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## Topography affected landscape fire history patterns in southern Arizona, USA

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## ABSTRACT

Fire histories contribute important information to contemporary fire planning, however, our knowledge is not comprehensive geographically. We evaluated the influence of topography on fire history patterns in two contrasting landscapes within the Santa Catalina Mountains of southeastern Arizona. Multiple fire-scarred trees from randomly selected 2-ha plots were used to develop plot composite mean fire intervals (PCMFIs) within the Butterfly Peak (BP) and Rose Canyon (RC) landscapes. BP is dominated by steep, northerly aspects and presence of potential fire spread barriers (exposed rock bluffs and scree slopes). RC is dominated by more gentle and southerly aspects with relatively few fire barriers. Within each landscape, PCMFIs did not differ significantly between aspect classes from A.D. 1748 to 1910 (BP:  $p = 0.73$  and RC:  $p = 0.57$ ). Pooled PCMFIs in the gentler RC landscape were, however, significantly shorter ( $p < 0.001$ ) than in the steeper BP landscape. The frequency of relatively widespread fires (i.e., number of fire years when  $\geq 2$  plots scarred) was similar between landscapes, but fires in the gentler RC landscape were significantly larger ( $p = 0.033$ ). The higher frequency of large fires (i.e., fires that burned  $>75\%$  of the landscape) in RC resulted in more area burned over time and shorter fire intervals at individual plots. Conversely, smaller fires in the dissected BP landscape resulted in less area burned and longer periods between fires at individual plots. The different topographies in the two landscapes likely result in different wind intensities, fuel moistures, and fuel/vegetation types—and consequently, different historical fire spread patterns. Our conclusion is that fire history patterns are not influenced primarily by stand-scale topography, but rather by the topographic characteristics of the broader, surrounding landscape.

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## 1. Introduction

Widespread and relatively frequent surface fires burned in forests of the western United States prior to Euro-American settlement (Agee, 1993; Swetnam, 1993). Understanding the spatial and temporal patterns of these historical fires is important for ecological, cultural, and managerial applications. The impacts of fire exclusion, including dead fuel accumulation and increased stand density, have resulted in larger and more severe wildfires (Covington et al., 1997; Allen et al., 2002). Recent warming temperatures and earlier springs may also have contributed to larger forest fires ( $>400$ -ha) in the western US, although there are important ecological, elevational and land use history-related differences in fire and climate trends at finer spatial scales (Westerling et al., 2006).

Regional analyses involving broad networks of fire-scar chronologies in the Southwest (e.g., Swetnam and Baisan, 1996; Swetnam et al., 2001), and western U.S. (Kitzberger et al., 2001, 2007) have produced multiple insights about long-term climate and land use controls on fire regimes. There have, however, been relatively few “spatially explicit” fire history investigations at landscape scales (i.e., mountain range to watersheds) in the Southwest (see Fulé et al., 2003; van Horne and Fulé, 2006; Falk and Swetnam, 2003, Farris, personal communication). By “spatially explicit” we mean intensively studied landscapes where fire-scarred trees were systematically and/or randomly sampled in fine-scale grids and networks. Such sampling designs enable spatial estimates of the extent of individual fires within a study area, and provide a more robust data set for statistical assessment of fire interval distributions and tests for differences in measures of central tendency (e.g., Heyerdahl et al., 2001; Taylor and Skinner, 2003; Hessler et al., 2007).

The goal of our study was to determine how fire history measures were influenced by stand ( $0.1$ – $1$  km<sup>2</sup>) and landscape ( $1$ – $10$  km<sup>2</sup>) scale topography. Such knowledge would inform the

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theories concerning the scale-dependent behavior of fire (Falk and Swetnam, 2003). We hypothesized that if fire frequencies were influenced by stand-scale topography, and assuming plots are representative of stands, then we would expect Plot Composite Mean Fire Intervals (PCMFI) to differ among different aspect classes. We therefore compared PCMFI among topographic aspect classes within two landscapes. If, however, fire history patterns were related to landscape-scale topography, then we would expect fire history measures to differ between landscapes with different topographies. We therefore compared PCMFI, fire frequency and fire extent between a dissected, mostly north-facing landscape, and a gentler mostly south-facing landscape.

### 1.1. Spatial fire history patterns

Fire regimes are controlled by different factors depending on the spatial scale of inference. In the Southwest, fire regimes are influenced at regional scales by inter-annual to multi-decadal climate factors (Swetnam and Betancourt, 1998; Grissino-Mayer and Swetnam, 2000), although humans have been important in some locations and time periods (Kaib, 1998; Kaye and Swetnam, 1999; Allen, 2002). Synchronous fires occur for example in numerous mountain ranges across the Southwest during drought years. Such regional drought/fire years often corresponded with La Niña events that reduced winter precipitation (Swetnam and Betancourt, 1990) and typically followed wet 'El Niño' years (Baisan and Swetnam, 1990; Westerling et al., 2003; Crimmins and Comrie, 2004). Periods of reduced fire frequencies occurred during some decades (e.g., early 1800s) and in some areas (e.g., Stephens et al., 2003; Brown and Wu, 2005), due possibly to reduced El Niño and La Niña amplitudes (Swetnam and Betancourt, 1998; Kitzberger et al., 2001).

Relationships between climate and regional fire activity have been studied widely, but little is known about fire history spatial patterns at stand and landscape scales (Taylor and Skinner, 2003; Heyerdahl et al., 2001). At stand scales (0.1–1 km<sup>2</sup>) topographic factors such as elevation, slope, and aspect affect fuel moisture, thus flammability (Schroeder and Buck, 1970; Rothermel, 1983). Fuels at higher elevations are usually less flammable than fuels at lower elevation because of temperature and relative humidity differences. In addition fuel moistures at higher elevations are also influenced by the timing of snowmelt. Similarly, fuels are less flammable on north than on south-facing aspects in the northern hemisphere. Fire spread is influenced also by slope because flames pre-heat up-slope fuels thus accelerate fire spread (Rothermel, 1983). In terms of fire history, surface-fire frequencies in eastern Oregon and Washington, for example, varied with stand aspect and elevation, but only in landscapes with steep topography (Heyerdahl et al., 2001). Fire interval differences in California and southern Oregon were associated also with stand aspect differences (Taylor and Skinner, 1998; Taylor, 2000; Caprio and Graber, 2000; Beaty and Taylor, 2001, 2008; Taylor and Skinner, 2003), with south-facing slopes generally having higher fire frequencies. In some semi-arid landscapes, aspect can also influence vegetative (fuel) productivity, thereby affecting fire ignition and spread in a negative manner. In the Gila Wilderness in southwestern New Mexico, for example, 20th century fire atlas records showed fires were more frequent than expected on northwest aspects and less frequent than expected on southwest aspects, due possibly to productivity differences (Rollins et al., 2002). In California's Sierra Nevada, pre-settlement surface fires were more frequent at relatively low than at high elevations possibly because of drier conditions and quicker recovery of fine (grasses) fuels at lower elevations (Caprio and Swetnam, 1995).

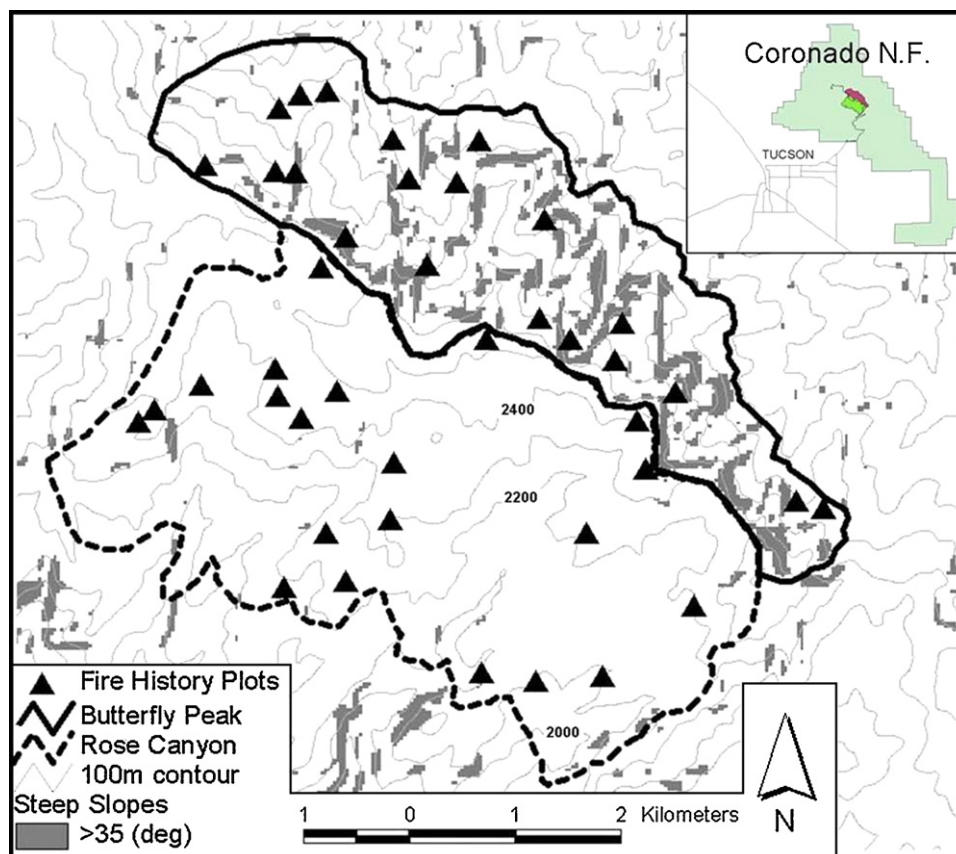
At landscape scales (1–10 km<sup>2</sup>) it is likely that fire regimes were influenced by topography and vegetative (i.e., fuels) patterns (Agee, 1993; Turner et al., 2001). Fire history studies have investigated these factors (e.g., Romme, 1982; Heyerdahl et al., 2001; Taylor and Skinner, 2003), but relatively little work has been done on this topic in the Southwest (Allen, 1989; Barton et al., 2001; Brown et al., 2001; Fulé et al., 2003). Landscapes are heterogeneous areas composed of multiple stands and flammability varies from stand to stand across the landscape. As a result, landscape fire spread is usually restricted to interconnected flammable stands, meaning fires do not usually spread to areas isolated by non-flammable fuels, i.e., "fire barriers" (Turner and Romme, 1994; Taylor, 2000). Hence, within a landscape, fire spread and extent are a function of the proportion and arrangement of flammable fuel (Turner et al., 1989). In surface fire regimes for example, areas with similar fire histories have been bounded with fire barriers such as riparian areas (Taylor and Skinner, 2003). Similarly, mean fire intervals in the southern Cascades differed among areas (100–400-ha) dominated by different aspects (Beaty and Taylor, 2001). In the Southwest, however, it is still unclear how and why fire frequencies varied within and between landscapes.

Previous fire history studies in the "Sky Island" mountain ranges of the U.S.–Mexico borderlands showed that fire frequency patterns were influenced by fire barriers within watersheds (e.g., Barton et al., 2001) and at mountain range-scales (e.g., Swetnam et al., 2001). Prior to the current study, however, systematically sampled and spatially explicit fire history reconstructions in this region have not been used to evaluate how and why fire frequencies varied within and between contrasting landscapes.

### 1.2. Study area

We selected a 2900-ha study area within the Santa Catalina Mountains in the Coronado National Forest in southeastern Arizona (Fig. 1). The Santa Catalina Mountains are part of the Madrean Archipelago, coniferous forest "Sky Islands" separated by low-elevation desert "seas" that are a northern extension of the Sierra Madre Occidental of northwestern Mexico (Warshall, 1995). The Madrean archipelago is located at the junction of four major biomes: the Sonoran and Chihuahuan deserts, and the Sierra Madre and Rocky Mountains (McLaughlin, 1995). The region has a bimodal precipitation pattern: In winter, high elevations (>1500 m) typically receive snow that falls as rain at lower elevations. In summer, tropical moisture promotes monsoonal weather producing localized thunderstorms. The average annual precipitation at the Palisades ranger station (2425 m elevation) within the study area was 80 cm between 1965 and 1981 ([www.wrcc.dri.edu/summary/climsmaz.html](http://www.wrcc.dri.edu/summary/climsmaz.html)).

The high vertical relief and unique geographic position of the Santa Catalina Mountains produce a diverse mosaic of plant communities that follow elevation/moisture gradients (Lowe, 1961; Whittaker and Niering, 1968; Niering and Lowe, 1984). Plant communities at higher elevations are related closely to the Cordilleran/Rocky Mountain floristic province (McLaughlin, 1995). Higher elevation/mesic communities are dominated by mixed-conifer species, including: ponderosa pine (*Pinus ponderosa* var. *scopulorum*, var. *arizonica*), Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), white fir (*Abies concolor*), southwestern white pine (*P. strobiformis*), Gambel oak (*Quercus gambelii*), quaking aspen (*Populus tremuloides*), and Rocky Mountain maple (*Acer glabrum*). Lower elevation/xeric communities are strongly influenced by Madrean floristics and are dominated mainly by: ponderosa pine, Chihuahuan pine (*P. leiophylla*), pinyon pine (*P. discolor*), and juniper (*Juniperus* spp.). The two main Madrean oaks are silverleaf oak



**Fig. 1.** Map of the Santa Catalina Mountain study area separated into Butterfly Peak (1200-ha) and Rose Canyon (1800-ha) landscapes. Fire history plot locations were selected randomly using an aspect-stratified sampling framework. Areas with steep slopes are shown because they are typically un-vegetated (rock-outcrops, talus slopes) and may have influenced fire spread patterns.

(*Quercus hypoleucoides*) and Arizona white oak (*Q. arizonica*). Common and scientific names follow [Epple \(1997\)](#).

Human land-use history of the Santa Catalina Mountains extends back to indigenous, desert dwelling people who visited these mountains to hunt and gather seasonal plants ([Hensel, 2005](#)). Apaches used this mountain range in the 1800s (and perhaps earlier) for cover as part of their nomadic raiding and warfare activities. Once the Apaches were completely removed in 1886, following Geronimo's surrender, Euro-Americans began mining and livestock operations ([Bahre, 1985](#); [Hensel, 2005](#)). Limited timber harvesting occurred as early as 1873, but affected a relatively small area. In 1908, the Santa Catalina Mountains became part of the National Forest system ([Hensel, 2005](#)).

Euro-American fire suppression efforts began at the turn of the 20th century with limited success due to a lack of roads and fire fighting equipment ([Holsinger, 1901](#); [Swetnam and Baisan, 2003](#)). A combination of livestock grazing, roads, and better organization promoted fire exclusion through the 20th century leading to increasing fuel loads and connectivity ([Swetnam and Baisan, 2003](#)). In the drought years of 2002 and 2003 the Bullock Fire (12,370-ha) and the Aspen Fire (34,400-ha) respectively, burned over most of the coniferous forests in the mountain and destroyed over 300 homes and businesses.

## 2. Methods

We compared landscape fire history patterns by selecting a study area that encompassed two topographically distinct landscapes separated by a major ridge. The landscape north of the main ridge (Butterfly Peak, BP) covered 1200-ha while the adjacent landscape

south of the ridge (Rose Canyon, RC) covered 1800-ha ([Fig. 1](#)). The lower elevation boundary of each landscape traced the lower border of pine-dominated forests. Lateral boundaries followed major ridges that separated landscapes with distinct topography. We mapped boundaries using a combination of 30 m digital elevation models (DEM), 1:24,000 topographic maps, digital orthophoto quarter quadrants and field reconnaissance. We compared the two landscapes topographically using elevation, slope and aspect distributions taken from a 30 m DEM. We aggregated elevation frequencies using 100-m bins and aggregated aspect and slope frequencies using 30° and 5° bins, respectively. These bin intervals were chosen because they appeared to best represent the topographic composition and structure in each landscape.

### 2.1. Fire history methods

We selected the location of fire history plots using an aspect-stratified random sampling design. First, we divided the study area into two landscapes, based on topography, as mentioned previously. Second, within each landscape we delineated eight geographic strata of roughly equal size, to guarantee complete spatial coverage. Third, we stratified each landscape into three aspect classes: North (300–360° and 0–60°), South-southeast (60–180°) and South-southwest (180–300°). We then selected three plots at random (one plot per aspect classes) within each of the eight geographic strata, for a total of 24 plots per landscape (48 plots total). In the field we characterized the vegetation by identifying and measuring all trees  $\geq 10$  cm diameter at breast height (1.4 m) within a 0.1-ha circular plot. In addition 4–6 of the largest trees were cored as close to the ground as possible.

The purpose of the fire-scar sampling was to obtain as complete and as long an inventory of fire events as possible within each plot (Swetnam and Baisan, 1996). Because no single tree is a perfect recorder of past fires, obtaining a complete fire record required sampling multiple trees (Dieterich and Swetnam, 1984). We located all fire-scarred trees (including live trees, downed logs and snags) within each 2-ha plot and sampled those with the maximum number of well-preserved, visible scars. We sampled a minimum of 4 and a maximum of 9 fire-scarred trees per 2-ha plot using chain saws; cutting full or partial cross-sections from the lower bole (Arno and Sneek, 1977). We sanded fire-scarred cross-section to a high polish using progressively finer sand papers, then crossdated samples using dendrochronological techniques to determine the calendar year of each fire-scar (Stokes and Smiley, 1968, Dieterich and Swetnam, 1984).

The fire-scar dates from all sampled trees within each plot were composited (Dieterich, 1980) for an estimate of plot fire frequencies, and no spatial inferences below the plot size (i.e., 2-ha) were made. This approach assumes a uniform fire history within each 2-ha plot (i.e., a fire recorded by any tree probably affected the entire 2-ha area). A plot was therefore “recording” when at least one sampled tree within that plot was living and had been scarred previously (i.e., a “fire-scar susceptible tree”, sensu Romme, 1980). Sampled tree portions were considered “not recording” if decay or subsequent fires made it impossible to date the fire-scar year. We analyzed sample depth (i.e., the number of plots “recording” each year) visually to identify a period of analysis that provided an adequate representation of temporal and spatial patterns.

2.2. Fire history analysis

We declared a fire year within a given plot when one or more trees within the plot recorded a fire. For each plot we calculated the plot composite mean fire interval (PCMFI) along with the median, range, standard deviation, and number of fire intervals. Each plot was assigned to one of three aspect classes (North = 300–360° and 0–60°, South-southeast = 60–180° and South-southwest = 180–300°) and we then tested for statistical differences in PCMFI among three aspect classes within each landscape using the non-parametric Kruskal–Wallis test. We tested also for potential differences between landscapes by pooling all the plots within each landscape and then comparing the distributions of PCMFIs between the two landscapes using the non-parametric Wilcoxon rank sum test (Ott, 1993). The null hypothesis was that PCMFIs did not differ significantly among the comparisons. We rejected the null hypothesis when probability levels (*p*-values) for the individual tests were less than 0.05.

Fire history differences between landscapes were also examined using landscape-based fire history measures, i.e., frequency of relatively widespread fires and fire extent (Agee, 1993). To examine fire frequency changes over time within and between landscapes, we calculated the number of widespread fires in 20-year moving windows (Swetnam and Betancourt, 1998). Widespread fire years were defined by two or more plots recording a fire during the same year within the study area. Sample depth differences between RC and BP were addressed using the SSIZ program. SSIZ is a re-sampling (bootstrap) program used to estimate confidence intervals of mean fire frequencies at different sample sizes (Holmes, 1995; Swetnam and Baisan, 2003; Stephens et al., 2003). Relative area burned for each widespread fire year was estimated based on the proportion of recording plots scarred. This measure is similar to the area burned index used by Taylor and

Skinner (2003) in their landscape/fire analyses and provides estimates similar to other area burned indices (Heyerdahl et al., 2001; Iniguez, 2006; Hessler et al., 2007). Fire size differences between landscapes were compared using chi-square goodness-of-fit test.

3. Results

3.1. Landscape topography comparison

The two landscapes occupied similar elevations, but differed in slope and aspect distributions (Fig. 2): The elevation range in BP (1840–2570 m) was slightly greater than RC (1960–2570 m), however, the majority of the land area (>80%) in both landscapes was between 2000 and 2500 m (Fig. 2a). RC was dominated by gradual slopes (<20°), while BP was dominated by steep slopes (>25°) (Figs. 1 and 2b). In addition, 68% of BP was dominated by north to northeast-facing aspects whereas the majority of the land area in RC faced south-southeast (Fig. 2c).

3.2. Period of analysis

We began field sampling in the summer of 2002, but the Bullock Fire in 2002 and Aspen Fire in 2003 burned in BP and RC respectively, affecting the quality and quantity of fire-scarred

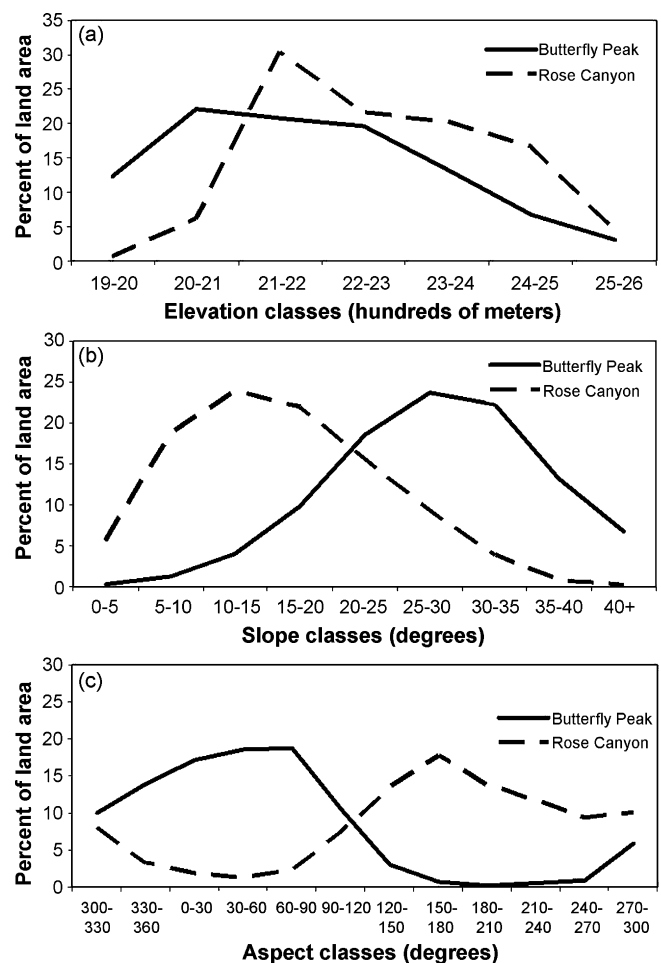


Fig. 2. Topographic comparison between the Butterfly Peak and Rose Canyon Landscapes in the Santa Catalina Mountains. The two landscapes occur at similar elevations (a), but differed in slope (b) and aspect (c) distributions.

material available for sampling. These wildfires consumed many logs and snags that contained old fire-scar records. Despite this loss of the record, we were able to salvage enough fire-scarred samples in 20 of the 24 plots in BP and 21 of 24 plots in RC. The distribution of sample plots was similar to the land area distribution across aspect classes in both landscapes, indicating the fire-scar sampling was a fair representation of the aspect distribution in each landscape (Iniguez, 2006).

A total of 115 fire years were recorded by at least one plot within the study area between A.D. 1618 and 2003. The year 1748 marked the earliest year when at least 30% of all plots were recording and 1910 marked the last widespread fire before fire suppression. On this basis we deemed 1748–1910 the most reliable period for analysis. This period was selected based on a compromise between the need to have an adequate sample depth, and our desire to focus on a fire regime unaltered by fire suppression.

### 3.3. Fire history results

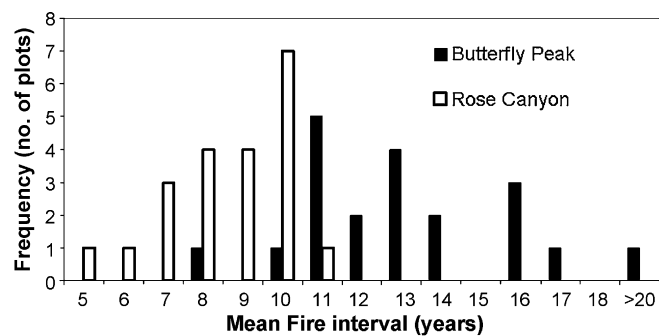
Plot composite mean fire intervals did not vary among different aspects within landscapes, but did vary between landscapes (Table 1). Although north-facing stands are typically mesic and contain less flammable fuel (due to higher moisture content), in RC north aspects experienced fire more frequently on average than other aspect classes, however these differences were not significant (Table 1,  $p = 0.57$ ). Within the dissected BP landscape, PCMFIs were shorter on average in south–southwest (SSW) aspects compared to northern aspects; however, these differences were also not significant (Table 1,  $p = 0.73$ ). Pooled PCMFIs were significantly shorter in the gentler south-tending RC landscape than in the mostly north-tending BP landscape (Table 1;  $p < 0.001$ ). In RC, all but one plot had a PCMFI less than ten years. In BP all but two plots had PCMFIs more than ten years long, and five plots had PCMFIs of 15 years or greater (Fig. 3).

**Table 1**

Aspect and landscape fire interval comparison in the Santa Catalina Mountains in southeastern Arizona. Plot composite mean fire intervals (PCMFIs) were compared (1748–1910) among aspect classes within each landscape. Landscape comparison between the Rose Canyon and Butterfly Peak landscapes were based on pooled PCMFIs from each landscape. Plot fire intervals were based on a composite of multiple fire-scarred trees (i.e., 4–9 trees) collected within 2-ha plots

	# of plots	Plot fire interval statistics					
		Mean	Median	Minimum	Maximum	S.D.	Skewness
<b>Butterfly Peak</b>							
North	9	14.8 <sup>a</sup>	13.3	11	29	5.6	2.3
SSE	7	13.9 <sup>a</sup>	14.8	12	16	1.5	0.2
SSW	4	12.7 <sup>a</sup>	12.1	9	18	3.8	0.8
All	20	14.1 <sup>1</sup>	13.4	9	29	4.1	2.4
<b>Rose Canyon</b>							
North	6	9.0 <sup>a</sup>	9.0	7	10	1.4	-0.4
SSE	8	9.8 <sup>a</sup>	9.8	8	12	1.5	0.2
SSW	7	9.5 <sup>a</sup>	9.5	6	11	1.8	-1.6
All	21	9.5 <sup>2</sup>	9.5	6	12	1.5	-0.6

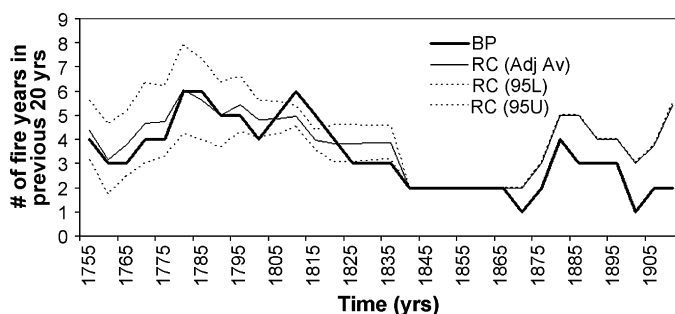
North (300–360° and 0–60°), SSW = South–southwest (60–180°) and SSE = South–southeast (180–300°). Superscripts with similar letter within each landscape represent no significant different among aspect classes based on PCMFI distribution (Kruskal–Wallis Test  $p = 0.57$  and  $0.73$  in RC and BP respectively). Aspect PCMFI differences were only tested within each landscape separately. Superscripts with different numbers represent significantly different pooled PCMFI distributions between landscapes (i.e., Rose Canyon and Butterfly Peak) (Wilcoxon rank sum test  $p < 0.001$ ).



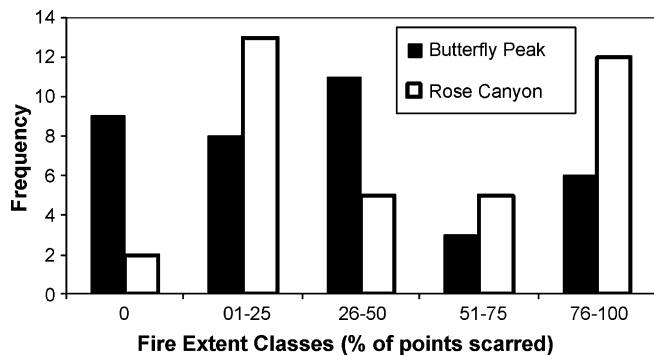
**Fig. 3.** Plot composite mean fire intervals (PCMFIs) distributions for the Butterfly Peak ( $n = 20$ ) and Rose Canyon ( $n = 21$ ) landscapes in the Santa Catalina Mountains in southeastern Arizona (A.D. 1748–1910). PCMFI distributions were significantly different between the two landscapes (Wilcoxon rank sum test  $p < 0.001$ ).

After correcting for sample size using SSIZ it appears that the number of widespread fire years per 20-year period was similar among landscapes (Fig. 4). Between A.D. 1748 and 1910 there were 37 widespread fire years within the entire study area. The gentler RC landscape sustained 35 of these widespread events and the dissected BP landscape recorded 28, leading to an average of one widespread fire every 4.6 and 5.8 years in RC and BP, respectively. The frequency of widespread fires was not constant through time: Between 1748 and 1810, both landscapes experienced 3–6 widespread fire years per 20-year period (Fig. 4). After 1810 the frequencies of widespread fire continued to be similar between landscapes, but the number of fires declined to 2 widespread fire years per 20-years. Fire frequency in both landscapes increased after 1870, but the gentler RC landscape supported 1–2 more widespread fire years per 20-year period than the dissected BP landscape (Fig. 4).

The frequency of widespread fires did not vary between landscapes, but fire extent did: Fires tended to be more extensive overall in the gentler south-tending RC compared to dissected north-tending BP landscape ( $p < 0.033$ , Fig. 5). For example, very extensive fires (i.e., fire events that scarred >75% of the recording plots) constituted 32% of the widespread fires in the gentler RC landscape compared to only 16% in the dissected BP landscape. By contrast, the majority (76%) of the widespread fire years in the north-tending BP landscape scarred less than half of the recording plots. In addition, nine of the 37 widespread fire years were recorded exclusively in the south-tending RC landscape.



**Fig. 4.** Number of widespread fire years (i.e., years when at least 2 plots recorded a fire) within 20-year moving windows for the Butterfly Peak (BP) and Rose Canyon (RC) landscapes in the Santa Catalina Mountains in southeastern Arizona. The frequency of widespread fires in RC was adjusted to reflect a similar sample size as BP using the re-sampling program SSIZ. Hence, the fire frequency for RC is shown as the adjusted average along with upper and lower 95% confidence intervals. The period of analysis was from A.D. 1748 to 1910.



**Fig. 5.** Fire extent distribution between A.D. 1748–1910 in the Butterfly Peak and Rose Canyon landscapes in the Santa Catalina Mountains in southeastern Arizona. Relative fire extent was measured as the percent of plots scarred for all widespread fire years (i.e., years when  $\geq 2$  plot recorded a fire). Using a chi-square statistic fire extents were significantly different between landscapes ( $p = 0.033$ ).

#### 4. Discussion

##### 4.1. Plot-based versus landscape-based fire frequency

We found that fire intervals at individual plots did not vary significantly among aspect classes within a landscape. When all plots within a landscape were pooled, however, PCMFIs did vary between landscapes ( $p < 0.05$ ) despite similar frequencies in widespread fires. In the gentle RC landscape, for example, the average interval between widespread fires was 4.8 years, yet PCMFIs typically ranged between 7 and 10 years (Fig. 3). The average interval between widespread fires was 6.0 years in the dissected BP landscape, yet most PCMFIs were between 11 and 16 years. The discrepancy between plot and landscape-based fire frequencies was a function of scale (i.e., plots versus the entire areas) and fire extent differences within the two landscapes. That is, the higher frequency of large fires (i.e., fires that burned  $>75\%$  of the landscape) in the gentler RC landscape resulted in more area burned over time and shorter fire intervals at individual plots. Smaller fires in the dissected BP landscape resulted in less area burned and thus longer periods between fires at individual plots.

##### 4.2. Topographic influences on fire history

Aspect and slope influence fuel flammability within a stand because they mediate solar irradiance and thus fuel moisture (Schroeder and Buck, 1970; Rothermel, 1983). North aspects that receive less direct sunlight are more mesic and less flammable than south-facing aspects. Solar irradiance depends also on slope steepness: On steep slopes ( $>10^\circ$ ), for example, solar irradiance differences are substantial, even among similar facing aspects (Frank and Lee, 1996). In the Santa Catalina Mountains aspects change over short distances, but PCMFIs were not statistically different among aspect classes. Across landscapes, however, PCMFI and fire size did vary significantly. These results indicate that fire intervals at individual locations (i.e., plots) were controlled historically by the larger, surrounding (i.e., landscape-scale) rather than by local (stand-scale) topography. More specifically, less extensive fires and longer PCMFIs can be attributed to the predominant steep, north-facing aspects in the BP landscape compared to mostly gentle south-facing aspects in the RC landscape. These findings are consistent with other studies that reported fire spread at landscape scales is primarily a function of the overall topographic and fuel characteristics (Turner et al., 1989; Agee and Skinner, 2005; Finney et al., 2005).

Our results contrast those found in the Gila Wilderness, where fires in the 20th century were more frequent than expected in northeastern aspects and less frequent than expected in southwest aspects (Rollins et al., 2002). Conversely, Brown et al. (2001) concluded that tree-ring based pre-settlement fire history patterns were controlled by landscape-scale topographic patterns in the Sacramento Mountains of southern New Mexico. The fire history patterns in the Santa Catalinas are more similar to those of Brown et al. (2001). This suggests that the relationship between topography and fire history found by Rollins et al. (2002) may have been specific to the types and time period of fire history data analyzed (i.e., fire atlas data from the 20th century, versus interpolated spatial fire patterns from fire-scar data covering the 18th and 19th centuries). That is, the extent and spatial pattern of 20th century fires may have been influenced by anthropogenic factors (e.g., suppression activities).

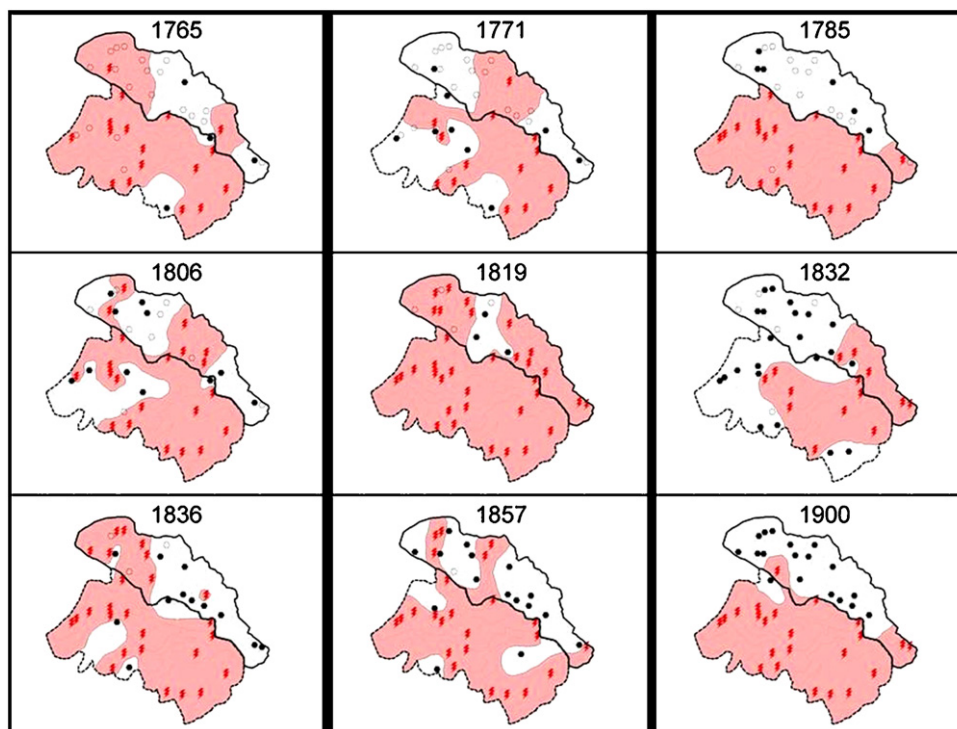
Fire extent and PCMFI differences between landscapes could be related also to fire barriers (Taylor, 2000). In the dissected BP landscape, for example, areas with very steep slopes ( $>35^\circ$ ) running north–south are commonly rock outcrops or talus slopes that may have impeded fire spread historically (Fig. 1). These steep, rocky slopes may have channeled fires vertically and slowed lateral fire spread. Such fire spread patterns were interpreted for several fire event years. Fire-scar patterns among plots suggested fires percolated extensively through the gentler RC landscape, yet had limited spread in the dissected BP landscape (Fig. 6). Although fire spread was not always obstructed by steep slopes, these fire impediments may have had a “shadow” effect on adjacent locations (Finney, 2005). That is, as fires spread around impediments they tend not to burn areas directly downwind from the impediment.

Fire history differences between landscapes could be related also to a combination of topography and prevailing wind patterns. In the peak burning months of May to July, Arizona experiences predominantly southwest winds. The main ridge that traverses the two landscapes sheltered the north-tending BP landscape from the prevailing winds, and may have favored down slope burning that was less effective at spreading over extensive areas than upslope burning. The dominant south-facing aspects on the RC landscape are perpendicular to the predominant wind pattern that may have promoted upslope fire spread, larger fires and hence shorter fire intervals at individual plots.

##### 4.3. Vegetation/fuels effects on fire history

In addition to the abiotic topographic factors, it is also likely that fire history differences between the two landscapes were related to distinctive vegetation/fuels. Because of topographic and parent material differences these two landscapes are dominated by different forest types, and have been for at least two centuries. The shallow south-facing slopes in the RC landscape are mainly granite based soils (Force, 1997) and thus support ponderosa pine dominated forest (Fig. 7). In the steep mostly north-facing aspects of the BP landscape, the parent materials are limestone and quartzite (Force, 1997) that support mixed-conifer forests composed of white fir, Douglas-fir, white pine and ponderosa pine (Fig. 7).

Historically, wildfires in ponderosa pine forests spread through grasses and long needle fuel beds (Swetnam and Baisan, 2003). These fuel types dry and burn relatively quickly compared to more compact forbs and short needle fuel beds found in mixed-conifer forests (Weatherspoon and Skinner, 1995; van Wagtenonk et al., 1998; Stephens et al., 2004). Differences in



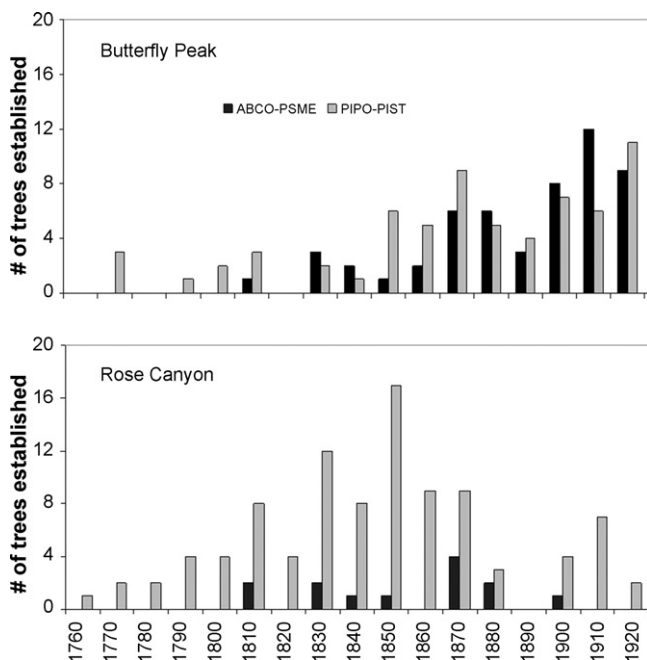
**Fig. 6.** Fire spread patterns in the Butterfly peak (top polygon) and Rose Canyon (bottom polygon) landscapes in the Santa Catalina Mountains in southeastern Arizona. The lightning symbols represent the location of plots recording a fire. Closed circles are plots that were recording (i.e., plots where trees had been previously fire-scarred), but did not record a fire that particular year. Open circles are non-recording plots (i.e., plots where trees had not previously recorded a fire). Shaded areas encompass the approximate fire extent within the study area. Scale and north arrow for the study area are provided in Fig. 1.

PCMFI between the gentle RC landscape compared to the dissected BP landscape could therefore be related to slope exposure, fuel drying rate, fuel bed characteristics, or some combination of these factors.

#### 4.4. Conclusion and management implications

To reduce the threat of stand-replacing fires and restore surface fire regimes in southwestern pine forests, it is essential that managers craft plans that account for the spatial variability in fire history patterns. Our results indicate that PCMFI were similar among different aspect classes, indicating that the local topography (i.e., aspect differences at 0.1–2 km<sup>2</sup>) tended to not influence fire frequencies at individual plots. Plot fire intervals were influenced instead by surrounding landscape topographic characteristics (i.e., 2–10 km<sup>2</sup> scales). Landscapes dominated by xeric south-facing shallow-slopes were associated furthermore with larger fires and shorter PCMFI compared to landscapes dominated by steep mesic north-facing slopes. We conclude that past surface fire regimes in the Santa Catalina Mountains operated at landscape scales (i.e., 2–10 km<sup>2</sup>) and were mediated strongly by the predominant landscape topography.

The topographic and vegetative/fuel characteristics of landscapes can be thought of as “fire habitat”. We introduce the term “fire habitat” to unify the suite of variables and in recognition of the historical presence of fire as a landscape inhabitant that promoted a natural cycle of renewal. A fire management strategy might use a fire habitat classification for extrapolating and mapping fire history patterns, and this might then be used in prioritizing fire use and forest restoration treatments (Taylor and Skinner, 2003; Hann et al., 2003; Sisk et al., 2005). The concept of fire habitats is in line with national interagency programs such as Risk Assessment and Mitigation Strategies (RAMS) that already use the concept to assess fuel hazards, ignitions risks, fire return intervals, values and protections capabilities ([https://www.nifc.blm.gov/nsdu/fire\\_planning](https://www.nifc.blm.gov/nsdu/fire_planning)). Mapping fire history units could be done using Digital Elevation Models (DEM) and topographic maps. Extrapolating fire regimes, however, will require new fire history studies and meta-analysis of existing fire



**Fig. 7.** Age structure patterns for dominant tree species in the Butterfly Peak and Rose Canyon landscapes in the Santa Catalina Mountains of southeastern Arizona. Species codes are: ABCO, *Abies concolor* (white fir); PSME, *Pseudotsuga menziesii* (Douglas-fir); PIPO, *Pinus ponderosa* (ponderosa pine) and PIST, *Pinus strobiformis* (white pine). Core sampling targeted the largest pre-settlement trees (trees that established prior to 1910) therefore younger trees are probably underrepresented.



history studies to characterize fire regimes from a wide variety of landscapes.

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