Temporal and Spatial Dynamics of Pre-Euro-American Fire at a Watershed Scale, Sequoia and Kings Canyon National Parks[1]

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ABSTRACT

Our understanding of fire as a process in the complex landscapes of the southern Sierra Nevada prior to Euro-American settlement is poor relative to contemporary ecosystem processes. Information primarily consists of fire return intervals from a relatively small number of sites that does not adequately represent past dynamics of fire at a watershed scale. To obtain a better landscape perspective on fire history I used a network of sites located throughout the coniferous zone in the East Fork watershed of the Kaweah River drainage and reconstructed fire regime attributes such as area burned annually and frequency patterns relating to aspect, vegetation type, and elevation. Initial analysis suggested striking differences in the fire regime between north and south aspects with differences strongest at mid-elevations. Fire return intervals on north aspects were less than half that observed on south aspects. Estimates of annual area burned, derived from Thiesson polygons, also showed considerable variability. During certain years fire extended throughout much of the drainage and in a some cases adjacent watersheds also. Pattern and variability in annual area burned were strongly influenced by aspect and annual climate variation. They underscored the importance of climate and topography as controllers of spatial and temporal patterns of fire occurrence. The patterns also suggested strong linkages between fire and ecosystem dynamics with important implications for resource managers restoring fire in the southern Sierra.

INTRODUCTION

Historically, fire played a key role in the dynamics of most Sierra Nevada ecosystems (Kilgore 1973), shaping ecosystems temporally and spatially. In much of the mixed-conifer zone, fires were primarily non-stand replacing surface fires (Kilgore and Taylor 1979; Warner 1980; Pitcher 1987; Caprio and Swetnam 1995), although exceptions exist (Caprio et al. 1994). The ignition source of fire prior to Euro-American settlement is usually attributed to lightning or Native Americans. Beginning with Euro-American settlement between 1850-1870, fire regimes in the Sierra Nevada changed dramatically, with sharp declines in fire return intervals in most plant communities (Kilgore and Taylor 1979; Warner 1980; Swetnam et al. 1992; Caprio and Swetnam 1995). Factors contributing to the initial decline include the loss of anthropogenic ignitions and heavy livestock grazing following Euro-American settlement that reduced herbaceous fuels, particularly at lower elevations, and effectively limited fire spread (Caprio and Swetnam 1995). Active fire suppression efforts, begun in the early twentieth century, further decreased or eliminated surface fire as an ecological influence in most Sierran ecosystems. This change in the fire regime led to unprecedented fuel accumulation, structural and composition changes, and resulted in an increased probability of widespread severe fires in many plant communities (Kilgore 1973).

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The National Park Service's mission mandates that the agency "protect and preserve" natural resources, which includes restoring and maintaining natural ecological processes. Restoring fire as a process is an important component in this mandate. Beginning in the 1960s land managers began to reintroduce fire within Sequoia and Kings Canyon National Parks (Bancroft et al.1985). While the original emphasis was fuel reduction, the ultimate goal is to restore attributes of past fire regimes in park ecosystems. This has led to a need to better understand the character of these regimes, and how they functioned at both local and ecosystem wide scales. Additionally, information about the range of variation in these attributes is important in understanding landscape level ecosystem processes and in designing and implementing ecologically sound fire management objectives. Unfortunately, most attributes of fire regimes prior to Euro-American settlement are poorly documented particularly in areas with a high frequency surface fire regime.

The Parks have recently begun to utilize and integrate current knowledge about past fire regimes into a GIS framework to provide information for ecologically sound management and for optimizing burn program planning (Caprio et al. in press; Caprio and Graber 2000; Keifer et al. 2000). Various models used in this GIS analysis are directly or indirectly derived from the fire history data (tree-ring analysis of fire scars) and historic fire records (obtained from mapped fires). Using this information to summarize fire return intervals (FRI) in various vegetation types, an "ecological needs" model was developed to produce a map of "fire return interval departures" (FRID). The model highlights areas that have deviated from their historic fire regime following Euro-American settlement. The FRID model is a dynamic and valuable decision support tool that integrates ecological information used to prioritize areas for initial treatment with prescribed fire, assists with scheduling successive burns, helps provide economic accountability, and evaluates progress towards achieving landscape-level ecological goals (Caprio and Graber 2000). The quality of the FRID output is dependent on the quality of the fire history information used in its calculation.

A number of fire history investigations, utilizing fire scar records from trees, have been carried out in or near the Parks over the last three decades (Kilgore and Taylor 1979; Warner 1980; Pitcher 1981, 1987; Swetnam et al. 1992; Swetnam 1993; Caprio et al. 1994; Caprio and Swetnam 1995; Swetnam et al. 1998). They provide important ecological and management information, such as documenting changes in fire frequency resulting from Euro-American settlement, illustrating relationships between fire and forest structure, and showing the interaction of climate and fire. As the breadth of areas and plant communities sampled from throughout the park has expanded, so has our knowledge and understanding about the underlying characteristics and variability of the pre-Euro-American fire regimes. As a result, we are not only becoming more aware of the complex patterns and relationships of past fire regimes but also of the variability in the quality of our knowledge for different vegetation communities and locations within the Parks. Inadequate site replication frequently results in overly simplistic interpretations of past fire regimes at the landscape level. A recent analysis suggests that good quality information is only applicable to about 26% of the Park's vegetated area (Caprio and Lineback in press). For example, one facet of past regimes that has been poorly studied is the effect of aspect on past fire occurrence and spread patterns although its influence on contemporary fire behavior and spread patterns is well documented (Agee 1993; Pyne et al. 1996). Several fire history investigations from other regions of North America have suggested there may be shifts in FRI by aspect (Allen et al. 1995; Laven et al. 1980; Taylor and Skinner 1998; Quanfa et al. 1999).

This study's objective was to obtain well replicated estimates of FRI to assess intra- and inter-site variation within specific vegetation types and aspects throughout a watershed that could then be projected with some confidence to larger land units to reconstruct fire size estimates. This paper presents preliminary details about the fire history sampling that has been conducted using a network of sites throughout a watershed with diverse topographic features and vegetation. Results will eventually answer a variety of questions associated with fire regime attributes–such as frequency and size– and how these vary across a landscape by aspect, elevation and vegetation type.

STUDY AREA

Sampling was conducted in the East Fork drainage (**Fig. 1**), one of five major drainages comprising the Kaweah River watershed, which historically flowed west into the Tulare Lake Basin in the southern San Joaquin Valley. Terrain is rugged with elevations ranging from 874 m (2,884 ft) to 3,767 m (12,432 ft). The drainage, 21,202 ha (52,369 ac) in size, is bounded by Paradise Ridge to the north, the Great Western Divide to the east, and Salt Creek Ridge to the south. Major topographic features in the watershed include the high elevation Mineral King Valley, Hockett Plateau, the Horse Creek subdrainage, the high peaks of the Great Western Divide, and the Oriole Lake subdrainage.

The elevation gradient from the foothills to the higher peaks is exceptionally steep with rapid transitions between vegetation communities. About 80% of the watershed is vegetated with most of the remainder being rock outcrops located on steep slopes and at high elevations. Three broad vegetation zones dominate the watershed: **foothill**s (485 to 1,515 m) composed of annual grasslands, deciduous oak, evergreen woodlands, and chaparral shrubland; **conifer forest** (1,515 to 3,030 m) with ponderosa pine (*Pinus ponderosa* Dougl.), lodgepole pine (*P. contorta* Dougl. var Murrayana Englm.), giant sequoia *(Sequoiadendron giganteum* [Lindl.] Buchholz), white fir (*Abies concolor* Lindl. & Gord.) and red fir (*A. magnifica* Murr.) forests; and the **high country** (3,030 to 4,392 m) composed of subalpine forests with foxtail pine *(P. balfouriana* Jeff.), alpine vegetation, and unvegetated landscapes. Vegetation is

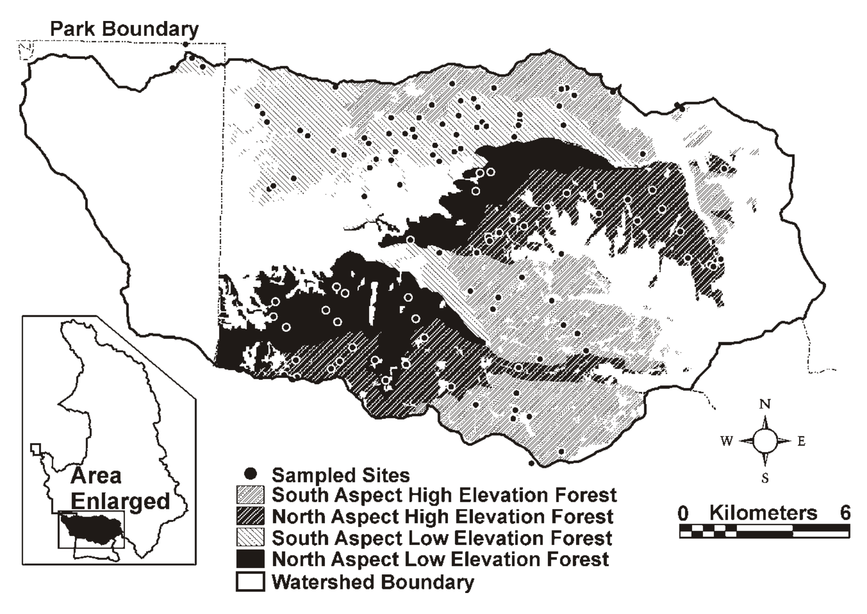


Figure 1. East Fork watershed of the Kaweah River drainage showing distribution of sites within the coniferous forest belt (inset shows watershed location within the Parks). Forest vegetation is categorized by elevation (high and low divided at 2286 m) and aspect (N >285° to <106°, and south 106° to 285°).

dominated by red and white fir forests with pine and foothill vegetation of somewhat lesser importance. Ten named sequoia groves are found within the drainage and include the large Atwell, East Fork, and Eden Groves. Portions of the Atwell and Oriole Lake Groves were logged at various times over the last 100 years before being incorporated into the Parks. Since 1990, 2,272 ha (5,611 ac) have burned within the watershed, most of this associated with the Mineral King Risk Reduction Project (Caprio 2000).

The climate is distinctly Mediterranean with cool moist winters and warm summers with little rainfall, although seasonal summer thunderstorms occur sporadically at higher elevations. Precipitation increases with elevation, from 1,515 to 2,424 m on the west slope of the Sierra, to about 102 cm (40 in) annually, then decreases at higher elevations and to the east (Stephenson 1988). Substantial snow accumulations are common above 1,515 m during the winter. Total annual precipitation during the period of record has varied from 30 to 130 cm at Ash Mountain in the foothills and from 38 to 214 cm in Giant Forest at a mid-elevation location.

Euro-American settlement of the area began in the 1860s with extensive grazing, minor amounts of logging, and scattered mineral exploration. Mineral King was the site of a brief speculative mining boom in the 1870s and 80s but little actual ore was recovered. However, a 25-mile long road was constructed into the area in 1878 that provided relatively easy access. Limited logging occurred in the Atwell Mill area in the late 1880s. Sequoia and General Grant National Parks were legislated in 1890, originally with the intent of protecting sequoia groves from logging, but have been expanded to include much of the surrounding rugged, high mountains and some foothills areas (Dilsaver and Tweed 1990). The Mineral King area of the drainage remained under the jurisdiction of the US Forest Service until 1978. Higher elevations of the watershed receive considerable recreation use while most lower elevations are seldom visited.

METHODS

Sample sites were located throughout the drainage in the conifer forest belt across all aspects and elevations. Sites were selected to provide good spatial coverage within the drainage. Site locations were constrained by accessability and availability of fire history material. They were located in homogeneous areas with uniform aspect, topographic position and elevation without barriers to fire spread. Areas sampled were small, generally less-than one hectare, to avoid the influence of area on frequency estimates (Arno and Peterson 1983). Samples from multiple trees were usually collected at each site. This strategy has been shown to provide the best record of past fire occurrence (Kilgore and Taylor 1979). It considers each site a single replicate, with individual trees as subsamples, from which a composite fire interval is calculated (Dieterich 1980). Replication is important since every scarred tree will not have a complete record of each fire or may have lost portions of the record in subsequent burns or from decomposition. Within site sampling was usually less intense at higher elevations because a complete record could be obtained with fewer trees since a FRI were longer and forest turnover rates slower (Pitcher 1981). Partial cross-sectional samples were collected using a chainsaw, primarily from dead trees (snags, stumps, or logs) although a few samples were collected from living trees to ascertain twentieth century fire history. Samples from living trees were removed as partial sections (Arno and Sneck 1977) or collected with an increment borer (Sheppard et al. 1988). Position coordinates (UTM) for all samples were recorded and topographic, vegetation, and fuels data collected at each tree sampled. Tree positions were averaged to obtain site coordinates.

Dendrochronological techniques (Stokes and Smiley 1968) were used to determine the calendar year of occurrence for each fire event, visible as a lesions in a catface, and in most cases the specific position within a ring (season) in which these events occurred (Stokes 1980; Ahlstrand 1980; Caprio and Swetnam

1995). Crossdating allowed temporally explicit fire dates to be obtained permitting spatial patterns of burns to be reconstructed.

Area burned annually prior to Euro-American settlement was reconstructed using Thiesson polygons (Davis 1986). Each irregular shaped polygon represents the area around a point (the sample site), in a field of scattered points, determined by Euclidean distance that is closer to that point than any other point. The resulting field of polygons represents the most geometric compact division of area, given the specific arrangement of points. It provides a valuable tool for quantifying and portraying spatial patterns over a landscape. This approach is commonly utilized for rainfall gauging networks when stations are not uniformly distributed and strong gradients occur (Dunne and Leopold 1978)–both characteristics of the network of fire history sites sampled in the East Fork. Polygons and polygon area were determined around the center point of each fire history site using ArcView 3.1 (ESRI 1997) and compiled to create maps of area burned annually from 1700 to 1860. Polygon border delineation was constrained by watershed boundaries and by aspect so a polygon located in one category would not overlap any area in another category.

Fire return intervals and reconstructed patterns of fire size across the landscape were examined by elevation (high/low) and aspect (north/south). Low and high elevations were separated at the transition zone between *Abies concolor* and *Abies magnifica* at 2286 m (Dennis 1999). South aspects were defined as aspects from 106° to 285° and north as >285° to <106° while level areas (<5% slope) were classed with south aspects (Caprio and Lineback in press). Areas smaller than about 2.5 km^2 were considered to be micro-aspects and categorized as being the same as the surrounding macro-aspect since fire occurrence would be strongly influenced by the overall macro-aspect in which they were imbedded. This was assumed because fire spread and not ignition source was considered the most important influence on fire occurrence on any specific unit of land.

RESULTS and DISCUSSION

Fire History Data

The fire history network is currently comprised of 124 sites with 544 individual trees sampled. Sites were located throughout the watershed's 12,991 ha coniferous forest belt (**Fig. 1**) with 82.4 % falling within 1000 m of another site. The data set included two giant sequoia sites previously collected in the Atwell Grove by Swetnam et al. (1992) and data from trees sampled by Pitcher (1987) supplemented material collected at two sites near Tar Gap. Sites were categorized as being in one of four categories; low-north, high-north, low-south, and high-south. Area in each of these categories was roughly equivalent, differing by less than a factor of two (**Table 1**). Greater sampling density on portions of the south aspect was a result of attempts to ascertain optimal sampling density in an area of easy access. Mean number of

Table 1. Number of sites and size of area by aspect and elevation category within the 12,991 ha conifer belt in the East Fork drainage.

	North (>285° to<106°)		South (106° to 285°)	
	Number of Sites	Area (ha)	Number of Sites	Area (ha)
High (>2286 m)	31	3,088	29	4,360
Low (<2286 m)	15	2,664	49	2,775

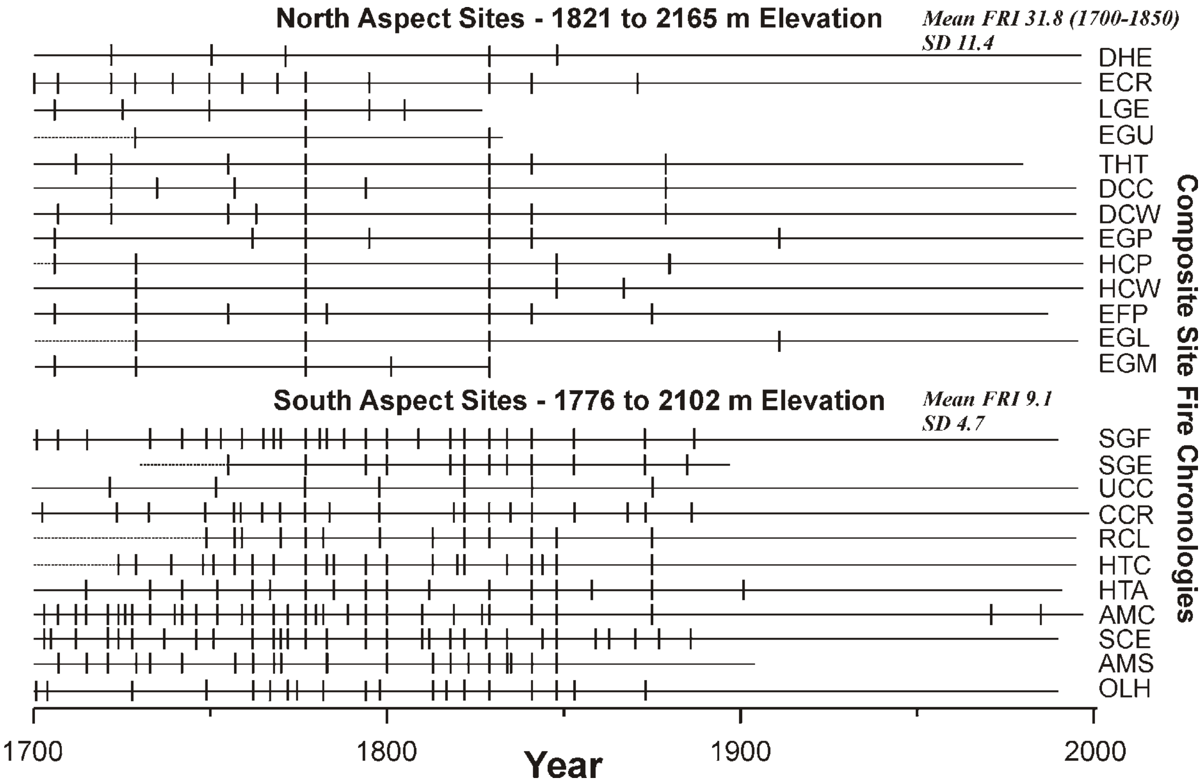


Figure 2. Composite fire interval chart for sites located at low to mid-elevations on north and south aspects. Each horizontal line represents the composite period of record for a specific site and short vertical lines indicate the fire events recorded by site.

samples collected per site was 4.4 (SD=2.4). Sampling intensity generally varied inversely with elevation. Fire history at higher elevation sites, with longer FRI, could be reconstructed with fewer samples. Fire dates have been determined at 92 sites and form the basis for the current fire return interval estimates and annual area burned reconstruction. A total of 255 dated samples were used in this analysis with over 2050 individual fire scars dated. A total of 304 fire events were recorded between AD 1400 and AD 1995 although fire dates extend back to 284 BC at the sequoia sites (Swetnam et al. 1992). The last fire of significant size occurred in 1889 (recorded at five sites) with 1994 the most recent fire. Most large 20th century fires were recorded by the sampling but spatial information was poor because recording trees had been destroyed by fire, a result of heavy fuel accumulations and severe fire following decades of unnatural fuel accumulation. This highlights the need to collect this historic record before it is lost.

Site sample depth varied through time and was used to determine a cutoff date for data analysis. Number of sites recording fire events peaked in about 1800 on both north and south aspects (39 and 52 respectively). Sample depth declined prior to 1700 (28 and 34 sites respectively) on both aspects so analysis was restricted to the post-1700 record.

Temporal Attributes

Fire frequency declined following Euro-American settlement (about 1860) with nearly complete cessation of fires by 1900. This is typical for sites in the southern Sierra Nevada (Kilgore and Taylor 1979;

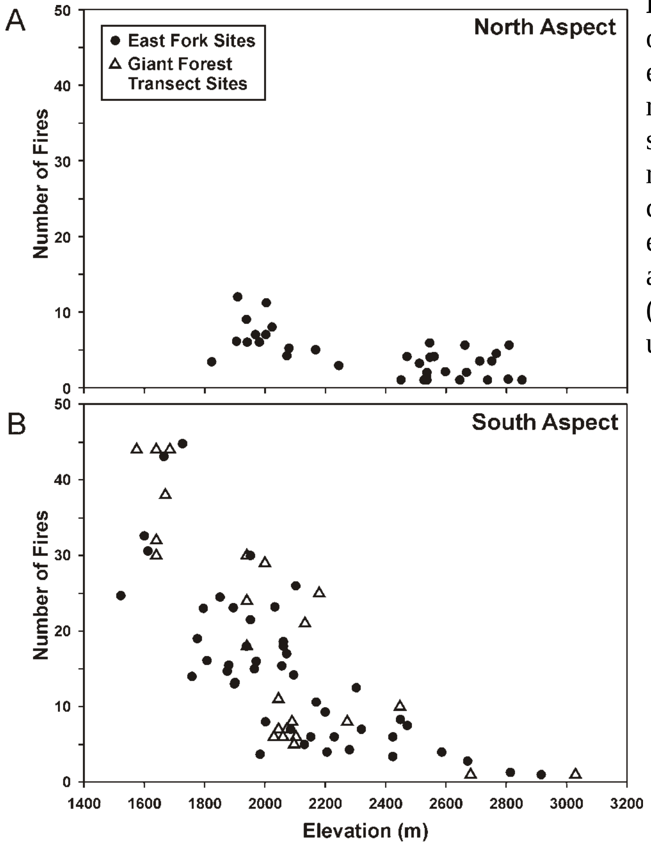


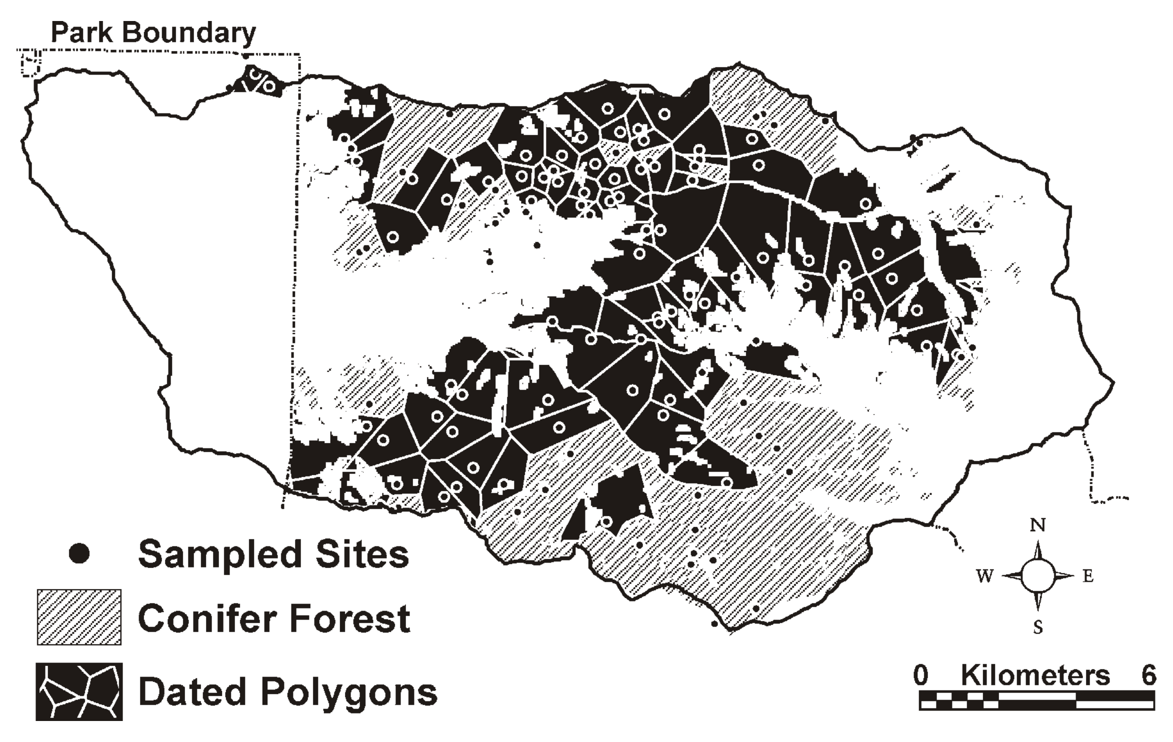
Figure 3. Relationship between number of fire events recorded at a site and elevation by aspect. A strong inverse relationship exists on south facing slopes (b) with a much weaker relationship on north slopes (a). For comparison, fire data from an elevational transect located on a south aspect near Giant Forest are also shown (Caprio and Swetnam 1995, Caprio unpublished data).

Swetnam et al. 1992; Caprio and Swetnam 1995; Swetnam et al. 1998). Comparison of master fire chronologies showed aspect difference among sites from similar elevations with differences strongest in lower elevation (1776 to 2165 m) conifer forest (**Fig. 2**). For the period from 1700 to 1850 the mean FRI on south aspects was 9.1 yr (N=11, SD=4.7 yr) in contrast to 31.8 yr (N=13, SD=11.4 yr) on north aspects. Differences were less marked between the upper elevation aspects. Within aspect differences were also apparent at local scales and may be the result of variation in vegetation type, specific topographic characteristics of a site, and the influence of elevation. Future analysis will look at these factors in more detail when the full data set for the watershed is developed.

The master fire chronologies also highlight fire years recorded at a large number of sites on both aspects, suggesting fires of widespread occurrence. Years recorded at the greatest number of sites were 1777, 1829, and 1841. Some fire events were only recorded at single sites suggesting locally confined fires. However, because the fire scar record was a conservative recorder of past fire events, the number of sites recording particular events should be viewed as a minimum estimate of fire occurrence. The relative differences among sites probably reflect actual variation in FRI across the landscape.

Striking differences were also apparent between north and south aspects when the relationship between elevation and fire frequency was examined. Data from the south aspect showed a strong inverse relationship between elevation and fire frequency (**Fig. 3b**). This pattern was similar to the relationship found when fire histories were reconstructed across an elevational transect on a south aspect in the Giant Forest area (Caprio and Swetnam 1995). However, the strength of this pattern did not extend onto the

Figure 4. Thiesson polygons constructed around all sites where fire history chronologies have been reconstructed. Current analysis is based on the data derived from this set of sites.



north aspect where I observed only a weak relationship between elevation and fire frequency (**Fig. 3a**). This difference exists even though the same general vegetation types occur on both aspects.

Spatial Attributes

Definite spatial patterns of past fire occurrence have emerged as the network of sites throughout the drainage has been collected and Thiesson polygons developed (**Fig. 4**). Mapping indicated patterns of area burned could be reconstructed over the landscape with some reliability (**Fig. 5**). This was significant because obtaining estimated size of pre-Euro-American fires has generally been restricted to ecosystems where stand replacing fires occur and fire-initiated seral age classes can be dated and mapped (Heinselman 1973; Romme 1982; Barrett 1994). In ecosystems with high frequency surface fire regimes the complex structural differences in the forest vegetation does not permit this type of mapping (Arno and Sneck 1977). However, the sampling strategy used in the East Fork indicates that by sampling a network of sites across a landscape, area attributes can be reconstructed with some accuracy.

While this approach provided an estimate of past fire size a variety of limitations were encountered. For example, the resolution of the final burn maps was commensurate with sampling intensity, and while rough estimates of past fire size may be obtained, precise locations of burn boundaries could not be determined. However, the approach was not biased against areas where understory burns have occurred as are fire size estimates from stand origin maps (Johnson 1992). Additionally, the distribution of point estimates over the landscape generally represented a minimal area burned by a particular fire or fires in a given year. Thus, evidence of a fire scar in a particular year was a definitive record of fires occurrence, while the lack of a scar could be the result of the area not burning or the fires passage leaving no record–either trees were not scarred, scars were subsequently lost, or a sample with the scar was not collected–even though a fire occurred. Fire size estimates from single or isolated sites probably have the greatest error. Size estimates should improve as any particular fire event is recorded at more sites. In contrast, fire events recorded at single sites could overestimate fire size since a small fire might be projected onto a larger polygon. Future sampling of a network of sites across an area where contemporary fires have been mapped would provide considerable insight and validation of the use of Thiesson polygons for fire size reconstructions.

Using the Thiesson polygons a chronosequence of maps showing annual area burned was reconstructed for the years 1700 to 1899 (mean polygon size 104.1 ha, SD=79.8, median 97.6). Several fire years illustrated spatial patterns of reconstructed area burned with a variety of patterns apparent (**Fig. 5**). The 1800 fire date indicated fire was confined to a well defined area on south aspect slopes within the main drainage. Estimated burn area, based on the sum of the polygons, was approximately 1,300 ha. In contrast, burn areas for 1829 and 1841 indicate widespread burns (~4,209 and ~1,938 ha respectively) and indicated areas burned in both the main East Fork drainage and the Horse creek drainage. The spatial pattern of these two burns suggested either conductance across lower elevations in the drainage through vegetation that is currently chaparral and evergreen forest or possibly multiple ignitions. In contrast to these widespread burns, in 1844 only a small cluster of four sites recorded what was probably a single relatively small fire event (~255 ha).

Also of interest were comparative maps showing extent of area burned in 1873 and 1875 after Euro-

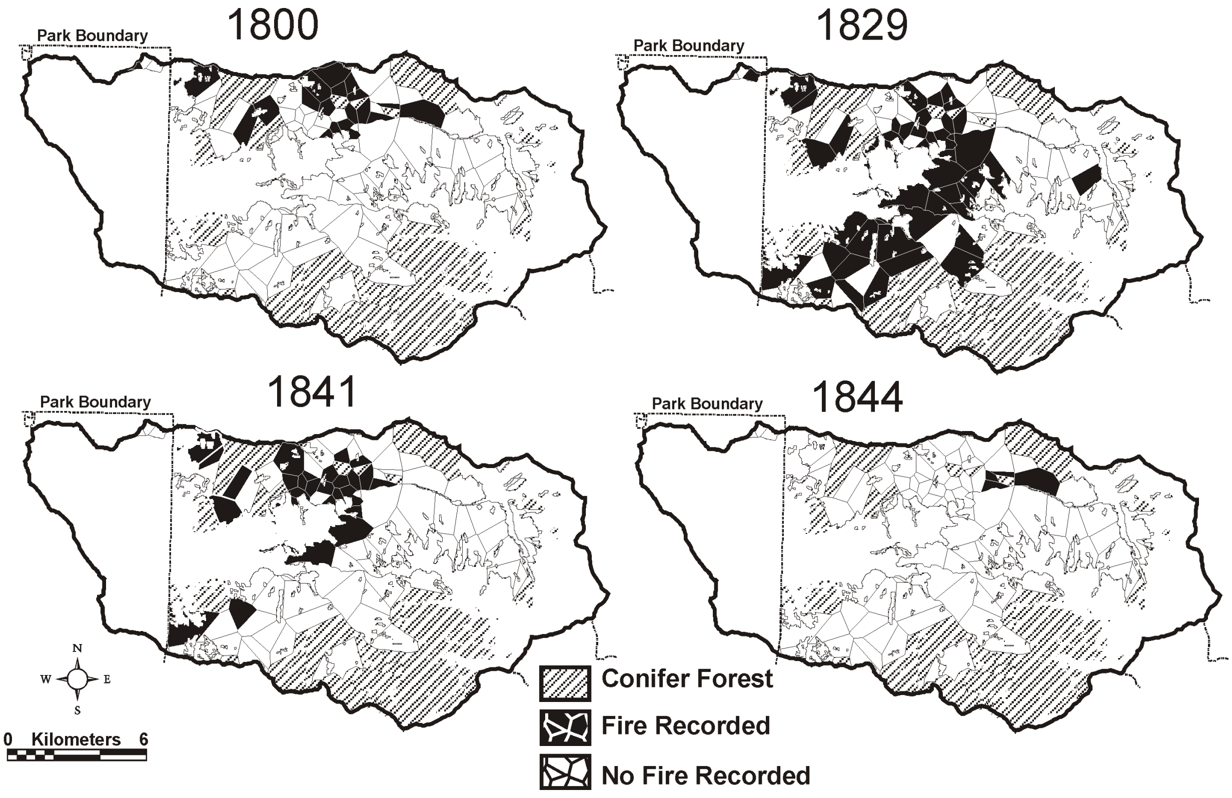


Figure 5. Reconstructed spatial pattern of area burned during four typical years based on polygons from currently dated fire history chronologies. The maps illustrate particular patterns of fire occurrence across the landscape.

American settlement. The reconstructed area for the 1873 burn (16 polygons) showed that fire was centered on the central portion of the Atwell Grove while the map for 1875 (26 polygons) indicates burning took place predominantly to the east and west of this area and on lower slopes of the north aspect. Overlaying the polygon burn maps from these two burns indicated that they were essentially mutually exclusive with both dates co-occurring at only one of forty-two sites. This indicated fuel recovery in two years (1873 to 1875) was not sufficient to permit extensive reburning. John Muir (1878) also made interesting historical observations about the 1875 fire that verifies its occurrence in chaparral vegetation between the south and north aspects of the watershed. He wrote that while traveling in the Atwell area he watched this fire burn intensely up-canyon through chaparral vegetation and enter the sequoia grove where intensity decreased markedly.

A time series of reconstructed annual area burned showed considerable year-to-year variation from 1700 to 1899 (**Fig. 6a**). Fires were recorded during 106 of the 200 years with years of particularly widespread fire (>2,000 ha based on polygon reconstruction) in 1777, 1829, and 1848. Reconstructed burn area in eleven other years exceeded 1,000 ha. Average area burned annually within the watershed was 320 ha or about 2.4% of the coniferous forest area. The distribution of area burned annually within the watershed from 1700 to 1899 showed an inverse J shaped distribution (**Fig. 6b**). Most fires were small (mean size 462 ha) with a few years when extensive fire occurred (~3,720 ha in 1777).

Fire sizes or area burned in some years probably exceeded fire area estimates based solely on the East Fork Study area. Fire in these years may have been a single widespread burn or a complex of burns across multiple watersheds. Fire history sampling in adjacent Kaweah River drainages (South, Middle, and Marble Forks) showed many years in common to the East Fork (Swetnam et a. 1992; Caprio and Swetnam 1995; Swetnam et al. 1998; Caprio unpublished data). Prominent fire dates in the record from the South Fork (south of the East Fork) included 1777, 1812, and 1841 whereas in the Middle Fork/Marble Fork areas (north of the East Fork) common dates include 1777, 1795, 1812, 1829, 1841, and 1873. These common fire years also occurred across the landscape at the regional scale (west slope of the southern Sierra Nevada) and appear related to annual climatic variation (Swetnam 1993; Swetnam et al. 1998).

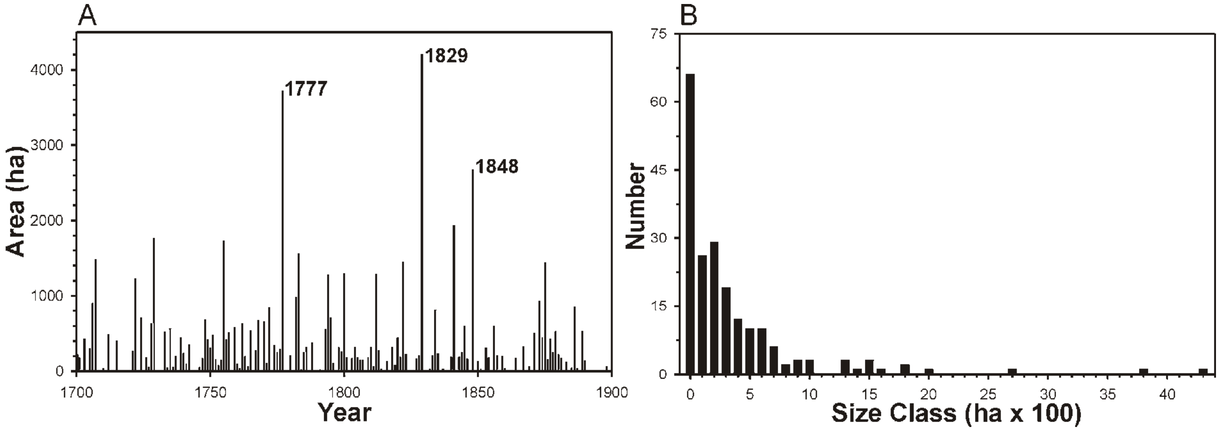


Figure 6. Area burned annually within the East Fork watershed from 1700 to 1899 (a). Area values were reconstructed from the 92 polygons for which fire chronologies have been developed. In most years area burned was small (mean 310 ha) with a few years when large areas burned. (b) Distribution of total area burned by size class for the period from 1700 to 1899 showing that small fire years were responsible for most of the area burned within the watershed.

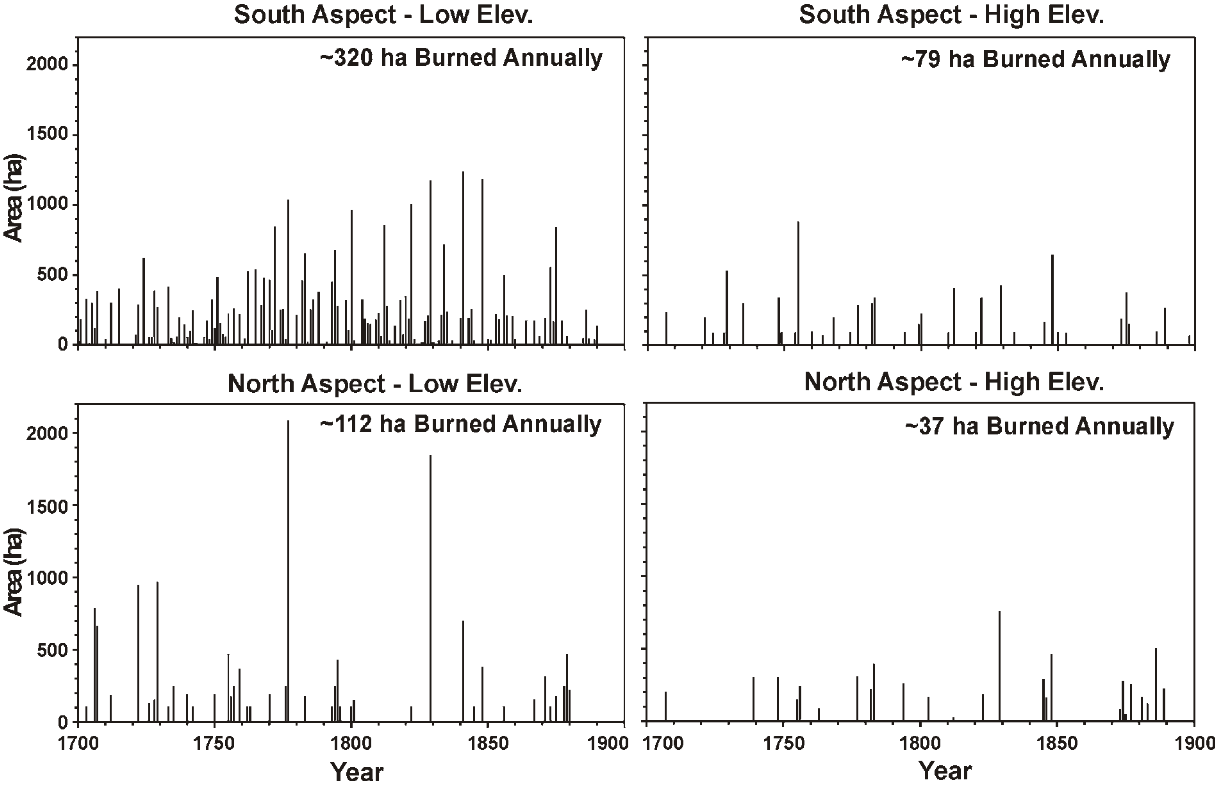


Figure 7. Area burned annually by topographic category, high/low elevation and north/ south aspect. Differences between aspects were greatest between the lower south aspect and the other three aspect categories while south aspects in general showed greater fire frequency.

Aspect and Elevational Influences

Dramatic differences in area burned annually became apparent when data were separated by elevation and aspect (**Fig. 7**). They were greatest between lower elevation north and south aspects and less striking between higher elevation north and south aspects. Annual area burned on south aspects was generally small but was regularly interspersed with years when moderately large fire years occurred. This pattern contrasted markedly with patterns from the north aspect and from higher elevation south aspects where the incidence of fire occurrence was lower and more irregular. However, among the latter groupings subtle differences also existed. For example, on the lower elevation north aspect the longer FRI were punctuated by years when large area burned (1777 and 1829).

Specific mechanisms driving these patterns are unknown but are likely associated with the interaction of fuels, vegetation, and climate. While reliable data on fuel and forest structure conditions prior to Euro-American settlement do not exist, there are proxy records of precipitation derived from dendroclimatic studies. A preliminary examination of the climatic relationship between past rainfall and fire event occurrence on north versus south aspects showed patterns suggesting at least partial mechanisms. The relationship was investigated by overlaying fire dates onto a time series of an indexed residual tree-ring chronology. The chronology was developed from climatically sensitive low elevation trees in the Kaweah drainage and has a significant correlation with January to April (winter) rainfall (Caprio unpublished data). When all fire events were considered, fire years on the south aspect (**Fig. 8a**) co-occurred with almost equal likelihood to years with less than average ring widths (50 dry years) or years with greater than average ring widths (75 wet years) while fire years on the north aspect (**Fig. 8b**) had a stronger

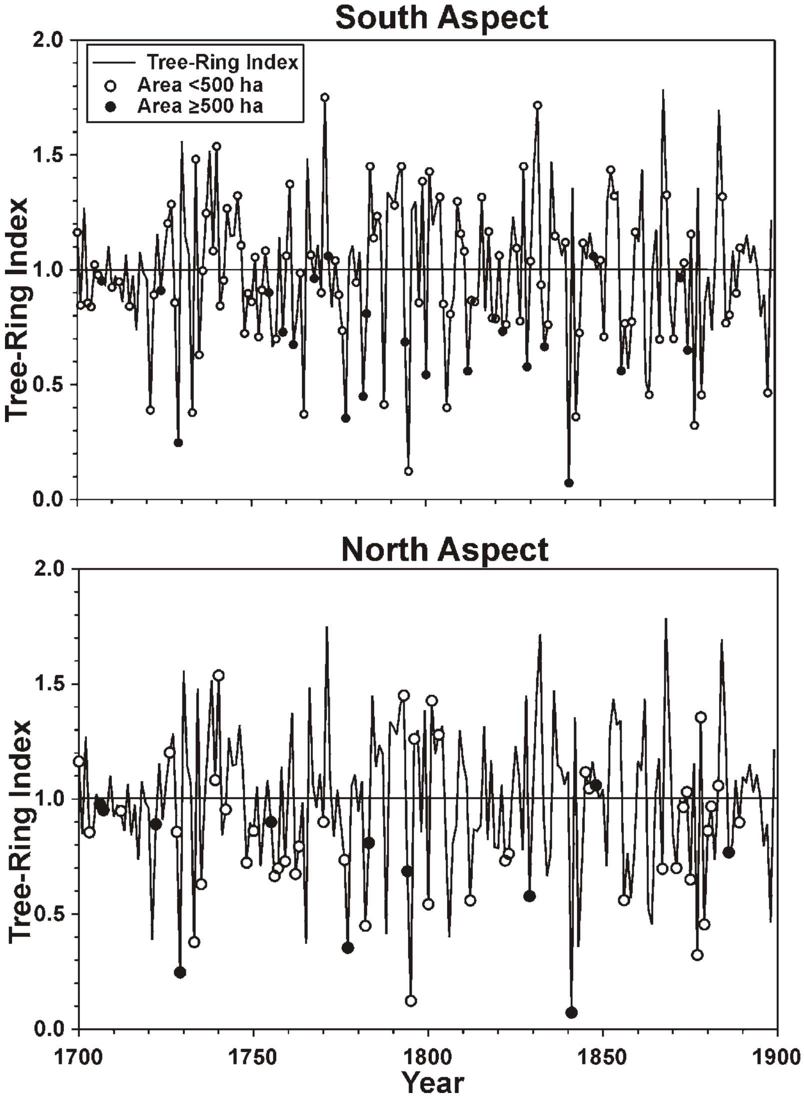


Figure 8. Relationship between fire occurrence and a proxy record of precipitation (drought sensitive standardized tree-ring chronology) on south (a) and north (b) aspects. Open dots show all fire events and solid dots show the relationship if only events ≥500 ha in size are superimposed on the tree-ring indices.

overall association with small rings (14 wet versus 42 dry years). However, in years when large areas burned (≥500 ha) fire years on both aspects were strongly associated with small ring widths (on south aspects two wet versus 18 dry years and on north aspects one wet versus 11 dry years). This suggested that both past fire occurrence and size were restricted on north aspects to years of below normal precipitation while on south aspects fire occurrence may have been governed by fuels, with climate largely determining fire size. When the data were further separated by elevation, both upper elevation north and south aspects exhibited burn patterns similar to the overall north aspect discussed above. Future analysis will examine relationships between climate and fire occurrence by specific vegetation types.

These patterns of fire on the landscape are similar to patterns described by foresters observing fire spread over the landscape in the late 19th and early 20th centuries. Show (1922) summarizes these observations and suggests that drought and lack of precipitation for long periods are necessary for extensive fires to occur and that in most years conditions do not permit fires of large size. He reports that fuel moisture differences between north and south aspects provide the mechanism for limiting fire spread in average years. He states "*...we can infer that fires may start every year, that every year they will spread, but that* *except in very dry years or following dry lightning storms, they may burn out on north slopes, due to the moisture content of the litter, though spreading freely on south slopes. Very extensive fires....are likely to be associated with unusual drought*." The historic patterns described by Show are very similar to patterns reconstructed from the contemporary tree-ring record. Both his observations and the burn patterns from the East Fork suggest that north aspects were effective barriers to the spread of large fires under pre-Euro-American conditions during years of average precipitation. Whether such mechanisms still operate given fuel and vegetation changes over the last 150 years is unclear.

Biotic and Management Implications

Fire regime differences between aspects may have been substantial not only in respect to FRI, but also in relation to biotic effects. The reconstruction of pre-Euro-American settlement FRI on lower elevation south-facing slopes indicated fires were typically light while the more episodic burns on north aspects and at higher elevations were probably of much greater severity. The episodic events would have been related to both fuel conditions (greater fuel loads) and occurrence of fires during dry years. These fires would probably have increased the frequency of gap formation and patch development (such as brush fields), influenced species composition, and created greater spatial and temporal heterogeneity in stand structure. The apparent outcome of fire suppression probably fostered more homogeneous vegetation on all aspects with increased potential for large severe fires occurring throughout an entire watershed or across several watersheds.

Fire regime differences by aspect will also have important implications for management efforts aimed at restoring fire to park ecosystems. Incorporation of the new FRI information into the Park's FRID analysis (Caprio et al. in press) will improve output quality, particularly when analyzed by vegetation type. The data presented in this paper on aspect differences showed that conifer forest on lower elevation south aspects have missed a larger number of fire events than those on comparable north aspects. As a result they have a larger fire return interval departure and have deviated the most from pre-Euro-American settlement conditions. Because these areas may have greater "ecological need" they may become higher priority areas for carrying out management burns than north aspects.

Information about both past fire frequency and annual area burned can also be used to derive targets for fire management planning, and to evaluate how well restoration goals are being met. Current estimates from Sequoia and Kings Canyon National Parks are that on average between 6,100 to 10,000 ha burned annually within the Parks prior to Euro-American settlement (Caprio and Graber 2000). In contrast, the current burn program averages about 1,663 ha burned annually (1985-1999 data), although it is having a significant effect restoring fire to key areas that protect important resources or break up large continuous areas of heavy fuel. While a variety of constraints exist (see Caprio and Graber 2000), a major obstacle to burning at pre-Euro-American levels is the backlog of areas that have missed many FRI where the extremely unnatural fuel loads and dense vegetation makes them difficult and costly to burn with significant smoke production. Until these hurdles can be overcome the Parks' burn program will continue to fall behind. The use of models such as FRID–using the best available fire history data–will continue to help target critical locations for restoring fire as an ecosystem process.

CONCLUSIONS

While most investigations of pre-Euro-American fire regimes have focused on patterns of fire frequency, other attributes of the fire regime may be equally important in understanding fire as a process in ecosystem dynamics. The data and analysis in this paper provide not only an estimate of frequency patterns across a large landscape but also a coarse understanding of annual area burned. Both are important in understanding ecosystem processes and dynamics and the scale of the task required to restore fire in this ecosystem.

Within the East Fork watershed considerable variation in FRI were found based on fire history chronologies developed from a network of sites throughout the drainage. The chronologies showed the importance of climate and topography as controllers of spatial and temporal patterns of fire occurrence. The reconstructions also showed (1) differences in mean FRI among sites related to both elevational and aspect, (2) occurrence of common fire years among sites at varying scales, and (3) a connection between fire regime and annual climate variation related to aspect and elevation. Comparisons of FRI between north and south aspects for low-to-mid elevation sites indicated fire was about three times more frequent on the south aspect. There was also a strong inverse relationship between number of fires and elevation on south aspects and a much weaker relationship on north aspects. Additionally, examination of burn patterns by aspect and elevation indicated fire could occur on lower south aspects during almost any year while fire at other locations and large fires across all aspects were related to dry years.

If such patterns are consistent in other drainages they will have important implications for fire and resource managers in terms of planning, anticipating potential fire effects in these areas, and in understanding processes responsible for restoring or maintaining attributes of past vegetation structure and composition. Such information also provides vital baseline data for judging the magnitude and extent of change in park ecosystems over the last 150 yrs and for evaluating whether our fire management accomplishments are meeting NPS mission goals. Eventually, predictive models of general fire regime characteristics across the landscape could be developed based on topographic and biotic influences.

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