -2.108 *
354 1 1.003 -1.035 1.319 -1.317 -0.092
355 2 0.987 -1.074 1.261 -1.520 -0.512
356 3 0.979 -1.069 1.295 -1.388 0.272
```

```

357     4     1.006   -0.988    1.307   -1.301     0.278
358     ---
359     Signif. codes: 0.01 '**' 0.05 '.'
360
361
362     > 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.

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 406 uct names is for descriptive purposes only and does not imply endorsement
 407 by the U.S. Government.

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Figure 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).

Figure 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.

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

Figure 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.