Reconstructing Annual Area Burned in the Northern Rockies, USA: AD 1626–2008

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Abstract

We used a tree-ring chronology as a proxy for annual area burned (AAB) in the northern Rockies, USA during AD 1626–2008. We correlated annual ring widths of alpine larch trees (Larex lyallii) sampled at a single high-elevation site in western Montana with AAB for the United States Forest Region 1. Radial growth was significantly associated with AAB (R2 = 0.35, p < 0.001), demonstrating the potential to use high-elevation conifers as markers of interannual variations in fire activity. The results suggest that the period 1929–1945 would have been the most active since the early 1600s had not extensive fire suppression and harvest activities altered the fire regime. Comparisons of the predicted values of area burned to a century-long fire atlas were significant for both the entire record (rs = 0.333, p < 0.01) and reconstruction period (rs = 0.645 p < 0.001). Similarly, predicted AAB was significantly correlated (r = 0.230) to fire-scar data during 1650–1900. These results suggest the feasibility of using tree-ring chronologies as an additional measure of fire activity, particularly as they allow an assessment and comparison of fire activity during centuries with and without fire suppression and harvest activities.

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1. Introduction

[2] Documenting fire history in western North America forests has traditionally been accomplished using a network of sites to develop fire-scar chronologies [*Romme and Despain*, 1989; *Swetnam and Baisan*, 1996; *Barrett et al.*, 1997; *Heyerdahl et al.*, 2008]. Implicit in these studies is that fire scars serve as "point record[s]" of the "relative extensiveness of fires at various spatial scales" [*Swetnam and Baisan*, 1996, p. 14]. Thus, interannual fire activity can be determined through the direct comparison based on how many sites record fires as well as the number of individuals affected per site. Further, because the season in which the scar occurred (e.g., dormant season) can often be determined, an additional temporal component is possible. Conversely, this method has limitations in that: 1) data are collected at a limited number of preserved sites with uneven spatial distributions; 2) the collection process is time extensive; 3) the amount of annual area burned (AAB) cannot be inferred unless fire-scar data are collected from all forest types found within the region (i.e., ranging from woodlands to high-elevation montane forests); and 4) fire-scar data are temporally limited as the amount of fire activity cannot be determined for years absent fire scars, particularly after intensive fire suppression and forest harvest activities began in the 20th century.

[3] Alternatively, tree-ring chronologies can be used to reconstruct AAB [e.g., *Larsen and MacDonald*, 1995; *Larsen*, 1996; *Girardin*, 2007; *Girardin and Sauchyn*, 2008], based on the principle that climatic conditions affecting ring-widths correlate with fire activity. In the American West, increased fire activity is principally associated with climatic conditions that promote warm springs and/or warm and dry summers [*Kipfmueller*, 2003; *Hessl et al.*, 2004; *Schoennagel et al.*, 2004, 2005; *Westerling et al.*, 2006]. Further, as these climatic conditions are driven by synoptic-scale meteorological controls [*Trenberth et al.*, 1988; *Knapp and Soulé*, 2007], fire activity is often spatially extensive and synchronous with climate [*Morgan et al.*, 2008], but the extent of AAB can be modified by anthropogenic activities [*Morgan et al.*, 2008].

[4] Fire suppression activities have been operative in the northern Rockies for a century and concurrent with extensive logging of the high-value mesic forests of ponderosa pine and Douglas-fir [*Gibson*, 2006]. As a result, the amount that would have burned absent anthropogenic disturbance is likely greater than what actually occurred, and comparisons between the relative extent of fire activity in the 20th/21st and prior centuries are difficult. Here we reconstruct AAB in the northern Rockies during AD1626–2008 using tree-ring data collected from a high-elevation, long-lived deciduous conifer that responds principally to summer temperature and moisture conditions. We then compare our reconstruction to a century-long record of AAB and examine how 20th century fire activity compared to the three previous centuries. Specifically, we demonstrate how: 1) this method may compliment wildfire studies by offering an additional means to assess fire activity by calculating AAB; and 2) the use of these data may offer insights on the extent of fire-suppression activities and forest harvest during the past century by comparing differences between actual and estimated AAB.

2. Methods

2.1. Tree-Ring Data

[5] We sampled 33 alpine larch (*Larix lyallii*) trees at Carlton Ridge Research Natural Area in western Montana (46.6946, −114.1827) in August 2009. When possible, we obtained two cores for each visibly healthy tree (absent fire scars, broken or dead top, or signs of disease) in a park-like stand located along a gentle (<10°), north-facing slope at

approximately 2440 m elevation. We attempted to reach the pith of the tree for each core and trees with heart rot were excluded from our sampling. We processed collected samples using standard methods [*Stokes and Smiley*, 1968], crossdated using the list method [*Yamaguchi*, 1991], and measured to 0.001 mm precision using an Accurite Linear Encoder. We examined the chronology for dating accuracy by using the program COFECHA [*Holmes*, 1983; *Grissino-Mayer*, 2001] and conservatively standardized (i.e., negative exponential, negative linear, or line through the mean) using the program ARSTAN [*Cook*, 1985]. Our standardized data set represented 38 cores sampled from 20 trees with a signal strength of 0.85 [*Wigley et al.*, 1984] beginning in AD 1626.

2.2. Climatic Data

[6] We obtained monthly precipitation, mean temperature, and Palmer Drought Severity Index data from the National Climatic Data Center (http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp) for the years 1895–2008 for Montana Climate Division 1, which covers the northwestern portion of the state and includes the sample site. We also created a series of climatic variables by averaging (e.g., summer temperature) or lagging (e.g., previous autumn precipitation) the monthly data. We compared climate data with the STANDARD, RESIDUAL, and ARSTAN outputs from the ARSTAN program chronologies using both Pearson and Spearman's Rank Order tests. As the highest correlation between the climatic data and tree-ring data occurred with the ARSTAN chronology, we retained this version for further analysis.

2.3. Fire Data

[7] We obtained fire data of annual hectares burned for 1940–1997 for Region 1 of the United States Forest Service using two data sets: 1) Fire History Western Region 1 1940–2001; and 2) Fire History for Region 1 1985–2005 (for 1988 only, which was incomplete in the other data set). These data were from the Northern Region Geospatial Library Regional Office Data at http://www.fs.fed.us/r1/gis/ThematicTables.htm#Fire). From 1998–2008, we obtained annual hectares burned in Region 1 from the National Interagency Fire Center [http://gacc.nifc.gov/nrcc/predictive/intelligence/ytd_historical/ytd_historical.htm]. We excluded fire data for the Custer National Forest as these eastern Montana/western South Dakota forests are geographically disjunct to our study site. Hectares burned were derived from polygonal as opposed to point data and excluded fires <40 ha. As these data have been impacted by fire suppression and land-use policies throughout the time span, and area burned was not separated by lightning- or human-caused ignition sources, the values are likely different than what would have occurred absent these activities.

[8] To compare the potential effects of land-use management on fire behavior over a longer period, we also used a century-length data set complied by *Morgan et al.* [2008] (hereafter the Morgan file) that included data from all national forests in Idaho and west of the Continental Divide in Montana. The Morgan file was complete from 1900–2003 and corresponded strongly ($r_s = 0.887$, $p < 0.001$) to our data set during the common interval of 1974–2003 that we used for regression analysis with our tree-ring data. Thus, we considered the Morgan file an excellent proxy to compare with our reconstructed AAB data even though the two data sets did not fully overlap spatially. Because the fire data are predominantly comprised of years with low AAB totals interspersed with a few major fire years, we transformed our data using a natural log to approximate a normal distribution prior to regression analysis.

2.4. Fire-Scar Data

[9] We accessed fire-scar data from five sites in western Montana located within approximately 100 km of Carlton Ridge RNA via the International Multiproxy Paleofire Database and included in the work of *Heyerdahl et al.* [2008]. Data were complete from 1650 through 1900 and included: Blue Mountain (46.82, −114.13), Butler Creek (47.12, −114.4), Corona Road (47.60, −114.93), McCormick Creek (47.15, −114.48), and Sheldon Flats (48.42, −115.13). We summed the number of scars per year by site, and then tallied all years where at least two scars per site occurred. Thus, for any year a value of 0 (no site with at least two scars) to 5 (all sites had at least two scars) was possible. We then correlated and graphically compared them to the area burned data over the same period.

2.5. Calibration and Validation

[10] We calibrated and validated regression models between standardized radial growth and AAB using data from 1974–2008 as this period represented the highest correlation between the two data sets. Verification statistics included the bivariate regression coefficients between actual and predicted AAB using the leave-one-out (L1O) method [*Michaelsen*, 1987] and the reduction of error statistic (RE) [*Fritts*, 2001]. The model verification statistics compared favorably with the final model (actual and predicted growth $r = 0.589$, $P < 0.001$ and $RE = 0.35$ for the calibration; $r = 0.532$, $P < 0.001$ and $RE = 0.28$ for the L1O validation). RE values > 0 suggest an acceptable skill level for the model [*Fritts*, 2001].

2.6. Statistical Analysis

[11] We correlated annual radial growth with AAB for Region 1 and then repeated the process after placing the data into running means with various durations. The best correlation absent serial autocorrelation occurred using annual data for both the tree-ring and fire data sets. Use of the same data smoothed to reduce interannual noise was autocorrelated and thus we excluded them from further analysis. Correlations between the larch and fire data decreased prior to 1974, possibly as an artifact of intense fire suppression and harvest activities in Region 1 [*Gibson*, 2006] or variations in record keeping. Our data set was thus represented by the years 1974–2008 ($n = 35$). We then ran linear regression using AAB and larch radial growth as the dependent and independent variables, respectively. Finally, we checked for autocorrelation for our model and found the Durbin-Watson value of 2.103 fell above the 5% threshold upper-bound value of 1.519. No outliers (i.e., residuals > 2.5) existed in the final model.

3. Results and Discussion

[12] Radial growth variations were positively associated with AAB, and major fires occurred during years when radial growth was especially large. Our model ($R^2 = 0.349$, $p < 0.001$, $n = 35$ years) indicated that approximately 35% of the interannual variation in AAB was associated with radial growth of high-elevation alpine larch trees at a single site in

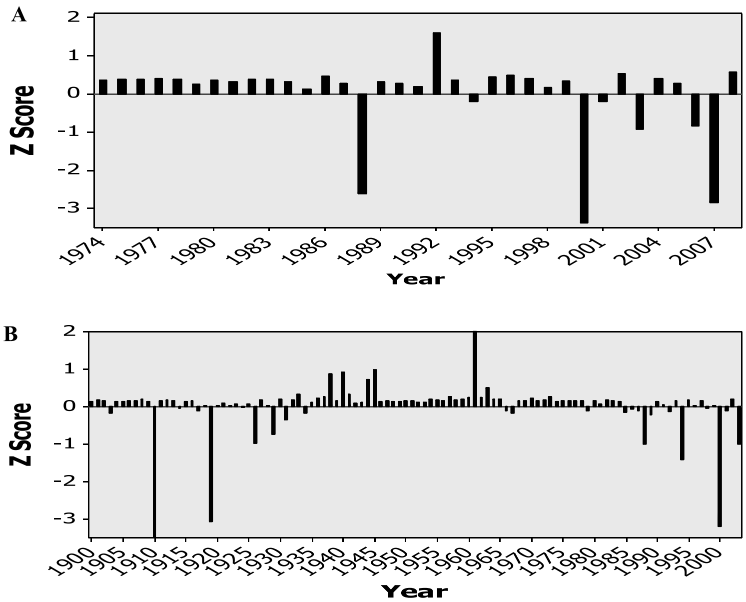

Figure 1. (a) Predicted area burned minus actual area burned in the northern Rockies, 1974–2008. Positive z scores represent over predictions and negative z scores represent under predictions. (b) Predicted area burned minus actual area burned (Morgan data) in the northern Rockies, 1900–2003. Positive z scores represent over predictions and negative z scores represent under predictions. Z scores for 1910 (−6.72) and 1961 (5.20) are truncated.

western Montana. These results are similar to comparable studies from other regions [e.g., *Larsen and MacDonald*, 1995; *Girardin*, 2010] and suggest favorable conditions that promote growth in these high-elevation coniferous forests are coincident with more severe fire years. During 1974–2008, alpine larch radial growth was most strongly correlated with August PDSI values ($r = -0.515$, $p < 0.000$), indicating that maximum growth occurs during time periods experiencing summer meteorological drought. Because alpine larch are found in high-elevation sites where soil moisture is typically not a limiting factor for growth [*Arno and Habeck*, 1972] and cool conditions prevail, climatic conditions promoting an earlier onset of the above-ground growing season facilitate increased growth [*Kipfmueller*, 2008]. Warmer and drier summers, as noted by negative PDSI values, promote both fire activity and alpine larch growth. In turn, radial growth of alpine larch can serve as an excellent proxy measure for AAB.

[13] Comparison of our reconstructed data with our AAB data set during 1974–2008 (predicted minus actual; Figures 1a and S1 of the auxiliary material) showed 1992 as the sole year where the model predicted substantially more (Z score > 1) AAB than was recorded.[1] Conversely, the model produced major underestimates (Z score < −1) for 1988, 2000 and 2007 (Figure 1a). Our model was conservative in predicting AAB for these major fire years. Model residuals were correlated with both September PDSI ($r = -0.363$, $p = 0.032$, $n = 35$) and October PDSI values ($r = -0.389$, $p = 0.022$, $n = 35$), suggesting some fire events continued into autumn and after the growing season [http://gacc.nifc.gov/nrcc/predictive/intelligence/ytd_historical/ytd_historical.htm]. Additionally, because our model was calibrated using fire data collected during a time period where fire suppression and timber harvest activities reduced fire activity within the region, AAB estimated by our model may be less than actual AAB, especially during major fire years (Figures 1a and S1 of the auxiliary material).

[14] For a broader historical perspective we compared our reconstructed data with the Morgan data set during the common period of 1900–2003. The predicted values of AAB to a century-long fire atlas were significantly related for both the entire record ($r_s = 0.333$, $p < 0.01$) and reconstruction period ($r_s = 0.645$ $p < 0.001$). The majority of overestimated fire-activity years occurred during 1935–1984 where three years had negative Z scores (Figures 1b and S2 of the auxiliary material) during a 50-year period. The onset and cessation of the over-estimations are abrupt and temporally concurrent with increased fire exclusion activities, excessive timber harvesting of low-elevation ponderosa pine and Douglas-fir forests [*Gibson*, 2006], and a predominance of years with unfavorable climatic conditions for fire [*Morgan et al.*, 2008] in the northern Rockies. A major outlier occurred in 1961, which had the single largest value for annual radial growth (1.9) and was 0.22 higher than the next highest value for the entire 383-year record, but did not correspond with major fire activity.

[15] Model underestimates (Z score < −1.0) of AAB occurred during well-documented major fire years of 1910 and 1919 [*Morgan et al.*, 2008] (Figure 1b), indicating that fire activity for those years was underrepresented, although to what degree is uncertain. Prior to the mid-1930s, area burned was determined using aerial photography coupled with a variety of secondary sources including newspaper accounts, maps, interviews, personal notes and fire reports [*Gibson*, 2006]. Critical to the use of aerial photography is a confirmation of stand age because without that fire dates were imprecise. However, this was done infrequently [*Gibson*, 2006], causing considerable ambiguity to the actual fire

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL048119.

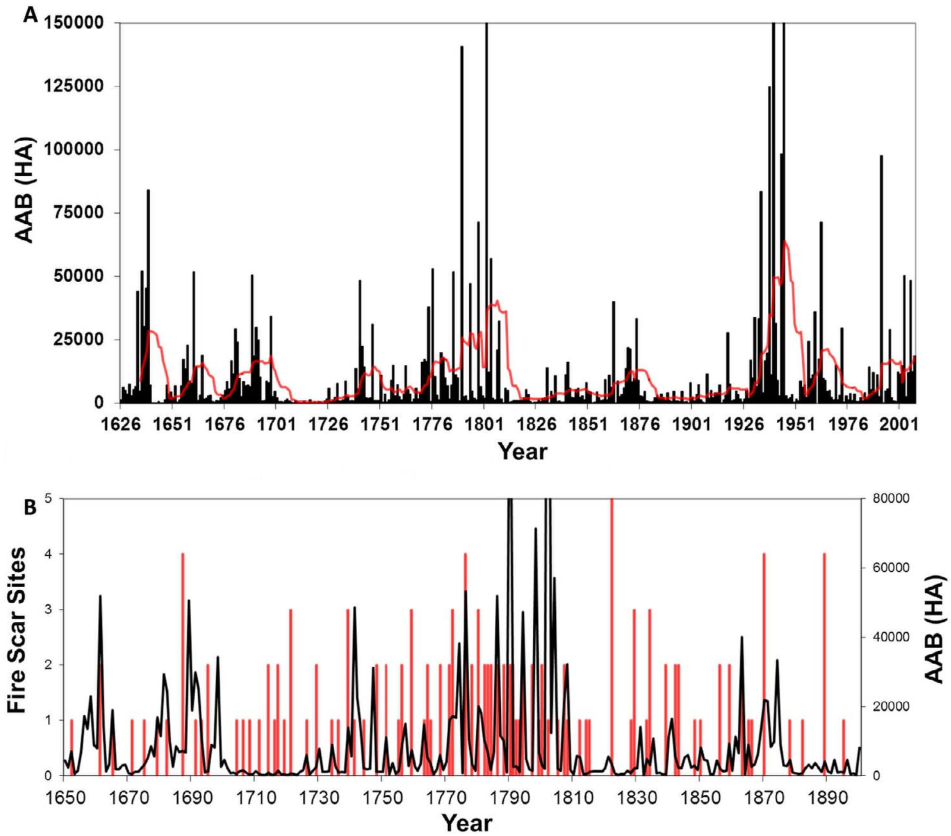

Figure 2. (a) Reconstructed fire history for the Northern Region of the USFS shown by histograms for the years 1626–2008. Bold line represents a centered 10-year moving average (e.g. Year 2004 is comprised of data from 1999–2008. The 1961 data point (891, 635 ha) was excluded as an extreme outlier. (b) Reconstructed AAB (line) with fire-scar data (histogram) 1650–1900 as marked by number of sites affected.

year. Further, *Morgan et al.* [2008] suggest that AAB in mesic forests, which comprise the majority of forest areas in the region, may have been over-reported during this period because of proximity to towns that reported the fires and concern about fires after the 1910 event. Thus, the annual accuracy of the early fire records is imperfect and underestimates may be an artifact of suboptimal records. There also may be an inherent inability of our model to capture the magnitude of major fire years because fire activity for a single year can be the cumulative result of climatic conditions over preceding multi-year periods [*Balling et al.*, 1992; *Swetnam and Betancourt*, 1998], the interactive effects of weather and disease/insect infestations [*Bentz et al.*, 2010; *Jenkins et al.*, 2008; *van Mantgem et al.*, 2009] or model bias.

[16] The extensive fire activity since the late 1980s is unremarkable in the context of the past four centuries, as periods of equal or greater magnitude occurred during each century (Figure 2a). Our model suggests that mean AAB during 1929–45 would have exceeded any other period had not fire suppression and timber-harvest activities been operative. This period experienced unusual climatic conditions with warm and dry weather dominant from 1929–45 (mean August PDSI = −2.83) and represented one-half of the top-10 largest predicted fire years excluding the 1961 outlier. The reconstruction suggests that the longest sustained period of fire activity occurred from 1771–1804 and that three periods are marked by low fire activity where no annual value of AAB exceed the 383-year mean: 1699–1738, 1809–30, and 1875–1907 (Figure 2a).

[17] Predicted AAB (log-transformed) and fire-scar data from 1650–1900 are significantly related (r = 0.230, p < 0.000; Figure 2b), with large area-burned years coinciding with more sites recording fire-scars. Again, the most active period occurred during 1771–1804 and no other period matched the temporal extent of fire activity. Most periods of elevated fire activity are matched by increased fire-scar records and our reconstructed data also show minimal area burned during the longest period of non-fire-scar records (1696–1703). Mismatches between the two data sets occurred in1689, 1743 and 1798 when fire scars were absent, but large AAB values occurred; and conversely, during 1714–21 and the single years of 1687, 1822 and 1889, when fire scar records existed with low AAB years. The lack of a stronger relationship between fire-scar activity and AAB may relate to intra-seasonal timing of fire activity, as peak fire season in the northern Rockies occurs from mid-July to mid/late September. Years when increased fire activity begins post mid-September would not be associated with large areas burned because of an insufficient number of days the fire could spread. For example, during the 1889 fire season four of the five fire-scar collection sites had at least two scars. The fire-scar data revealed all fires occurred in either the dormant season or the date of occurrence was unknown, suggesting a late-season fire. Conversely, the 1776 fire season affected

four fire-scar sites with the scars situated in all parts of the trees except the earlywood, suggesting an earlier occurrence of the fire that matches with a year of increased area burned.

4. Conclusions

[18] Our findings demonstrate that AAB, a component of fire activity difficult to determine from analyses of fire-scar data, can be successfully reconstructed using a tree-ring chronology developed from a single site. Our reconstruction extends the record of AAB in the northern Rockies to AD1626 and suggests that fire suppression and logging likely reduced AAB during the 20th century to minimal levels during a time period (1929–45) where climatic conditions should have promoted the most active fire period during the past four centuries.

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