Fire history and fire-climate interactions in high elevation whitebark pine dominated forest

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Keywords

Whitebark pine, fire history, fire-climate relationships, tree mortality, drought, mixed severity fire, Rocky mountains, Idaho, Sawtooth National Forest

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Abstract

The objectives of this study were to identify whitebark pine fire-climate interactions, and tree establishment and mortality patterns in a landscape context. Specific objectives were to : 1) develop a whitebark pine tree-ring chronology to date fire scar samples and reconstruct climate from tree rings; 2) identify fire climate relationships for white bark pine forests; and 3) determine how fire regimes in whitebark pine forests related to lower elevation forest types (Douglas-fir and subalpine fir).

Our fire history shows fires occurred less frequently than in forests at lower elevations dominated by Douglas fir (15 years vs 66 years). Variability in time between fires recorded in fire scarred trees scars was high (ranging from 5 to 242 years). Most fires in whitebark pine were small in size and occurred during dry years, likely carried by grassy fuels. However, fire did connect lower elevation forests to whitebark forest. Widespread fires recorded in the lower elevation Douglas fir forest burned through the whitebark pine stands during especially dry years.

We document a century of slowing regeneration and recent elevated mortality rates of trees older than a century. Whitebark pine establishment peaked in the 1890s, after the last widespread fires occurred, at the same time as livestock grazing began. Establishment declined precipitously after the 1930s. In contrast, subalpine fir establishment in whitebark stands peaked in the 1920s and 1930s and has continued. The effects of grazing and fire suppression on the whitebark regeneration are likely confounded because fire suppression and grazing began at about the same time. The lightning ignited fires that burned small areas at high elevations and ridgetops during the last century were probably constrained by low fuel connectivity rather than fire suppression. Fires starting at low elevations are more likely to have been suppressed by shepherds or forest staff.

The majority of whitebark pine established around the time of the last fire. Fires may have created a mosaic of open habitat that attracted, Clark's nutcracker, the bird responsible for whitebark seed caching and subsequent regeneration. For managers seeking to manage for whitebark persistence, our findings of small, local fires every 66 years, widespread fires in dry years, and slowed whitebark regeneration since the last widespread fire in 1889 support a multi-pronged approach including removing competing subalpine fir, conducting burns to encourage whitebark regeneration, and planting seedlings resistant to blister rust. Managers are likely aware grassy fuels have been reduced by over a century of livestock grazing. Sparser grass may limit the local spread of natural lightning ignited fires further necessitating prescribed fires or actions to mimic fire disturbance. Regarding the timing management actions, our whitebark chronology shows trees are most stressed in the growing season following a warm, dry summer.

Objectives

The objectives of this study were to identify whitebark pine fire-climate interactions and tree establishment and tree mortality patterns. This required: 1) development of a study area specific whitebark pine tree-ring chronology to data fire scar samples and reconstruction climate from tree rings; 2) identifying fire climate relationships for white bark pine forests; and 3) determining how fire regimes in whitebark pine forests are related to lower elevation forest types (Douglas-fir and subalpine fir).

Based on the Douglas-fir forest fire patterns, we hypothesized that during especially dry years, climate-fire interactions connected lower elevation Douglas-fir and high elevation whitebark pine forests as a result of dry fuel connectivity whereas during wetter periods, fires were smaller and patchier. However, after 1890, as a result of settlement activities including livestock grazing and mining, ground fuels became discontinuous and fire connectivity between low and high elevation forest likely declined.

Background

Knowledge of historical fire-climate interactions is valuable to efforts to predict and plan for how fire regimes may respond in a changing climate (Flannigan et al. 2009). However, little is known about fire-climate relationships in high elevation whitebark pine, *Pinus albicaulis,* forests (Larson and Kipfmueller 2012). Devising effective management strategies for whitebark pine is time sensitive because, across much of its range, the species has suffered dramatic declines attributed to a combination of mountain pine beetle, exotic blister rust, and fire suppression. Reintroduction of fire is a primary recommendation for whitebark pine restoration (Keane and Parsons 2010), yet fire frequency and effects in whitebark pine stands appear highly variable and debate remains about what constitutes appropriate application of fire in this system (Larson & Kipfmueller 2012).

In other high elevation forests, especially in the Northern Rockies, the timing and severity of fires is associated with extreme drought years (Schoennagel, Veblen, and Romme 2004; Sibold and Veblen 2006). However, most whitebark pine fire history studies have been conducted using stand age structure and lack the resolution necessary to relate fire years to annual climatic conditions. Furthermore, cross- dated fire scars from whitebark pine stands in Montana did not reveal a consistent relationship between climate and fire years at the stand level (Larson et al. , 2009). And a landscape-scale study found limited evidence of fire spread between contiguous lower and upper elevation forests in an isolated mountain range (Murray et al., 1998). But, this study lacked annual resolution. Our study investigates whether climate and fuel connectivity are important in the whitebark pine fire regime from the stand to landscape scale. By adding whitebark pine fire history and climate chronology components to an ongoing dissertation on fire history and vegetation change in Douglas-fir and subalpine fir forests, we are able to analyze whitebark pine fire-climate interactions within a landscape context. For managers developing long-range plans, this information could help determine which forests types may be increasingly vulnerable to climate-change driven shifts in fire regime.

Methods

Field work was conducted to 1) develop a local whitebark pine-based chronology to cross-date dead trees and examine whitebark pine growth response functions and local climate patterns 2) collect fire history information from dead fire-scarred whitebark, and 3) collect stand age structure data to describe fire extents and effects and regeneration patterns.

Study Site

The study site is in south central Idaho in the Soldier Mountains part of the Sawtooth National Forest. The Soldier Mountains formed from the Cretaceous granodiorite of the Idaho Batholith and are part of the northern Rocky Mountains. January temperatures range from -10 to 0 C and August temperatures from 5 to 28 C. Around 80% of the precipitation falls in winter and spring as snow, with annual totals around 60 cm (http://www.wrcc.dri.edu/cgibin/cliMAIN.pl?id0491). The driest period occurs from July through October and summer moisture deficits make the region vulnerable to late-summer drought and fires. The site is largely north facing with eastern and western slopes on either side of north-south oriented drainages that run from ridge-top to the South Fork of the Boise River. The vegetation gradient follows the elevation gradient from Douglas-fir (*Psuedotsuga menziensii*) dominated forest at the river around 1700m up to subalpine fir (*Abies lasiocarpa*) at intermediate elevations around 2200m, with whitebark pine at the highest elevations along the ridgetops around 2800m. Sagebrush (*Artesmia tridentata*) and grasslands are found on drier slopes, particularly west facing, throughout the site. Fire suppression has been in effect since the early 1900s. The site has supported sheep grazing beginning around 1890 and continuing to the present.

Tree-ring Chronology

We developed a tree-ring chronology to assist in cross-dating tree sections, cores, and fire scars, and to identify how local climate influenced whitebark pine growth and fire patterns. We collected 2 cores from each of 35 trees growing on steep exposed slopes in open stand conditions on the ridgetop/westerly aspect. Trees on these sites are most likely to exhibit climate sensitivity. Trees on drier south-facing slopes were usually occupied by grasslands. Cores were mounted and sanded, and scanned at 1200 to 3200 dpi. The ring-widths were measured using CooRecorder and cross-dated using Cdendro (Larsson 2013). The accuracy of dating was assessed using Cofecha (Holmes 1983). Cores were considered correctly dated once Cofecha confirmed the highest significant correlation occurred at the dated position. The cross-dated core measurements were combined to create a site chronology. Since low frequency growth trends were common in our samples, we detrended the series using a 50-year smoothing spline to remove non-climatic trends in the ring-width pattern. Detrending and standardization to create the master chronology was conducted with ARSTAN(Cook 1985)

The master chronology was used to date dead tree cores and fire scars by matching the ring pattern of the chronology to the pattern of individual cores and cross-sections. Correlation and response functions were calculated using DendroClim (2002) to determine annual ring growth response to monthly temperatures and precipitation and reveal which years were especially dry and wet. Data from the Western Regional Climate Center's West Wide Drought Tracker (https://wrcc.dri.edu/wwdt/) for the years 1895 to 2015 were used for the analysis. The WRCC relies on PRISM data to generate fine scale (4-km) grid-based estimates of monthly precipitation and temperature.

Fire history

Following intensive survey of the study site, we documented 22 dead and 9 live whitebark pine, each with 1 to 3 external fire scars. Because whitebark pine is an imperiled species, samples were collected from dead trees only. Cross-sections were collected with a chainsaw from 11 trees determined to be safe for the sawyer. Complications making collecting samples from some dead scarred trees dangerously impractical included location on steep slopes, proximity to other trees, and suspected internal rot.

Fire dates were identified on cross-sections by first sanding each specimen to a high polish (400 grit), then crossdating the tree rings with the local tree ring chronology and identifying the year and season of each fire. Of samples collected, 8 (72%) were successfully cross-dated using the whitebark chronology.

Stand age-structure and tree mortality

To determine the whitebark pine forest age structure and composition, we established 14 plots in locations identified using aerial photography as containing live whitebark pine. In each plot, the 30 live trees (whitebark pine and subalpine fir) larger than 10 centimeters in diameter at breast height were cored at 30 cm. Cores were also taken from up to 15 dead whitebark pine from each of 9 plots to determine years of tree mortality. Cores were glued to wooden blocks, sanded to reveal ring patterns, and cross-dated to determine the decade of establishment and year of death. The age structure for each stand was determined from the innermost dates for the living and dead trees. A correction was added to the innermost date of cores that did not contain pith, based on the curvature of the innermost rings and a pith estimator made of concentric circles that represented different growth rates (Appelquist 1958).

Fire-climate-mortality relationships

We used superposed epoch analysis (SEA) to assess the fire–climate and tree mortality-climate relationships. We used the reconstructed mean summer (June through August) Palmer's Drought Severity Index (PDSI), which is a measure of available soil moisture, for grid point 70 (42.5° N, 115.0° W) developed by Cook et al. (2004) as our climate parameter, because drought is linked to fire activity (Westerling et al. 2006) and moisture limits annual growth of whitebark pine at our site. PDSI values indicate relatively wet (positive values) or relatively dry conditions (negative values) based on the qualitative scale suggested by Palmer (Alley 1984). SEA was also performed with the local standardized whitebark chronology and residuals chronology to test whether fires and tree deaths occurred in years where tree growth was reduced.

Results and Discussion

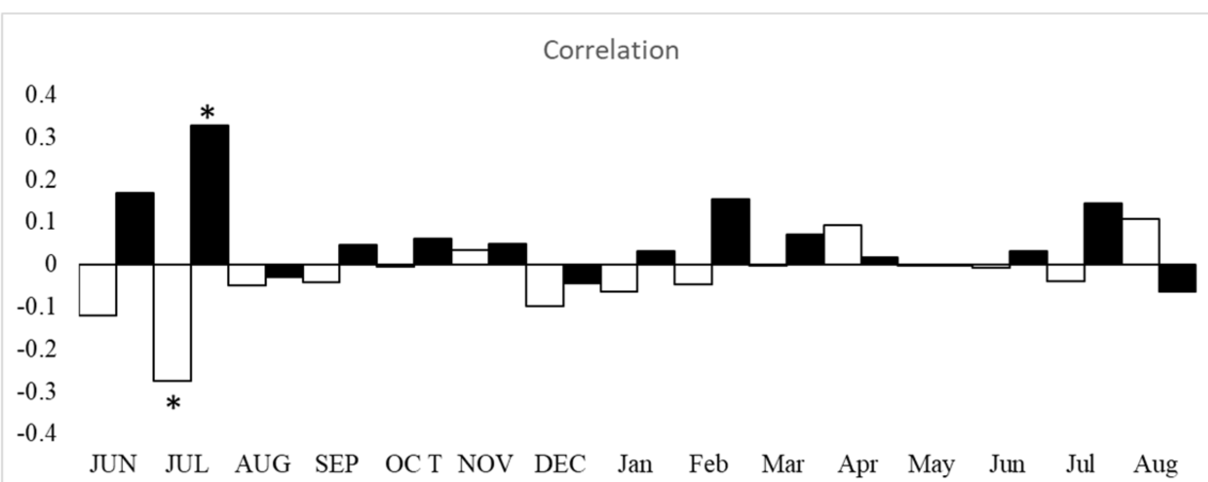
Chronology

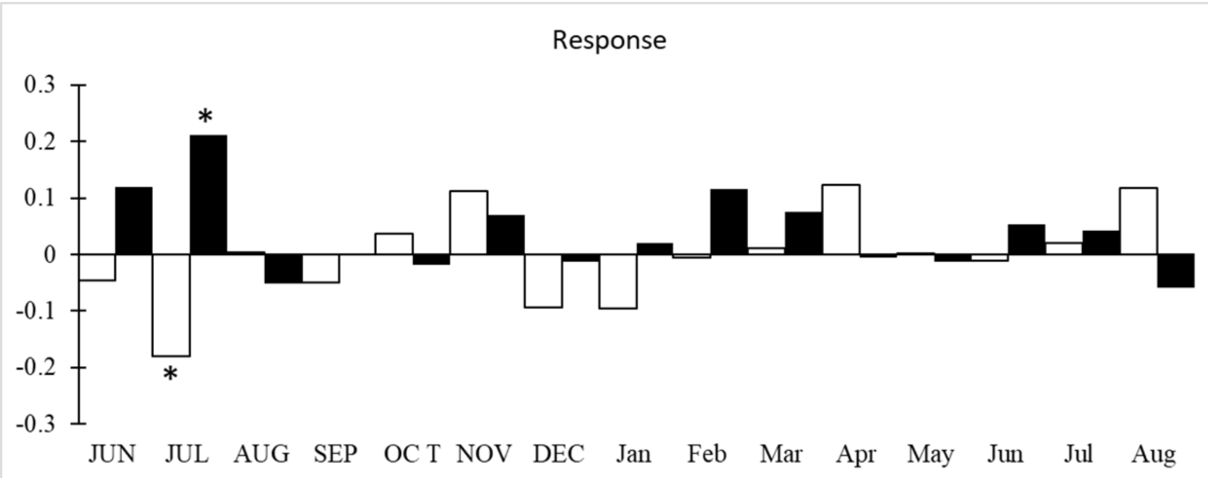
Whitebark pine are long-lived trees. The oldest known whitebark, 1270 years, was documented in the Salmon River portion of the Sawtooth National Forest, northeast of our study site (Perkins and Swetnam 1996). Cross-dating the whitebark at our site was challenging because the intercorrelation among and within individual trees was low. It was common for the ring widths from two cores of the same tree to have only correlation coefficients of 0.3-0.4. To supplement our initial sample of 20 whitebark pine chronology trees, we returned to the study site a second time to collect additional samples (20 trees). The final chronology was comprised of 38 samples from 26 trees (Table 1). The oldest sample dated to 1479. The threshold of an expressed population signal (EPS) above 0.85 was maintained to 1730. An EPS of above 0.85 is considered statistically acceptable for climate reconstruction (Wigley, Briffa, and Jones 1984). The inter-series correlation was 0.441. This is a relatively low correlation for tree-ring chronologies in general, but similar to those for other published whitebark pine chronologies (see Millar et al 2012 for example). The mean sensitivity was 0.191, which is considered appropriate for climate reconstruction (Speer 2010).

Table 1 – Whitebark chronology statistics	
Length of chronology (years)	538
# trees	26
# cores	38
Mean ring width (mm)	0.85
Interseries correlation	0.441
Mean sensitivity	0.191
1st order autocorrelation	0.76

Correlation and response function analyses with residuals from the chronology revealed that whitebark pine growth is negatively correlated with temperature in July and positively correlated with June and July precipitation of the preceding calendar year of growth (Figure 1A, 1B). This implies above average growth when the previous summer was cool and wet. Two other studies also found whitebark growth in the Sawtooth was inversely related to prior July temperature (Perkins and Swetnam 1996) and positively responsive to current July temperature Additionally, Perkins and Swetnam (1996) found a positive responsive to August temperature and to winter/spring precipitation, i.e. snowpack. In the Sierra Nevada, spring precipitation and temperature were positively correlated and summer precipitation negatively correlated with whitebark pine growth. Our site is at the southern edge of the Sawtooth National Forest. Spring temperature and snowfall may have less impact on growth at our site because temperatures here are higher and snowfall totals are less than in more northern sites and at higher elevations. The lagged growth responses found in our and other whitebark pine stands likely reflect a complex response to annual and longer-term climate patterns. Others have posited that prior year conditions affect the timing of bud development in that year with implications for carbohydrate accumulation and thus growth in subsequent years (Millar et al. 2012).

Figure 1A and 1B: Pearson correlation and response functions for Soldier Mountain whitebark pine. Months for the year prior to the growing season are in all capitals. Coefficients are significant at $p<0.05$ where indicated by an asterisk *.





Fire history

The fire record from 9 cross-sections in whitebark pine stands spans the period1496 to 1933 with 26 scars recording 19 fires (Figure 2). The mean fire return interval was 66 years and the median 51 years, with a minimum return interval of 5 years and maximum of 242 years (Table 2). The Weibull mean and median probability interval were 66 and 49 years, respectively. Most fires were recorded in a single tree suggesting fires were small and patchy. Fires in years 1795, 1829, 1834 and 1889 were also recorded in Douglas fir trees at lower elevation. Two fires, in 1795 and 1889, were widely recorded in the Douglas fir, with 1795 the most widely detected fire across forest types.

Figure 2: Sample fire history and composite fire history for whitebark pine in the Solider Mountains. Dates of fires indicated by black lines in each of 9 fire-scarred cross sections. Composite graph shows years of all fires combined.

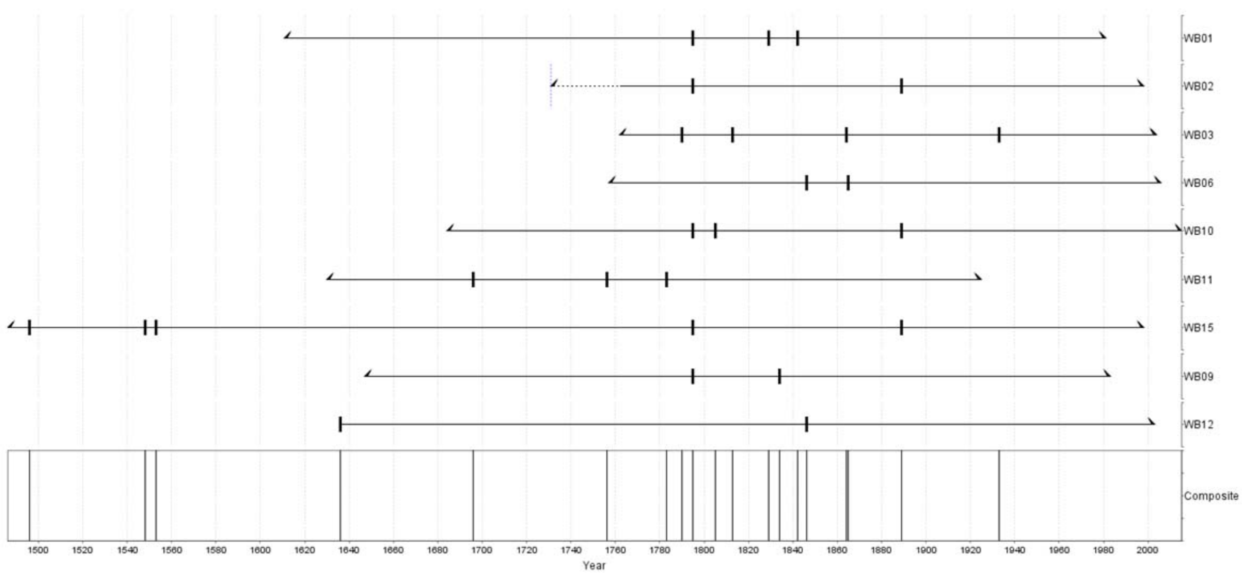


Table 2. Description of fire history data

No of trees	9
Time span	1486-2015
Earliest fire	1496
No of fires	19
No fires scarring single tree	14
Mean years between fires	66
Range of years between scars	5-242

While most fire scarred trees have long periods between fire scars, from several decades to more than a century, three trees have shorter intervals of 18, 10, and 5 years between two subsequent scars. This relatively short period between scars further suggests most fires were light and patchy carried by grassy fuels that could easily recover in a few years. The wide range of time between fires on individual trees may be because many fires were light and did not scar the trees. Only 1 fire was detected in one tree in 1933 in the years after the 1889 fire. Sheep grazing began in the 1890s and was unregulated for about 10 years. With the establishment of the Sawtooth Forest Reserve in 1903, sheep grazing was monitored. However, annual reports describe intensive grazing over the first part of the 20th century. The 1929 report states the tops of ridges are being overgrazed (Minear 1929). By 1936, the report cautions “practically all sheep ranges are overstocked,” with sheep grazing “the same ground many times (Minear 1936).

Stand structure

We dated the establishment decade of 140 live and 71 dead whitebark pine and 229 subalpine fir trees from 14 plots across the whitebark pine forest (Figure 3). The oldest living whitebark pine in the plots established in the late 1600s and early 1700s with most trees establishing in the late 1800s and early 1900s, generally earlier than the subalpine fir. In more open stands, both fir and pine continued to regenerate into the 20th century, compared to closed stands (Figure 4 and 5).

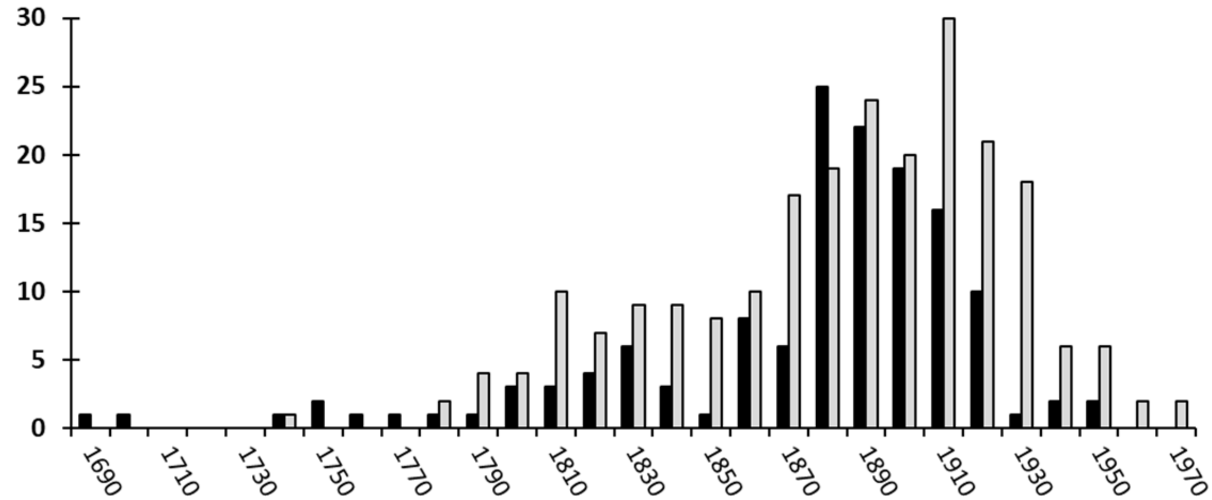


Figure 3. Decade of establishment of all whitebark pine in black bars and all fir in gray bars (n=369) on Solider Mountain, Idaho.

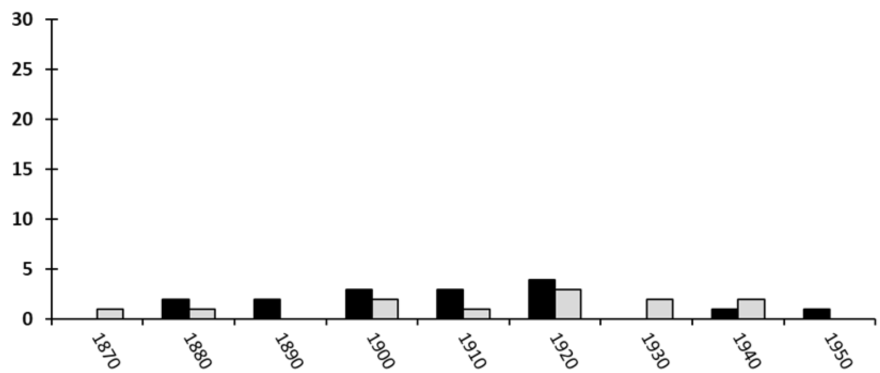


Figure 4. Establishment decade of whitebark pine (black bars) and subalpine fir (gray bars) in relatively open forest stand in the Solider Mountains Idaho.

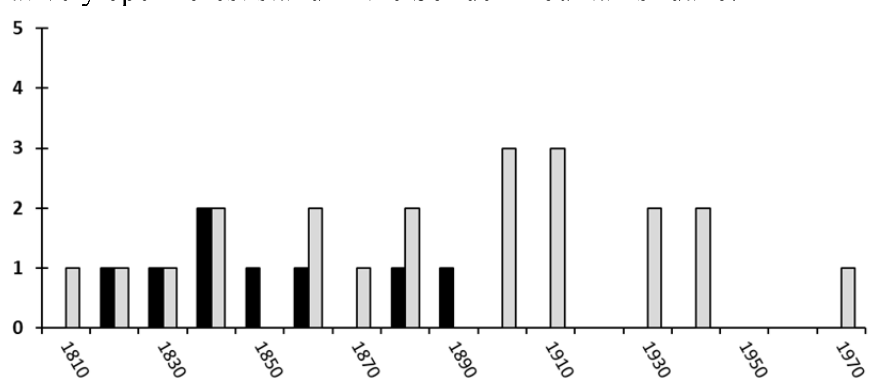


Figure 5. Establishment decade of whitebark pine (black bars) and subalpine fir (gray bars) in relatively closed forest stand in the Solider Mountains Idaho.

At the landscape scale, whitebark pine establishment peaks in the 1880s and 1890s and then declines precipitously with no new establishment by the 1920s. Some standing dead whitebark pine had established as early as the 15th and 16th century, although most dated from the peak of live tree establishment in the 1880s. Fir establishment increases in the late 1800s through the 1930s. The absence of more recently established trees could be the result of only coring trees greater than 10cm. However, young fir are more abundant than young whitebark. Seedling counts show fir regeneration currently exceeds pine in all plot by 8-fold and fir saplings exceed whitebark by 3-fold (data not shown).

We determined the year of death for 124 standing dead whitebark pine from 9 plots (Figure 6). Trees died as early as the 1910s and as recently as 2015. Whitebark pine death dates were concentrated in four decades. Most whitebark pine trees died in the 2000s (75%), with additional peaks in the 1990s (7%), 1970s (7%), and 1930s (4%) with all other decades representing 6%. We determined establishment dates for a subset of these trees (n=71). The trees dying in the 2000s were mixed in age. The oldest had established before the 1480s and the youngest in the early 1900s, with most trees (30%) establishing in the 1880s and 1890s (data not shown).

Figure 6. Death decade of standing dead whitebark (n=124) in Soldier Mountains, Idaho.

The early 2000s had five consecutive dry years, an event that had not occurred since the early 1900s. Every year in the 2000s decade also experienced above average temperatures. Drought stress is known to reduce tree production of secondary metabolites against beetle attack and may have weakened the trees' resistance to beetles and blister rust (Raffa and Berryman 1983).

Fire-Climate and Mortality-Climate Relationships

Superposed epoch analysis showed fires in whitebark occurred in years that were statistically ($p<0.05$) drier than average as measured by the Palmer Drought Severity Index (PDSI) (Figure 7). Years with widespread fires recorded in Douglas-fir and whitebark had PDSI values that were statistically ($p<0.001$) much drier than average and years were wet four years before widespread fire years (Figure 8).

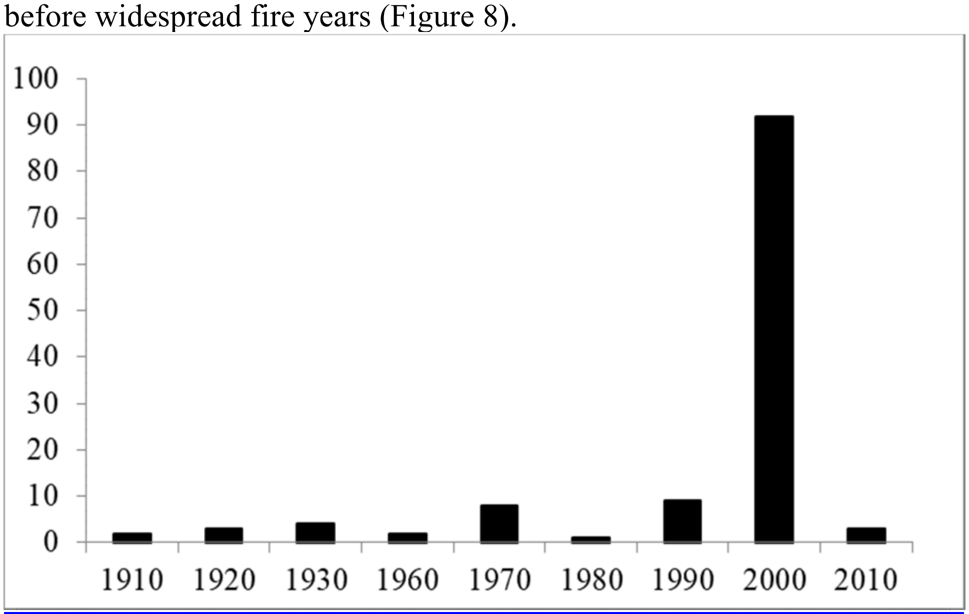


Figure 7. Superposed epoch analysis of all years (n=15) with fire scars in whitebark pine trees in Soldier Mountains, Idaho

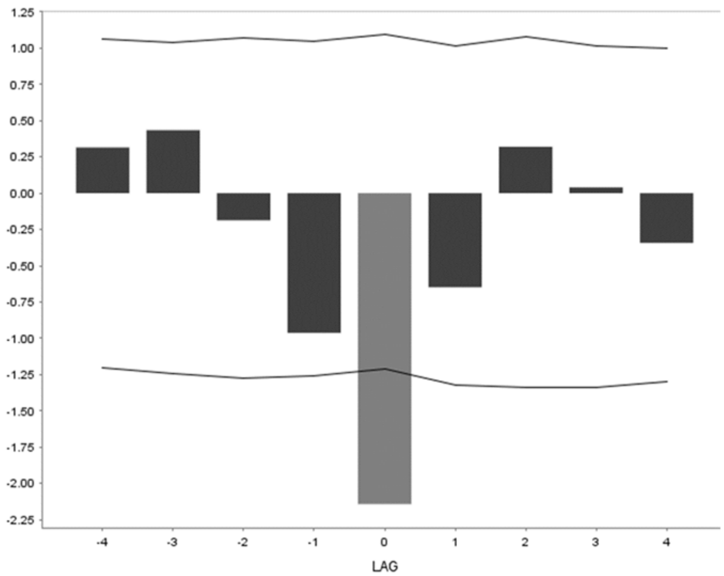
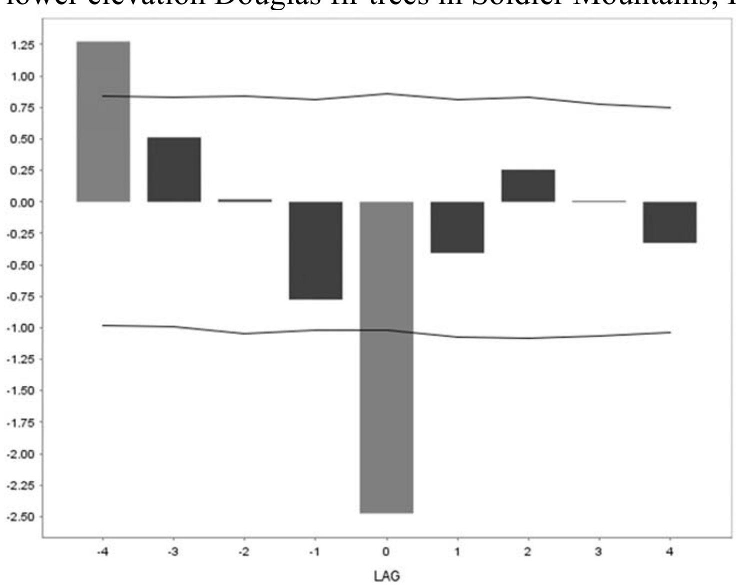


Figure 8. Superposed epoch analysis of years (n=4) with widespread fires in whitebark pine and lower elevation Douglas fir trees in Soldier Mountains, Idaho



We tested whether the relationship between our local whitebark pine tree-ring chronology and years with fires was similar to the PDSI relationship. SEA confirmed the year after fire events had a statistically narrower -width than other years ($p<0.05$). Since tree-ring width is negatively correlated with previous year July temperature and June and July precipitation, the SEA indicates fires were more likely in years with high summer temperatures and low precipitation.

Related work

Fire histories in whitebark pine have documented all three types of fire regimes, low, mixed, and high severity, with a majority of studies finding a mixed severity pattern with intervals from 60 to 300 years (Keane and Parsons, 2010). Our return interval was 66 years. Larson et al (2009) found similar fire patterns to ours in Montana such that most whitebark pine fires were small and patchy while some widespread fires did occur. Tree establishment patterns included a combination of both post-fire initiated stands and uneven age stands indicating mixed severity fires. They did not find a relationship between fire years and climate. However, they also found widespread fires in two of the same years, 1889 and 1834, as our study. Fires were documented across much of the western US in 1834 with smaller regional fires also documented in 1889 (Hessl et al. 2004; Heyerdahl et al. 2001).

Other studies in grassland-forest mosaics have also documented both within-vegetation-type fires and less frequent widespread fires burning during very dry years across vegetation types and elevations (Harvey et al. 2017). However, some studies find little evidence of fire spread between lower and upper elevation forests despite apparent fuel connectivity (Murray et al. 1998).

Throughout the western US and across the globe in the 2000s decade, tree deaths occurred at an increased rate due to warmer growing seasons sometimes combined with ensuing insect outbreaks in what scientists describe as climate-related mortality. Trees stressed by warmer temperatures combined with below average precipitation are less resistant to pathogens (Wong and Daniels 2017). In some sites, the stress may have multiple and interacting causes and begin years to decades before elevated tree mortality begins. In the Canadian Rockies, whitebark pine showed stress in the form of reduced growth decades before widespread die-off from beetle and blister rust (Wong and Daniels 2017). Because of the potential for more frequent severe droughts and warmer temperatures, efforts to maximize whitebark pine forest health and resilience need high priority.

Science delivery activities

See Appendix B

Conclusions / Key Findings

Fire scarred whitebark pine trees reveal a pattern of small fires with less frequent widespread fires, where small fires are recorded in the whitebark pine but not in the lower elevation Douglas fir, and widespread fires are recorded across high and low elevation forests. In the whitebark, the sample mean fire return interval was 66 years and the median 51 years, with a minimum return interval of 5 years and maximum return interval of 242 years. The Weibull mean and median return intervals were 66 and 49 years, respectively. Superposed epoch analysis showed fires in whitebark occurred in years that were statistically ($p<0.05$) drier than average as measured by the Palmer Drought Severity Index (PDSI).

Widespread fires, or fires recorded in both high and low elevation forests, burn under similar climatic conditions. Superposed epoch analysis shows years with fire scars in both ridgetop whitebark pine tree cross-sections and lower elevation Douglas fir were exceptionally dry and were preceded by wet years. During these very dry conditions fires burned fuels generated in the wet years and fires burned across forest types in the forest – sagebrush- grassland landscape.

Drought acts as a connective process promoting fire spread from low to high elevations particularly when preceded by wet years that increase fuels.

The most recent widespread fire occurred in 1889. One small fire occurred after 1889, in 1933. The lack of widespread fires since 1889 is likely a result of fire suppression efforts that began in the early 1900s. The near absence of smaller fires within the whitebark pine forest may be a result of sheep grazing which began in the late 1800s and has continued to the present. Grazing reduces fine or grassy fuels that could carry fires within whitebark pine stands. Annual grazing reports for the area describe overgrazing beginning in the 1920s.

Across the landscape, whitebark pine regeneration has slowed since the early 1900s with few trees establishing after fire suppression began. In contrast, subalpine fir establishment increased during the early 1900s. The oldest whitebark pines established in the late 1600s and early 1700s with most establishing in the late 1800s and early 1900s, generally earlier than the subalpine fir. In more open stands, both fir and pine continued to regenerate through the 20th century, compared to closed stands. Seedling and sapling counts show fir regeneration currently exceeds pine in all plots by 8-fold and 3-fold, respectively.

Whitebark pine and subalpine fir showed an increase in establishment coinciding with the decades following the most recent widespread fire. However, trees that established before the fire survived, indicating fire effects were not severe. The decrease in regeneration of whitebark pine after the 1920s suggests the 127-year absence of widespread fire disturbance has contributed to reduced whitebark regeneration. The smaller fires also may have served to maintain open mixed age stands that are conducive to pine regeneration. Since fire suppression, subalpine fir has continued to regenerate and has surpassed whitebark pine regeneration.

A site whitebark pine tree-ring chronology was developed to examine local climate growth responses and climate fire patterns. Correlation and response function analyses revealed whitebark pine growth is negatively correlated with temperature in July and positively correlated with July precipitation in the preceding calendar year. This implies above average growth when the previous summer was cool and precipitation above average.

Cores from standing dead whitebark show mortality occurs during years that are statistically ($p<0.05$) drier than average. We found standing dead trees that died as early as the 1910s and as recently as 2015. Whitebark pine death dates were concentrated in four decades. Most whitebark pine trees died in the 2000s (75%), with additional peaks in the 1990s (7%), 1970s (7%), and 1930s (4%) with all other decades representing 6%. The early 2000s had five consecutive dry years, an event that had not occurred since the early 1900s. Every year in the 2000s also experienced above average temperatures. Drought combined with high temperatures occurred throughout the western US in the 2000s and represent a novel stress on forests with potentially long-term consequences. The prolonged water deficit likely weakened the trees' resistance to insect and pathogen attacks. Beetle galleries were present in all dead trees and were probably an ultimate cause of most tree deaths.

Management Implications

Managers face multiple challenges when trying to restore and maintain imperiled whitebark pine stands in the face of blister rust, beetle attack, fir competition, fire suppression, and climate change. Deciding whether to employ prescribed fire, thin competing tree species, or plant blister rust resistant seedlings must often be made with little or no site specific historical information. Our goal was to understand how natural processes connect whitebark with the lower elevation forest-sagebrush grassland mosaic to inform planning for landscape scale management. Our findings of small, local fires every 66 years and widespread fires in dry years and slowed whitebark regeneration since the last widespread fire in 1889 support a multi-pronged approach, including removing competing subalpine fir, conducting burns to encourage whitebark regeneration, and planting resistant seedlings. Managers are likely aware that grassy fuels have been reduced by over a century of livestock grazing, and this may limit the local spread of natural lightning started fires further necessitating prescribed fires or actions that mimic fire disturbance. The whitebark chronology shows trees at this site are particularly stressed in the growing season after a dry year. Potentially stressful management activities may be less detrimental to the whitebark if conducted following wetter, cooler years. Finally, the mortality of century or more old whitebark during dry years in the 2000s was high. If current climate trends continue with more warmer, drier years, the likelihood of mortality and increased potential for landscape scale fires during extreme weather adds urgency to efforts to promote whitebark resilience and regeneration.

Future Research

Future research will be needed to answer important questions about whitebark ecology and about strategies for effective management of landscapes with mixed severity fire regimes. Research at our site or others facing similar challenges with whitebark could include determining if the existing whitebark population is viable. Is the density of cone producing trees sufficient to maintain the population? In the locations where seedlings are currently abundant, are these seedlings continuing to mature and are these locations protected from fire? What portion of the population is resistant to blister rust? What are the optimal locations and conditions in which to plant blister rust resistant seedlings? Are the mature trees showing signs of chronic stress in the form of reduced growth? Does thinning competing species effectively help reduce whitebark mortality during drought periods? To improve understanding of mixed severity fire regimes, are there fire refugia or places that did not burn on the landscape and places that burned severely or consistent fire hotspots? How can these patterns effectively be reestablished with prescribed fires? How does whitebark pine respond to mixed severity fire including immediate and long-term responses to low, moderate, and high severity fire effects?

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Appendix A: Contact Information for Key Project Personnel

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Completed

Newsletter Contribution- Airey Lauvaux, C. (2016), Understanding the influence of fire and climate on whitebark pine, Nutcracker Notes, Journal of the Whitebark Pine Ecosystem Foundation. Fall, Issue 31.

Poster, Alex Marden , Subalpine fir invasion of whitebark pine stands in Idaho's Soldier Mountains, American Association for Geographers , Chicago, IL April 22, 2015

Presentation Catherine Airey Lauvaux, Salt Bowns Fire History and Vegetation Change, Sawtooth National Forest Fairfield Ranger District, August 5, 2015

Presentation Catherine Airey Lauvaux , Fire and drought across a northern Rocky Mountain Forest Intl Assocation for Landscape Ecology, Asheville NC, April 5, 2016 –

Planned

Presentation- Catherine Airey Lauvaux From the river to the ridgetops, fire history and vegetation change in a Rocky Mountain landscape , Association for Fire Ecology Conference Nov 29, 2017

Presentation- Catherine Airey Lauvaux , Salt Bowns Fire History and Vegetation Change, Sawtooth National Forest TBD Spring 2018

Dissertation- Towards understanding trajectories of landscape change: An investigation of the responses of a Rocky Mountain forest-sagebrush-grassland landscape to fire suppression, livestock grazing and climate change, Catherine Airey Lauvaux , Spring 2018

Article- History of mixed severity fire in a sagebrush forest grassland landscape

Article- Drought triggered whitebark mortality

Article-Forest expansion into sagebrush grassland in the norther Rocky Mountains

Appendix C: Metadata

Attached spreadsheets