Available online at www.sciencedirect.com
ScienceDirect
Forest Ecology and Management 251 (2007) 205–216
Forest Ecology and Management
www.elsevier.com/locate/foreco

Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands

Scott L. Stephens *, Robert E. Martin, Nicholas E. Clinton

Division of Ecosystem Science, Department of Environmental Science, Policy, and Management, 137 Mulford Hall, University of California, Berkeley, CA 94720-3114, USA

Received 16 February 2007; received in revised form 2 June 2007; accepted 6 June 2007

Abstract

In the majority of US political settings wildland fire is still discussed as a negative force. Lacking from current wildfire discussions are estimates of the spatial extent of fire and their resultant emissions before the influences of Euro-American settlement and this is the focus of this work. We summarize the literature on fire history (fire rotation and fire return intervals) and past Native American burning practices to estimate past fire occurrence by vegetation type. Once past fire intervals were established they were divided into the area of each corresponding vegetation type to arrive at estimates of area burned annually. Finally, the First Order Fire Effects Model was used to estimate emissions. Approximately 1.8 million ha burned annually in California prehistorically (pre 1800). Our estimate of prehistoric annual area burned in California is 88% of the total annual wildfire area in the entire US during a decade (1994–2004) characterized as ''extreme'' regarding wildfires. The idea that US wildfire area of approximately two million ha annually is extreme is certainly a 20th or 21st century perspective. Skies were likely smoky much of the summer and fall in California during the prehistoric period. Increasing the spatial extent of fire in California is an important management objective. The best methods to significantly increase the area burned is to increase the use of wildland fire use (WFU) and appropriate management response (AMR) suppression fire in remote areas. Political support for increased use of WFU and AMR needs to occur at local, state, and federal levels because increasing the spatial scale of fire will increase smoke and inevitability, a few WFU or AMR fires will escape their predefined boundaries.

Keywords: Wildfire; Fire regime; Fire policy; Fire suppression; Fire rotation; Smoke; Air resources; Air quality; Particulates; Fire exclusion; Carbon

1. Introduction

The effects of wildfires on the ecosystems of the United States (US) has received great attention in the last decade, particularly in the western US where wildfire area has increased over the last 60 years (Stephens, 2005). US Forest Service's wildfire suppression costs have exceeded 1 billion US dollars in three of the past six years and there is little hope that these costs will decline without significant reform (USDA, 2006). Public concern over wildfire prevention has eclipsed other forest values (Williams and DellaSala, 2004) and this trend will probably continue for the next several decades (Stephens and Moghaddas, 2005).

In the majority of US political settings wildland fire is still discussed as a negative force (Kauffman, 2004). Lacking from current wildfire discussions are estimates of the spatial extent of wildland fire before the influences of Euro-American settlement. This type of information could inform the creation of land management strategies designed to conserve fire-adapted ecosystems. Furthermore, the establishment of baseline or reference conditions in terms of both the amount and effects of fire is a logical first step in terms of conservation planning.

The state of California has worked to reduce the negative effects of wildland fire (i.e. losses in the urban-wildland intermix) while at the same time, promote the important positive effects of fire in many plant communities. The California Fire Plan (CDF, 1996) was created as the blueprint to move the state forward regarding wildfire issues. The plan 'Places the emphasis on what needs to be done long before a fire starts, reduces fire fighting costs and property losses, increase firefighter safety, and is to contribute to ecosystem health.' The plan does not consider what wildland fire did in California before Euro-American settlement and this is the focus of this work.

Fires ignited by lightning and Native Americans have been a component of the majority of California ecosystems for thousands of years. Lightning was the most common source of

* Corresponding author. Tel.: +1 510 642 7304; fax: +1 510 643 5438.
E-mail address: stephens@nature.berkeley.edu (S.L. Stephens).

0378-1127/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2007.06.005

ignitions in California before human populations increased in the mid Holocene (Jones, 1992; Keeley, 2005). After this period, ignitions from both lightning and Native Americans were common in many areas before Euro-American settlement in the 19th century (Pyne, 1982; Biswell, 1989; Anderson and Moratto, 1996; Skinner and Chang, 1996; Keeley, 2002; Anderson, 2005). Modern vegetation assemblages in California have been influenced by humans for thousands of years, first by Native Americans and then by present-day populations.

The prehistoric presence of fire in much of California has been documented using dendrochronology and from studies of past Native American burning practices (Anderson, 1993; Skinner and Chang, 1996; Anderson and Moratto, 1996; Keeley, 2002; Anderson, 2005). Dendrochronology reconstructs past fire regimes (primarily those of low-moderate severity) from the analysis of tree-rings and tree ages (Stokes and Smiley, 1977; McBride, 1983; Swetnam et al., 1985) and therefore, can only be used in forests and woodlands. Tree-ring based fire history studies that employ crossdating (Swetnam et al., 1985) can give accurate and precise information on past fire regimes if appropriate trees are available for sampling (old, fire scarred trees resistant to decay that do not have complacent ring series).

Dendrochronology cannot be used to reconstruct past fire regimes in shrublands and grasslands because these ecosystems commonly do not include trees. Analysis of charcoal deposits from some of these areas can be used to reconstruct past fire regimes but the temporal and spatial resolution of these studies is generally limited (temporal scales of decades to centuries, spatial scales that are difficult to define) (Whitlock et al., 2004).

Past Native American burning practices can be used to estimate fire frequency in many of California's grasslands and woodlands because many of these areas were once managed with fire for diverse objectives (Anderson, 1993; Lewis, 1993; Huntsinger and McCaffrey, 1995; Anderson and Moratto, 1996; Keeley, 2002; Anderson, 2005; Keeley, 2005). Native American fire uses in California have primarily been documented from ethnographic interviews (Anderson, 1993, 2005). The accuracy of these accounts is verified through cross-referencing with testimony from other families, both within and between tribes (Anderson and Moratto, 1996). Oral histories are then combined with information from museum studies, ethnographic and ethnohistoric accounts, and the archaeological record to provide the most thorough reconstruction of past human activities on the land.

After some debate, California's fire regimes were abruptly changed by the policy of fire exclusion that was adopted early in the 20th century (Pyne, 1982; Brown et al., 2004; Dombeck et al., 2004; Stephens and Sugihara, 2006). Fire suppression eventually produced undesirable ecosystem effects including increased tree densities (Parsons and DeBendeetti, 1979), higher fuel loads (Dodge, 1972; Biswell, 1989), and changes in wildlife habitats (Leopold et al., 1963), primarily in ecosystems that once experienced frequent, low-moderate intensity fires.

Presently some prescribed fire is used in California to manage forests, woodland, shrublands, and grasslands but it is constrained by smoke production, crew availability, the urban-wildland interface, possible effects on rare or endangered species, and risks that the fire will escape its boundaries (Stephens and Ruth, 2005). Smoke management is one of the most challenging issues facing burning operations because burning contributes to the cumulative effects of smoke along with other anthropogenic emissions from automobiles, industry, homes, and agriculture. In contrast, smoke production from large wildfires is unregulated and can inundate large areas of the state for months and can produce serious health effects. This work will estimate how much smoke was produced annually in California by prehistoric fires.

The objectives of this paper are to develop estimates of the area burned and resultant emissions from California during the prehistoric period (before 1800) and to compare this to recent wildfire area in the state. Whereas fire suppression had been the goal of land management and fire protection agencies for decades, there has been a gradual trend toward recognition of the role of fire in managing ecosystems. Information from this study can assist land managers by providing an evaluation of what fire once did in California and can provide a baseline of atmospheric conditions against which modern conditions could be compared. This information could also be useful to scientists interested in pre-historic atmospheric dynamics and carbon cycling.

2. Methods

2.1. Prehistoric fire area

The amount of area in California by vegetation type was obtained from Barbour and Majors' widely cited Terrestrial Vegetation of California (1988). Information on the fire history of each vegetation type was obtained and synthesized from the published literature (Tables 1–3). A complication of using the fire history literature is different methods have been used in estimating past fire extent.

The most appropriate metric that could be used to estimate past fire area is the fire rotation because it is directly linked to area burned (Heinselman, 1973; Romme, 1980). It is calculated by taking the time period of interest divided by the proportion of the study area burned in that time period and is generally applied to ecosystems that burn under high-severity crown fires (Agee, 1996). It is relatively easy to distinguish the spatial extent of past high severity fires because of abrupt changes in ecosystem structure; it is much more difficult to delineate past fire extent in low-moderate severity fire regimes because many organisms (trees, shrubs) survive these fires making fire rotation difficult to estimate (Stephens et al., 2003). Few of California's ecosystems (pre-historically) had a fire regime that was dominated by high severity fires (Sugihara et al., 2006) making fire rotation estimates relatively rare for California's vegetation types.

Another metric that can be used to estimate past fire extent is the fire return interval (Agee, 1996). The fire return interval is the time between two successive fire events at a given site or area of a specified size. Past fire frequency can be determined from the years between fire scars from a single tree or composite fire return interval calculated from fire scars on several trees in a selected area (Dieterich, 1980; Swetnam et al., 1985). Composite fire chronologies of multiple trees have been found to provide a more

Table 1
California forest types (Barbour and Major, 1988) and literature used to estimate prehistorical fire return intervals

Vegetation type	Literature
Spruce/cedar/hemlock	Agee (1993); White et al. (2002); Stuart and Stephens (2006)
Cedar/hemlock/Douglas-fir	Agee (1991, 1993); Wills and Stuart (1994); Taylor and Skinner (1998, 2003); Brown et al. (1999); White et al. (2002); Skinner et al. (2006); Stuart and Stephens (2006)
Mixed conifer	Kilgore and Taylor (1979); Caprio and Swetnam (1995); Skinner and Chang (1996); Beaty and Taylor (2001); Bekker and Taylor (2001); Taylor and Skinner (2003); Stephens and Collins (2004); Moody et al. (2006); Skinner et al. (2006); van Wagtendonk and Fites-Kaufman (2006); Fry and Stephens (2006); R. Everett (personal communication, 2006)
Redwood	Jacobs et al. (1985); Finney and Martin (1989); Brown and Swetnam (1994); Keter (1995); Brown et al. (1999); Brown and Baxter (2003); Stephens and Fry (2005); Stuart and Stephens (2006)
Red fir	Taylor and Halpern (1991); Taylor (1993); Skinner and Chang (1996); Taylor (2000); Beaty and Taylor (2001); Bekker and Taylor (2001); Taylor and Solem (2001); Skinner et al. (2006); van Wagtendonk and Fites-Kaufman (2006)
Lodgepole pine/subalpine	Skinner and Chang (1996); Taylor (2000); Stephens (2001); Bekker and Taylor (2001); Taylor and Solem (2001); Skinner (2003); Skinner and Taylor (2006); Riegel et al. (2006); Skinner et al. (2006)
Closed cone pine-cypress	Sugnet (1985); Vogl et al. (1988); Riegel et al. (2006); Davis and Borchert (2006); Skinner et al. (2006)
Ponderosa pine/shrub	Caprio and Swetnam (1995); Skinner and Chang (1996); Riegel et al. (2006); Skinner and Taylor (2006); van Wagtendonk and Fites-Kaufman (2006)
Great basin pine	Skinner and Chang (1996); Taylor (2000); Stephens (2001); Norman and Taylor (2003); Stephens et al. (2003); Taylor and Beaty (2005); Moody et al. (2006); Riegel et al. (2006); Skinner and Taylor (2006); Skinner et al. (2006)
Pinyon-Jjuniper	Baker and Shinneman (2004); Brooks and Minnich (2006); Riegel et al. (2006)
Juniper steppe	Baker and Shinneman (2004); Riegel et al. (2006)

comprehensive record (versus single tree fire return interval) of past fires for the site in question (Dieterich, 1980; Agee, 1993). It should be noted that the grand mean fire return interval across multiple sites in a vegetation type is equal to the fire rotation (McKelvey et al., 1996; Baker and Ehle, 2001) but estimating the grand mean interval requires extensive fire scar sampling which is difficult because of a lack of fire scarred materials or lack of time and/or funding (but see several papers by Taylor and Skinner for studies that have estimated the grand mean fire return interval for forested areas of California).

Table 2
California woodland, shrubland, and grassland vegetation types (Barbour and Major, 1988) and literature used to estimate prehistorical fire return intervals

Vegetation type	Literature
California mixed evergreen	Stephens and Fry (2005); Davis and Borchert (2006); Skinner et al. (2006)
Chaparral	Minnich (1983); Moritz et al. (2004); Davis and Borchert (2006); Keeley (2006); Skinner et al. (2006)
Montane chaparral	Nagel and Taylor (2005); Skinner and Taylor (2006)
Coastal sagebrush	Davis and Borchert (2006); Keeley (2006)
California oakwoods and coastal sagebrush	McClaran and Bartolome (1989); Greenlee and Langeheim (1990); Mensing (1992); Anderson (1993); Anderson and Moratto (1996); Keeley (2002); Anderson (2005); Wills (2006)
California oakwoods	McClaran and Bartolome (1989); Greenlee and Langeheim (1990); Mensing (1992); Anderson (1993); Anderson and Moratto (1996); Keeley (2002); Anderson (2005); Wills (2006)
Fescue-oatgrass	Johnson and Smathers (1976); Greenlee and Langeheim (1990); Anderson (1993); Anderson and Moratto (1996); Keeley (2002); Anderson (2005); Riegel et al. (2006)
California steppe	Johnson and Smathers (1976); Anderson (1993); Anderson and Moratto (1996); Keeley (2002); Wills (2006)
Tule marshes	Anderson (1993); Anderson and Moratto (1996); Anderson (2005); Wills (2006)
Alpine meadows	van Wagtendonk and Fites-Kaufman (2006)
Sagebrush steppe	Brooks and Minnich (2006); Riegel et al. (2006)

Table 3
California forest and shrubland vegetation types from Barbour and Major (1988) and estimates of fire rotation before the influences of Euro-American settlement

Vegetation type	Average fire rotation (years)	Literature
Cedar/hem./Douglas-fir	40	Agee (1991)[a]; Taylor and Skinner (1998)
Mixed conifer	27	Taylor and Skinner (2003); Beaty and Taylor (2001); Bekker and Taylor (2001)
Red fir	63	Taylor (2000); Bekker and Taylor (2001); Skinner et al. (2006)
Lodgepole/subalpine	46	Bekker and Taylor (2001)
Great basin pine	22	Taylor (2000); Bekker and Taylor (2001); Stephens et al. (2003)
Chaparral	70	Minnich and Chou (1997)[b]
Juniper-pinyon	440	Baker and Shinneman (2004)[c]

[a]Estimate for mesic white fir-Douglas-fir in southern Oregon; [b]Estimate is from chaparral from northern Baja California without fire suppression; [c]Estimated from the period covered by fire suppression.

In this analysis, we first summarized fire rotation information that was applicable to California ecosystems because it can be directly used to estimate area burned during the prehistoric period. Since this information is only available for a limited number of vegetation types, we then summarized fire history information derived from dating fire scars. Specifically, the median fire-return interval (MFRI) for each forest and woodland vegetation type was estimated as the grand mean of all individual studies that reported a median fire return interval. Where ranges, but no MFRI were reported, we estimated the MFRI to be one-third of the way from the shortest interval to the longest interval. The rationale for this is that fire return intervals data in most vegetation types are skewed toward the low intervals within the range (Stokes and Smiley, 1977; Finney and Martin, 1989). Also estimated was the high fire return interval (HFRI). This interval was the grand mean of the high end of the average fire interval range reported from the literature and is a more conservative estimate of past fire frequency (e.g. average fire return interval reported to vary from 8 to 15 years for a particular vegetation type; HFRI is therefore 15 years if only one study was available for this vegetation type). It is assumed in this analysis that the HFRI is similar to the fire rotation. A comparison of HFRI and fire rotation was done in those ecosystems where both metrics were reported. A map showing the locations of forest and woodland fire history studies used in this analysis is given in Fig. 1. Mapping the locations of grassland fire history information was not possible because these studies were referenced by vegetation type and not tied to a specific part of the state. Past Native American burning practices were used to estimate fire frequency primarily in grasslands.

Once fire metrics were established (fire rotation, MFRI, HFRI), they were divided into the area of each corresponding vegetation type to arrive at estimates of area burned each year. These burn area estimates were then summed to obtain an annual area burned for California. Prehistoric fire regimes have not been quantitatively described for most of the desert regions of Southeastern California (which comprise about 26% of the state), largely because the usual tools for reconstructing fire histories, such as analyzing fire scars or coring sediments in lakes, cannot be used where these structures are not present (Brooks and Minnich, 2006). Fire was probably rare in California deserts because of low productivity and low horizontal fuel continuity before invasive species were introduced (Brooks and Minnich, 2006), and therefore, deserts were excluded from our area burned and emission analysis. Tables 1–3 summarizes the literature used to estimate past fire return intervals and fire rotation.

2.2. Prehistoric emissions

Emissions estimates corresponding to estimated annual burned areas were computed for 10 μm particulates (PM 10), 2.5 μm particulates (PM 2.5), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NOX), and sulfur dioxide (SO_2) using the First Order Fire Effects Model (FOFEM) version 5.21 (Keane et al., 2004; Reinhart et al., 1997; Clinton et al., 2006). FOFEM does not estimate the carbon fraction that could be transformed by fire into relatively inert forms that could be a significant sink of carbon (Kuhlbusch and Crutzen, 1995).

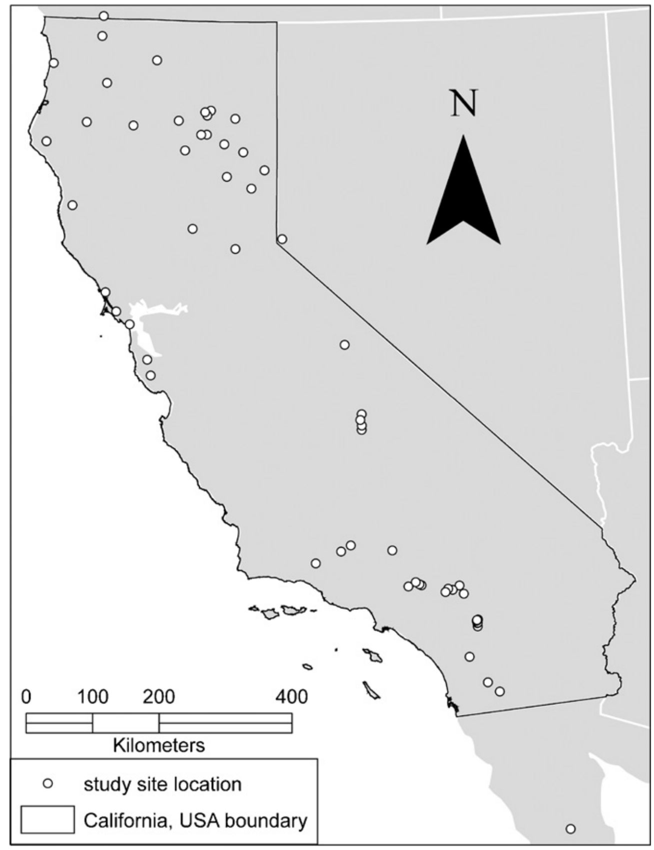

Fig. 1. Approximate location of forest and woodland fire history studies used to estimate past fire occurrence in California. Each study location has between 2 and 10 sampled stands.

FOFEM fuel models were assigned based on similarity of dominant vegetation to the Barbour and Major (1988) vegetation types. The lowest ('light') pre-burn fuel load present in the FOFEM fuel models were used in all cases (Table 4). Selection of 'light' fuel loads was done in an attempt to use data that are representative of pre-historic conditions. While estimates of pre-historic fuel loads in Californian ecosystems are rare, the values used in the simulation for great basin pine, ponderosa pine (*Pinus ponderosa* Laws), and mixed conifer forests are similar to fuel loads measured in forests in the Sierra San Pedro Martir (SSPM) that have never been logged and fire suppression did not begin until 1970 (Stephens, 2004). In all emission estimates fuel type was 'natural-fuel' and the log loading distribution was set to default values. Fuel loads used in some FOFEM models are given in Table 4; percent consumption of canopy fuels are given in Table 5.

Simulations were performed for each vegetation type, corresponding to one-third of the annual area burned in the late-summer with 'very dry' fuel moisture conditions, and two-thirds of the annual area burned in the fall with 'dry' fuel moisture conditions. A dominant fall burning period was chosen because the majority of tree-ring (Stephens et al., 2003; Stephens and Collins, 2004; Caprio and Swetnam, 1995; Taylor

Table 4
First Order Fire Effects Model (FOFEM) fuel loads (t/ha) for selected Barbour and Major (1988) vegetation types

	Barbour and Major type							
	Redwood	Ponderosa-scrub	Mixed conifer	Lodgepole-subalpine	Great Basin pine	Juniper pinyon	California steppe	Alpine meadows
Litter	1.12	1.57	1.68	0.67	1.57	0.04	0	0
1 h (0–0.64 cm)	1.01	0.09	0.27	0.20	0.09	0.20	0	0
10 h (0.64–2.54 cm)	2.35	0.69	0.85	0.81	0.69	0.56	0	0
100 h (2.54–7.62 cm)	3.14	0.90	1.68	0.67	0.90	0.38	0	0
1000 h sound (>7.62 cm)	50.44	5.04	20.18	15.13	5.04	0	0	0
1000 h rotten (>7.62 cm)	5.6	0.56	2.24	1.68	0.56	0	0	0
Herbaceous	0.22	0.11	0.22	0.22	0.22	0.09	1.05	1.39
Shrubs	0.38	0.56	0.45	0.27	0.45	0.27	0	0
Crown foliage	0	6.73	6.73	6.73	6.73	0	0	0
Crown branchwood	0	0.78	3.36	5.38	0.78	0	0	0

and Skinner, 2003; Taylor and Beaty, 2005; R. Everett personal communication, 2006) and oral history (Anderson, 2005) based fire histories have identified this period as the dominant burning period although these studies also report on some fires that occurred in the summer, especially in the southern portion of the state. Simulations used moisture contents for 10-h (0.63–2.54 cm in diameter) and 1000-h (7.62 cm and larger) time-lag fuels for dry and very dry conditions of 10% and 15%, or 6% and 10%, respectively. These moisture contents are similar to those measured in California fires during similar periods (Finney and Martin, 1993; Stephens and Finney, 2002). Using these parameters, FOFEM produces estimates of emissions created by a simulated fire for each vegetation type. Total emissions were calculated by multiplying the area of each vegetation type by the emissions estimate per area. This was done using both the MFRI and HFRI.

2.3. Historic fire area

To provide a comparison of the area burned prehistorically in California, we determined the average annual area burned in the states' wildlands from 1950 to 1999. Data used in this analysis were provided by the California Department of Forestry and Fire Protection Fire and Forest Resource Assessment Program (FRAP, 2005) that includes state, federal, and private lands. Annual area burned data were summarized in four categories (grassland, woodland, shrubland, forest) to facilitate a comparison to the estimates of prehistoric burned area. The FRAP data does not include deserts, urban areas, agriculture, and lands above 1982 m (6000 ft).

3. Results

3.1. Prehistoric fire area

There was a large amount of diversity in fire return intervals and fire rotations among California's ecosystems before fire suppression was initiated (Tables 3, 5 and 6). Fire return intervals (MFRI, HFRI) and fire rotations varied depending on vegetation type with the shortest intervals in grasslands and oak woodlands and the longest intervals in northwestern coastal coniferous forests, alpine meadows, and

Table 5
California forest types and areas from Barbour and Major (1988) and estimates of fire return intervals and annual areas burned before the influences of Euro-American settlement

Vegetation type	Area (ha)	Crown burned (%)	Period between fires (years)		Hectares burned per year	
			MFRI	HFRI	MFRI	HFRI
Spruce/cedar/hemlock	2004	75	100	250	20	8
Cedar/hem./Douglas-fir	806278	30	20	110	40314	7330
Mixed conifer	5522676	5	8	20	690334	276134
Redwood	928102	0	10	30	92810	30937
Red fir	761396	50	15	50	50760	15228
Lodgepole/subalpine	860378	7.5	25	60	34415	14340
Pine-cypress	49290	80	20	50	2465	986
Ponderosa/shrub	678043	5	5	12	135609	56504
Great basin pine	19636	2.5	7	20	2805	982
Juniper-pinyon	985407	5	30	100	32847	6854
Juniper steppe	363867	5	40	120	9097	3032
Calif. mixed evergreen	1359693	5	10	30	135969	45323
Total					1227445	457658

MFRI—median fire return interval and HFRI—high fire return interval.

Table 6
California woodland, shrubland, and grassland vegetation types and areas from Barbour and Major (1988) and estimates of fire return intervals and annual areas burned before the influences of Euro-American settlement

Vegetation type	Area (ha)	Period between fires (years)		Hectares burned per year	
		MFRI	HFRI	MFRI	HFRI
Chaparral	3400234	30	70	113341	48575
Montane chaparral	229220	30	50	7641	4584
Coastal sagebrush	989414	20	40	49470	24735
Coastal sagebrush-California oakwoods	256470	5	20	51294	12824
California oakwoods	3821807	3	8	1273936	477726
Great Basin sagebrush	740558	20	60	37028	12343
Fescue-oatgrass	351484	3	8	117161	43936
California steppe	5288897	3	8	1762966	661112
Tule marshes	743764	5	15	148753	49584
Alpine meadows	298948	50	100	5979	2989
Sagebrush steppe	1298380	30	70	43279	18548
Total				3610848	1356956

MFRI—median fire return interval and HFRI—high fire return interval.

juniper woodlands (Tables 3, 5 and 6). Information from past Native American burning practices (interval between anthropogenic ignitions) was important to characterize grassland fire regimes.

Using the estimates of MFRI and HFRI by vegetation type (Tables 5 and 6), the amount of area burned annually in California varied from 1,814,614 to 4,838,293 ha (excluding the desert region in Southeastern California) during the prehistoric period. With the land area of California equaling 40,396,822 ha (CCDB, 2003), this results in 4.5–12.0% of the state's lands burning annually.

3.2. Prehistoric emissions

Emission products for each vegetation type are summarized in Tables 7 and 8 using the MFRI and HFRI. The largest constituent produced by fire (using the MFRI) during the prehistoric period was carbon dioxide at approximately 89.7 Tg per annum (Table 9). Using a HFRI estimate of past fire frequency by vegetation type produced an estimate of 33.6 Tg of carbon dioxide per annum (Table 9).

Particulates (PM 10) produced during combustion were approximately 1.5 Tg annually using the MFRI and 0.56 Tg annually using the HFRI (Table 9). Carbon monoxide production was approximately 16.7 Tg annually using the MFRI and was 6.2 Tg annually using the HFRI (Table 9). NOX and sulfur dioxide were produced in smaller amounts (Table 9). Changing all FOFEM fuel models loads to 'typical' (versus 'light' that was used in this analysis) and fire season to fall increased emission outputs by a factor of approximately 2.3.

3.3. Historic fire area

Wildfires in California shrublands have burned at the highest rates from 1950 to 1999 (approximately 51,000 ha $year^{-1}$) (Fig. 2). Forested areas in California have burned at

Table 7
Wildfire emissions (Gg) produced annually from California forests using the HFRI/MFRI

Vegetation type	Emission type						
	PM 10	PM 2.5	CH_4	CO	CO_2	NOX	SO_2
Spruce/cedar/hemlock	0.01/0.03	0.01/0.03	0.01/0.02	0.15/0.38	0.65/1.64	0/0	0/0
Cedar/hem./Douglas-fir	12.34/68.12	10.46/58.37	6.34/34.98	138.94/766.26	598.73/3301.91	0.05/0.32	0.54/2.62
Mixed conifer	331.38/828.44	280.93/702.32	169.92/424.79	3719.01/9297.52	16576.58/41441.38	2.58/6.45	13.21/33.01
Redwood	52.28/156.84	44.29/132.88	26.85/80.55	588.03/1764.08	2533.91/7601.64	0.25/0.76	2.01/6.03
Red fir	14.56/48.55	12.35/41.15	7.43/24.77	162.42/541.41	788.32/2627.74	0.24/0.80	0.06/2.01
Lodgepole/subalpine	8.70/16.48	5.82/13.98	3.53/8.46	77.04/184.90	341.05/818.49	0.05/0.12	0.27/0.64
Pine-cypress	0.48/1.20	0.41/1.02	0.24/0.61	5.34/13.34	27.81/69.51	0.01/0.03	0.02/0.05
Ponderosa/shrub	8.72/20.93	7.39/17.73	4.41/10.59	94.48/226.75	631.24/1514.96	0.44/1.06	0.44/1.06
Great Basin pine	0.15/0.43	0.13/0.36	0.08/0.22	1.64/4.69	10.74/30.67	0.01/0.02	0.01/0.02
Juniper-pinyon	1.65/7.92	1.40/6.73	0.85/4.06	18.60/89.16	78.75/377.42	0.01/0.04	0.06/0.31
Juniper steppe	0.02/0.06	0.02/0.05	0.01/0.02	0.19/0.58	2.72/8.16	0.00/0.01	0/0
Calif. mixed evergreen	31.99/95.96	27.09/81.28	16.41/49.23	359.04/1077.12	1606.07/4818.21	0.25/0.76	1.30/3.91
Total	460.45/1244.94	390.3/1055.37	236.07/638.31	5164.9/13966.17	23196.5/62611.74	3.9/10.37	18.4/49.67

Forest types from Barbour and Major (1988).
MFRI—median fire return interval; HFRI—high fire return interval; PM 10—10 μm particulates; and PM 2.5—2.5 μm particulates.

Table 8
Wildfire emissions (Gg) produced annually from California woodlands, shrublands, and grasslands using the MFRI/HFRI

Vegetation type	Emission type						
	PM 10	PM 2.5	CH_4	CO	CO_2	NOX	SO_2
Chaparral	5.17/12.07	4.41/10.29	1.36/3.18	10.99/25.66	2997.76/6994.73	5.39/12.58	1.69/3.94
Montane chaparral	0.36/0.60	0.30/0.51	0.16/0.26	3.14/5.23	67.67/112.79	0.10/0.17	0.04/0.07
Coastal sagebrush	0.12/0.35	0.16/0.31	0.06/0.11	0.91/1.83	72.037/144.07	0.12/0.24	0.05/0.09
Coastal sagebrush-California oakwoods	2.34/9.37	1.99/7.95	1.17/4.68	25.37/101.47	168.44/673.72	0.11/0.46	0.13/0.52
California oakwoods	85.67/228.46	72.47/193.24	43.01/114.71	941.87/2511.66	5379.41/14345.08	2.68/4.28	4.28/11.42
Great Basin sagebrush	0.19/0.57	0.15/0.46	0.06/0.19	0.87/2.60	79.78/239.35	0.14/0.43	0.05/0.14
Fescue-oatgrass	0.15/0.39	0.10/0.26	0.05/0.13	0.29/0.79	82.34/219.57	0.15/0.39	0.05/0.13
California steppe	2.22/5.93	1.48/3.95	0.74/1.98	4.45/11.86	1238.97/3303.91	2.22/5.93	0.74/1.98
Tule marshes	3.17/9.50	2.65/7.95	1.56/4.67	33.10/99.31	293.99/882.00	0.28/0.83	0.22/0.67
Alpine meadows	0.01/0.03	0.01/0.02	0.00/0.01	0.03/0.05	7.39/14.78	0.01/0.03	0.00/0.01
Sagebrush steppe	0.13/0.31	0.12/0.27	0.04/0.10	0.69/1.60	54.02/126.04	0.09/0.21	0.03/0.08
Total	99.59/267.58	83.83/225.22	48.22/130.01	1021.72/2762.07	10441.80/27056.05	11.30/28.41	7.28/19.04

Vegetation types from Barbour and Major (1988).
MFRI—median fire return interval; HFRI—high fire return interval; PM 10—10 μm particulates; and PM 2.5—2.5 μm particulates.

Table 9
Summary of wildfire emissions (Tg) produced annually from California forests, woodlands, shrublands, and grasslands during the prehistoric period

Fire interval	Emission type						
	PM 10	PM 2.5	CH_4	CO	CO_2	NOX	SO_2
MFRI	1.512	1.281	0.768	16.728	89.667	0.039	0.069
HFRI	0.560	0.474	0.284	6.187	33.638	0.015	0.026

MFRI—median fire return interval; HFRI—high fire return interval; PM 10—10 μm particulates; and PM 2.5—2.5 μm particulates.

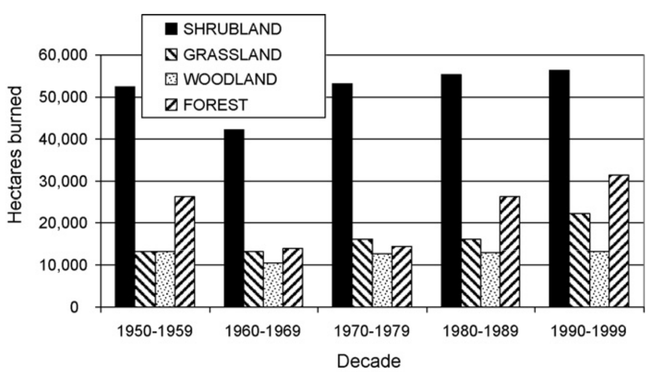

Fig. 2. Average annual area burned in California by wildfires from 1950 to 1999 (does not include desserts, urban areas, agriculture, and lands above 1982 m).

approximately 23,000 ha $year^{-1}$ over the same time period. The amount of area burned by wildfire in grasslands and woodlands was lower at approximately 16,000 and 12,000 ha $year^{-1}$, respectively (Fig. 2). The average area burned annually by wildfire in all wildlands from 1950 to 1999 was approximately 102,000 ha $year^{-1}$.

4. Discussion

Even using our low estimates of annual area burned (using the HFRI), a high amount of wildfire emissions were produced in California on an annual basis. Our estimated annual rate of carbon monoxide emission for pre-settlement California is 6.2 Tg using the HFRI estimate of past fire occurrence (Table 9). This estimate is about half the CO emission estimates for a month of boreal forest fires in the Canadian Northwest Territories (12 Tg, Wotowa and Trainer, 2000), approximately one-fifth that annually generated from tropical forest conversion and clearing in Brazilian Amazonia (31.3 Tg, Fearnside, 2000), larger than emissions associated with forest, grassland, and agricultural burning in Texas in 1996 (4.6 Tg, Dennis et al., 2002), larger than emission estimates for the 2003 Southern California wildfires (0.46 Tg, Clinton et al., 2006), and much larger than emission estimates from year 2000 wildfires and prescribed burning in California (0.7 Tg, Clinton et al., 2003).

At a broad spatial scale, Leenhouts (1998) estimates approximately 55 Tg of "pre-industrial" CO emissions annually from the conterminous U.S. Hoelzemann et al. (2004) estimate 33–39 Tg of CO emissions from North America in year 2000. Andrae and Merlet (2001) estimate 6100 Tg of annual, global CO emissions from "Extratropical Forests" and "Savanna and Grassland." In terms of area burned annually, our estimates are smaller than those from Bachelet et al. (2003) who predicted approximately 19–33 million ha of annual burning in the conterminous U.S. or Leenhouts (1998) that predicted approximately 35–86 million ha burning annually in the conterminous U.S. In the context of these continental and larger scale estimates, the area burned and resultant emissions we report do not seem extreme.

Fire rotation estimates for mixed conifer, red fir (*Abies magnifica* Murr.), and great basin pine forest types were approximately 25% larger than the corresponding values of HFRI (Tables 3 and 5). This can be partially explained because many studies that estimated fire rotation are from the cooler and wetter Cascade Range (Taylor, 2000; Bekker and Taylor, 2001) and Klamath Mountains (Taylor and Skinner, 2003) of northern California whereas HFRI was estimated from literature that included central, southern, and western populations that were drier and experienced more frequent fires. In most cases, fire rotation and HFRI were similar with the exception of pinyon-juniper woodlands (Tables 1 and 3). Estimates of fire rotation and fire return intervals from pinyon-juniper woodlands are poorly understood (Baker and Shinneman, 2004) making it difficult to estimate past fire area for this vegetation type.

It is recognized here that past Native American fire uses were the main source of information when estimating prehistoric fire area in grasslands (Table 2). We believe that this information is sound because California Indian elders are still a substantial source of information about former traditional plant uses and management practices (Anderson and Moratto, 1996; Anderson, 2005). The impacts of Native American burning probably varied throughout the state with the highest impacts near larger population centers in coastal California and the Central Valley where lightning ignitions were rare (Keeley, 1982, 2002, 2005; Stephens and Libby, 2005).

Coastal California is one area where recorded information from past Native American burning practices can be compared to a fire scar chronology. In this region anthropogenic ignitions dominated because of the rarity of lightning ignited fires (Keeley, 1982, 2002, 2005; Stephens and Libby, 2005). Coast redwood (*Sequoia sempervirens* (D. Don) Endl.) forests are found in north-central coastal California and is an excellent recorder of past fires. Many studies have documented relatively frequent fires in this forest type (Table 5) and most of these fires were ignited by Native Americans for a variety of resources objectives.

Most reported applications of fire-use in coastal California forests were targeted at prairies, grasslands, or oak woodlands (Huntsinger and McCaffrey, 1995; Anderson, 2005; Stephens and Fry, 2005). These fires were intentionally ignited and certainly burned into the surrounding coast redwood forests because there were few barriers to fire spread. Coast redwood forests have the highest canopy cover, height, and densities of any vegetation type in the coastal California and such characteristics influence local microclimates (Dawson, 1998). Specific microclimate changes include increases in relative humidity, decreases in surface air temperatures, reduction in ground level windspeeds, and higher fuel moistures. Some anthropogenic fires that were ignited in surrounding prairies, grasslands, or oak woodlands would naturally go out themselves at the coast redwood ecotone because of the differing fire environments (Stuart, 1987; Finney and Martin, 1989; Stephens and Fry, 2005). It is probable that the number of fires recorded in the annual growth rings of coast redwood trees is but a subset of those fires that burned in adjacent prairies, grasslands, and oak woodlands in this region (Stephens and Fry, 2005). The redwood forests of coastal California is one area where there is abundant physical evidence of past Native American fire use that coincides with that recorded from ethnographic interviews. In this case, the oral and physical evidence are in general agreement.

Our estimates of Californian prehistoric fire area are between 1.8 and 4.8 million ha year^{-1} which resulted in 4.5–12.0% of the states lands burning annually. If one considers that only three-quarters of the California's lands were taken into account in this analysis (we removed the deserts in South-eastern California), then the figures represent 6–16% of the area studied burning annually. One complication in this analysis is most tree-ring and cultural fire history information comes from the end of the Little Ice Age but estimates of the area covered by different vegetation types in California came at least a century later. The later vegetation map was used because we do not have good estimates of vegetation coverage's in California that correspond to the Little Ice Age.

The use of the MFRI to estimate past fire area likely over estimates the actual area burned. This occurs because most fire history studies are not extensive enough to estimate the grand mean fire return interval for the vegetation type being investigated. Using the MFRI would over estimate area burned because not all areas within a wildfire's perimeter will actually burn, especially if the fires occur within an intact fire regime. Fire regimes that are intact produce high amount of spatial heterogeneity and low amounts of horizontal fuel continuity (Stephens, 2004; Stephens and Gill, 2005; Stephens et al., 2007). Many areas within a fire's perimeter would probably not burn, and therefore, using the MFRI would overestimate past fire area and emissions. The use of the HFRI to estimate past fire area and emissions reduces the chance of this error because HFRI is similar to the fire rotation. Using estimate of HFRI still results in very large fire areas when compared to fire occurrence in California over the last several decades (Tables 5 and 6, Fig. 2).

There are also other sources of error in this analysis. First, the study sites for individual fire histories (fire return intervals and fire rotation) might not have been representative of the entire vegetation type given in Barbour and Major (1988). Second, the estimates we used for MFRI and HFRI in some vegetation types may be low, especially those estimated primarily from past Native American burning practices and located in areas away from California's coast and Central Valley where Native American populations were lower. Third, many dendrochronology based fire history studies developed a composite MFRI but all fires sampled might not have covered the entire sampled area.

Regardless of the possible errors in this study, we have to conclude that prehistorically a large amount of California burned every year. From 1950 to 1999 the average annual area burned by wildfire in all vegetation types in California was approximately 102,000 ha year^{-1} (Fig. 2). This amounts to 5.6% what would have burned in a similar period of time during the prehistoric era using the HFRI. Land use practices from 1950 to 1999 have converted relatively large areas of grassland and woodlands to other land uses (agriculture, urban areas) but even with these changes, the annual area burning in California from 1950 to 1999 is very small when compared to the prehistoric period. Higher amounts of management ignited prescribed burning would be desirable in California but other management methods that incorporate fire need to be developed to increase the amount of burning.

An increase in Wildland Fire Use (WFU) in remote areas of California is one method that could be used to significantly increase the area burned (Collins and Stephens, in press). WFU is the management of naturally ignited lightning fires to accomplish specific resource management objectives in pre-defined geographic areas outlined in fire management plans;

most WFU fires occur in wilderness but a few are burning in non-wilderness areas (Mills, 2006). The idea of increased use of WFU is supported by a recent audit of fire management programs in the US Forest Service (USDA, 2006). This audit determined that the US Forest Service can further strengthen the cost-effectiveness of its firefighting without sacrificing safety by increasing the use of WFU. To control the risk of costly, catastrophic wildfires, the US Forest Service could give WFU and fire suppression equal consideration. However, existing firefighting policies and the lack of qualified WFU personnel restrict managers from doing so (USDA, 2006).

Under current fire policies, US Forest Service can either manage a fire for WFU or suppression, and once a fire has been fought for suppression it can never again be managed for WFU (USDA, 2006). Since the agency bears considerable pressure to begin fire operations as suppression, these restrictions increase the likelihood that even potentially beneficial fires will be suppressed. No human-caused fires can be managed as WFU fires under current policy, all of them fall under fire suppression.

There is an option to manage suppression fires under 'Appropriate Management Response' (AMR) and this allows a suppression fire to be managed with less suppression activities. AMR was successfully used to manage the 2005 Wooley Fire in the Klamath National Forest's Marble Mountain Wilderness in California (Lewis, 2006). The ignition of this fire was likely anthropogenic so managers could not use WFU but they could use AMR. The Wooley fire burned 1268 ha and costs were US \$313 ha^{-1}. The use of WFU and AMR managed fires may be the only methods where fire could be reintroduced into California's ecosystems at even moderate spatial scales.

4.1. *Comparison of prehistoric fire area in California to US wildfire area*

A broader comparison of prehistoric fire area in California is possible when we compare it to the annual area burned by wildfire in the entire US. The average annual area burned in lands administered by the US Bureau of Land Management, US Bureau of Indian Affairs, US National Park Service, US Fish and Wildlife Service, US Forest Service, and all State Lands from 1994 to 2004 was 2,055,031 ha (NIFC, 2005). During this period (1994–2004) several extensive fire policies were developed including the National Fire Plan, Ten-Year Comprehensive Strategy, Healthy Forest Restoration Act, and California Fire Plan.

All of the recent US federal and state fire policies were initiated after years of ‘‘extreme’’ wildfire activity. In this work, we estimated that approximately 1,800,000 ha of California wildlands burned annually (using the HFRI). Certainly fuels have accumulated in many California ecosystems and this has resulted in more fires of higher intensity (i.e. lower pyrodiversity) but recent annual wildfire areas in the entire US are comparable to what probably burned in California alone during the prehistoric period. Particulates produced from annual prehistoric fires were substantial and may have moderated ground sunlight intensity by dispersing incoming solar radiation to space.

5. Conclusion

This work estimates that approximately 1,800,000 ha of California wildlands burned annually in the prehistoric period. Our estimate of prehistoric annual area burned in California is 88% of the total annual wildfire area in the entire US during a decade (1994–2004) characterized as ‘‘extreme’’ regarding wildfires (Stephens and Ruth, 2005). The idea that US wildfire area of approximately 2 million ha annually is extreme is certainly a 20th or 21st century perspective.

Skies were likely smoky in the summer and fall in California before fire suppression. An eye-witness account of smoke in northern California forests (C.H. Merriam 1898, quoted in Morford, 1993) reported ‘‘Of the hundreds of persons who visit the Pacific slope in California every summer to see the mountains, few see more than the immediate foreground and a haze of smoke which even the strongest glass is unable to penetrate.’’ C.H. Merriam traveled extensively in California and was Chief, Division of Biological Survey for the US.

Air quality policies could be modified to allow more WFU, classifying these events as natural sources of emissions would be a positive step. Currently WFU fires are classified as anthropogenic sources of emissions and this reduces the capacity to burn even moderate spatial scales. Increasing the spatial extent of AMR suppression fire in California is another important management objective. Political support for increased use of WFU and AMR needs to occur at local, state, and federal levels because increasing the spatial scale of fire will increase smoke and inevitability, a few fires will escape their predefined boundaries.

Despite the complexity inherent in local fire regimes, regional fire activity often oscillates in phase with year-to-year climatic variability (Clark, 1988; Swetnam, 1993; Collins et al., 2006). For example, the area burned annually by wildfire across the southern US tends to decrease in El Nino years and increase during La Nina years (Swetnam and Betancourt, 1990) but our analysis only produced estimates of average annual burned area. Future research may be able to incorporate climate variability when estimating the area burned in California during the prehistoric period.

Acknowledgments

We thank Max Moritz, Danny Fry, and Neva Sotolongo for reviewing this manuscript. We thank David Sapsis and James Spero, California Department of Forestry and Fire Prevention—Fire and Forest Resource Assessment Program, for their assistance in obtaining recent wildfire data for California. We thank Carl Skinner for discussions regarding past fire occurrence in CA.

References

Agee, J.K., 1991. Fire history along an elevational gradient in the Siskiyou Mountains. Oregon. Northwest Sci. 65, 188–199.

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Covelo, California, p. 493.

Agee, J.K., 1996. Fire regimes and approaches for determining fire history. USDA Forest Service General Technical Report INT-341. Intermountain Forest and Range Experiment Station, Ogden, Utah. pp. 3–7.

Anderson, M.K., 1993. The experimental approach to assessment of the potential ecological effects of horticultural practices by indigenous peoples on California wildlands. Ph.D. Dissertation. University of California, Berkeley, 211pp.

Anderson, M.K., 2005. Tending the Wild: Native American Knowledge and the Management of California's Natural Resources. University of California Press, Berkeley, CA, p. 526.

Anderson, M.K., Moratto, M.J., 1996. Native American land-use practices and ecological impacts. Sierra Nevada Ecosystem Project: Final Report to Congress. Vol. II Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37, Centers for Water and Wildland Resources, University of California, Davis, pp. 187–206.

Andrae, M.O., Merlet, P., 2001. Emission of trace gases and aerosols from biomass burning. Global Biogeochem. Cycles 15, 955–966.

Bachelet, D., Neilson, R.P., Hickler, T., Drapek, R.J., Lenihan, J.M., Sykes, M.T., Smith, B., Sitch, S., Thonicke, K., 2003. Simulating past and future dynamics of natural ecosystems in the United States. Global Biogeochem. Cycles 17, 1045.

Baker, W.L., Ehle, D., 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Can. J. Forest Res. 31, 1205–1226.

Baker, W.L., Shinneman, D.J., 2004. Fire and restoration of pinon-juniper woodlands in the western United States. For. Ecol. Manage. 189, 1–21.

Barbour, M.G. Major, J., 1988. Terrestrial Vegetation of California, expanded edition. California Native Plant Society Special Publication 9. Sacramento, California, pp. 3–10.

Beaty, R.M., Taylor, A.H., 2001. Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, southern Cascades, California, USA. J. Biogeogr. 28, 955–966.

Bekker, M.F., Taylor, A.H., 2001. Gradient analysis of fire regimes in Montane forests of the Southern Cascade Range, Thousand Lakes Wilderness, California, USA. Plant Ecol. 155, 15–28.

Biswell, H.H., 1989. Prescribed Burning in California Wildland Vegetation Management. UC Press, Berkeley, California, p. 255.

Brooks, M.L., Minnich, R.A., 2006. Southeastern deserts bioregion. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, California, pp. 391–414.

Brown, P.M., Swetnam, T.W., 1994. A cross-dated fire history from coast redwood near Redwood National Park, California. Can. J. Forest Res. 24, 21–31.

Brown, P.M., Kaye, M.W., Buckley, D., 1999. Fire history in Douglas-fir and coast redwood forests at Point Reyes National Seashore, California. Northwest Sci. 73, 205–216.

Brown, P.M., Baxter, W.T., 2003. Fire history in coast redwood forests on the Mendocino Coast, California. Northwest Sci. 77, 147–158.

Brown, R.T., Agee, J.K., Franklin, J.F., 2004. Forest restoration and fire: principals in the context of place. Conserv. Biol. 18, 903–912.

Caprio, A.C., Swetnam T.W., 1995. Historic fir regimes along an elevational gradient on the west slope of the Sierra Nevada. In: Brown, J.K., Mutch, R.W., Spoon, C.W., Wakimoto, R.H. (Technical coordinators). Proceedings of the symposium on fire in wilderness and park management. USDA Forest Service General Technical Report INT-320. Intermountain Forest and Range Experiment Station, Ogden, Utah., pp.173–179.

CCDB, 2003. County and city data book of California: Consolidated file. The California Digital Library, Oakland, California, http://countingcalifornia.cdlib.org/matrix/c101.html.

CDF, 1996. California fire plan. California Department of Forestry and Fire Protection. Sacramento, CA, 117 pp.

Clark, J.S., 1988. Effects of climate change on fire regimes in Northwestern Minnesota. Nature 334, 233–235.

Clinton, N., Ruiliang, P., Gong, P., Yong, T., Scarborough, J., 2003. Extension and input refinement to the ARB wildland fire emissions estimation model. Final Report. California Air Resources Control Board Contract 00-729, Sacramento, California.

Clinton, N.E., Peng, G., Klaus, S., 2006. Quantification of pollutants from very large wildland fires in southern California, USA. Atmos. Environ. 40, 3686–3695.

Collins, B.M., Omi, P.N., Chapman, P.L., 2006. Regional relationships between climate and wildfire-burned area in the Interior West, USA. Can. J. Forest Res. 36, 699–709.

Collins, B.M., Stephens, S.L. Managing natural wildfires in Sierra Nevada wilderness areas. Frontiers in Ecology and the Environment, 57 (7), in press.

Davis, F.W., Borchert, M.I., 2006. Central coast bioregion. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, California, pp. 321–349.

Dawson, T.E., 1998. Fog in the California redwood forest: ecosystem inputs and use by plants. Oecologia 117, 476–485.

Dennis, A., Matthew, F., Steohen, A., Allen, D., 2002. Air pollutant emissions associated with forest, grassland, and agricultural burning in Texas. Atmos. Environ. 36, 3779–3792.

Dieterich J.H., 1980. The composite fire interval – a tool for more accurate interpretation of fire history. Proceedings of the Fire History Workshop. USDA Forest Service General Technical Report RM-81, pp. 8–14.

Dodge, M., 1972. Forest fuel accumulation—a growing problem. Science 177, 139–142.

Dombeck, M.P., Williams, J.E., Woods, C.A., 2004. Wildfire policy and public lands: integrating scientific understanding with social concerns across landscapes. Conserv. Biol. 18, 883–889.

Fearnside, P.M., 2000. Global warming and tropical land use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climatic Change 46, 115–158.

Finney, M.A., Martin, R.E., 1989. Fire history in a Sequoia sempervirens forest at Salt Point State Park, California. Can. J. Forest Res. 19, 1451–1457.

Finney, M.A., Martin, R.E., 1993. Modeling effects of prescribed fire on young-growth redwood trees. Can. J. Forest Res. 23, 1125–1135.

FRAP, 2005. Fire and resource assessment program. California Department of Forestry and Fire Prevention. Sacramento, California, http://frap.cdf.ca.gov/.

Fry, D.L., Stephens, S.L., 2006. Influence of humans and climate on the fire history of a ponderosa pine-mixed conifer forest in the Southeastern Klamath Mountains, California. Forest Ecol. Manage. 223, 428–438.

Greenlee, J.M., Langeheim, J.H., 1990. Historic fire regimes and their relation to vegetation patterns in the Monterey Bay Area of California. Amer. Midland Nat. 124, 239–253.

Heinselman, M.L., 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quat. Res. 3, 329–382.

Hoelzemann, J.J., Schultz, M.G., Brasseur, G.P., Granier, C., 2004. Global Wildland Fire Emission Model (GWEM): evaluating the use of global area burnt satellite data. J. Geophys. Res. 109, D14S04.

Huntsinger, L., McCaffrey, S., 1995. A forest for the trees: Euro-American forest management and the Yurok environment, 1850 to 1994. Am. Indian Cult. Res. J. 19, 155–192.

Jacobs, D.F., Cole, D.W., McBride, J.R., 1985. Fire history and perpetuation of natural coast redwood ecosystems. J. Forest 83, 494–497.

Johnson, A.H., Smathers, G.A., 1976. Fire history and ecology, Lava Beds National Monument. In: Proceedings of the 15th Tall Timbers Fire Ecology Conference, Portland, Oregon, October 16–17, 1974. Tall Timbers Research Station, Tallahassee, Florida, pp. 103–116.

Jones, T.L., 1992. Settlement trends along the California coast. In: Jones, T.L. (Ed.), Essays on the Prehistory of Maritime California. Center for Archaeological Research, University of California, Davis, pp. 1–37.

Kauffman, J.B., 2004. Death rides the forest: perceptions of fire, land use, and ecological restoration of Western forest. Conserv. Biol. 18, 878–882.

Keane, B., Reinhardt, E., Brown, J. Gangi, L., 2004. Release information provided with FOFEM 5.21. USDA Forest Service Rocky Mountain Research Station. Missoula, Montana.

Keeley, J.E., 1982. Distributions of lightning and man-caused wildfire in California. In: Conrad, C.E., Oechel, W.C. (Eds.), Proceedings of the Symposium on Dynamics and Management of Mediterranean-Type Ecosystems. USDA Forest Service. General Technical Report PSW-58, Pacific

Southwest Forest and Range Experiment Station, Berkeley, CA, pp. 431–437.
Keeley, J.E., 2002. Native American impacts on fire regimes of the California coastal ranges. J. Biogeogr. 29, 303–320.
Keeley, J.E., 2005. Fire history of the San Francisco east bay region and implications for landscape patterns. Int. J. Wildland Fire 14, 285–296.
Keeley, J.E., 2006. South coast bioregion. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, California, pp. 350–390.
Keter, T.S., 1995. Environmental history and cultural ecology of the North Fork of the Eel River Basin, California. Eureka, California. USDA Forest Service, Pacific Southwest Region, R5-EM-TP-002, 116 pp.
Kilgore, B.M., Taylor, D., 1979. Fire history of a sequoia mixed conifer forest. Ecology 60, 129–142.
Kuhlbusch, T.A.J., Crutzen, P.J., 1995. Toward a global estimate of black carbon in residues of vegetation fire representing a sink of atmospheric CO_2 and source of O_2. Global Biogeochem. Cycles 9, 491–502.
Leenhouts, B., 1998. Assessment of biomass burning in the conterminous United States. Conserv. Ecol. 2, 1 [Online] http://www.consecol.org/vol2/iss1/art1/.
Leopold, S.A., Cain, S., Cottam, C.A., Gabrielson, I.N., Kimball, T.L., 1963. Wildlife management in the national parks. Am. Forest. 69 32–35, 61–63.
Lewis, H.T., 1993. Patterns of Indian burning in California: ecology and ethnohistory. In: Blackburn, T.C., Anderson, M.K. (Eds.), Before the Wilderness: Native Californians as Environmental Managers. Ballena Press, Menlo Park, CA, pp. 55–116.
Lewis, G.E., 2006. Management action on the Wooley Fire is the appropriate one. Fire Manage. Today 66, 33–35.
McBride, J.R., 1983. Analysis of tree rings and fire scars to establish fire history. Tree-Ring Bull. 43, 51–67.
McClaran, M.P., Bartolome, J.W., 1989. Fire related recruitment in stagnant *Quercus douglasii* populations. Can. J. Forest Res. 19, 580–585.
McKelvey, K.S., Skinner, C.N., Chang, C.-R., Erman, D.C., Husari, S.J., Parsons, D.J., van Wagtendonk, J.W., Weatherspoon, C.W., 1996. An overview of fire in the Sierra Nevada. In: Sierra Nevada Ecosystem Project: Final Report to Congress, vol. 2. Assessments and Scientific Basis for Management Options. University of California, Davis, pp. 1033–1040.
Mensing, S.A., 1992. The impact of European settlement on blue oak (*Quercus douglasii*) regeneration and recruitment in the Tehachapi Mountains, California. Madrono 39, 36–46.
Mills, D.P., 2006. Nonwilderness wildland fire use is born on Kaibab National Forest. Fire Manage. Today 66, 13–14.
Minnich, R.A., 1983. Fire mosaics in southern California and northern Baja California. Science 219, 1287–1294.
Minnich, R.A., Chou, Y.H., 1997. Wildland fire patch dynamics in the chaparral of southern California and northern Baja California. Int. J. Wildland Fire 7, 221–248.
Moody, T.J., Fites-Kaufman, J., Stephens, S.L., 2006. Fire history and climate influences from forests in the northern Sierra Nevada, USA. Fire Ecol. 2, 115–141.
Morford, L., 1993. 100 Years of Wildland Fires in Siskiyou County, California. International Association of Wildland Fire, Fairfield, Washington, 124 pp.
Moritz, M.A., Keeley, J.E., Johnson, E.A., Schaffner, A.A., 2004. Testing a basic assumption of shrubland fire management: how important is fuel age? Frontiers Ecol. Environ. 2, 67–72.
Nagel, T.A., Taylor, A.H., 2005. Fire and persistence of montane chaparral in mixed conifer forest landscapes in the northern Sierra Nevada, Lake Tahoe Basin, California, USA. J. Torrey Bot. Soc. 132, 442–457.
NIFC, 2005. National Interagency Fire Center. Wildland fire statistics. Boise, Idaho [available on web at http://www.nifc.gov/stats/wildlandfirestats.html].
Norman, S.P., Taylor, A.H., 2003. Tropical and north Pacific teleconnections influence fire regimes in pine-dominated forests of North-eastern California, USA. J. Biogeogr. 30, 1081–1092.
Parsons, D.J., DeBendeetti, S.H., 1979. Impact of fire suppression on a mixed-conifer forest. For. Ecol. Manage. 2, 21–33.
Pyne, S.J., 1982. Fire in America: a Cultural History of Wildland and Rural Fire. Princeton University Press, Princeton, New Jersey, USA, p. 654.
Reinhart, E., Keane, R.E. Brown, J.K., 1997. First order fire effects model: FOFEM 4.0, user's guide. USDA Forest Service, Intermountain Research Station, General Technical Report INT-GTR-344. Missoula, Montana.
Riegel, G.M., Miller, R.F., Skinner, C.N., Smith, S.E., 2006. Northeastern plateaus bioregion. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. California: University of California Press, Berkeley, pp. 225–263.
Romme, W., 1980. Fire history terminology: report of the ad hoc committee. In: Stokes, M.A., Dieterich, J.H. (Eds.), Proceedings of the Fire History Workshop. USDA Forest Service General Technical Report RM-81, pp. 135–137.
Skinner, C.N., 2003. Fire history of upper montane and subalpine glacial basins in the Klamath Mountains of northern California. In: Galley, K.E.M., Klinger, R.C., Sugihara, N.G. (Eds.), Proceedings of Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. Miscellaneous Publication No. 13, Tall Timbers Research Station, Tallashssee, Florida, pp. 145–151.
Skinner, C.N., Chang, C., 1996. Fire regimes, past and present. Sierra Nevada Ecosystem Project: Final Report to Congress. Volume II, Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37. Centers for Water and Wildland Resources, University of California, Davis, pp. 1041–1069.
Skinner, C.N., Taylor, A.H., Agee, J.K., 2006. Klamath mountain bioregion. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. California: University of California Press, Berkeley, pp. 170–194.
Skinner, C.N., Taylor, A.H., 2006. Southern Cascades bioregion. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, California, pp. 195–224.
Stephens, S.L., 2001. Fire history of adjacent Jeffrey pine and upper montane forests in the eastern Sierra Nevada. Int. J. Wildland Fire 10, 161–176.
Stephens, S.L., 2004. Fuel loads, snag density, and snag recruitment in an unmanaged Jeffrey pine-mixed conifer forest in Northwestern Mexico. Forest Ecol. Manage. 199, 103–113.
Stephens, S.L., 2005. Forest fire causes and extent on United States Forest Service lands. Int. J. Wildland Fire 14, 213–222.
Stephens, S.L., Finney, M.A., 2002. Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effects of crown damage and forest floor combustion. Forest Ecol. Manage. 162, 261–271.
Stephens, S.L., Skinner, C.N., Gill, S.J., 2003. Dendrochronology-based fire history of Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir. Mexico Can. J. Forest Res. 33, 1090–1101.
Stephens, S.L., Collins, B.M., 2004. Fire regimes of mixed conifer forests in the north-central Sierra Nevada at multiple spatial scales. Northwest Sci. 78, 12–23.
Stephens, S.L., Fry, D.L., 2005. Fire history in coast redwood stands in the Northeastern Santa Cruz Mountains, California. Fire Ecol. 1, 2–19.
Stephens, S.L., Gill, S.J., 2005. Forest structure and mortality in an old-growth Jeffrey pine-mixed conifer forest in Northwestern Mexico. Forest Ecol. Manage. 205, 15–28.
Stephens, S.L., Libby, W.J., 2005. Anthropogenic fire and bark thickness in coastal and island pine populations from Alta and Baja California. J. Biogeogr. 33, 648–652.
Stephens, S.L., Moghaddas, J.J., 2005. Silvicultural and reserve impacts on potential fire behavior and forest conservation: 25 years of experience from Sierra Nevada mixed conifer forests. Biol. Conserv. 25, 369–379.
Stephens, S.L., Ruth, L.W., 2005. Federal forest fire policy in the United States. Ecol. Appl. 15, 532–542.
Stephens, S.L., Sugihara, N.G., 2006. Fire management and policy since European settlement. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, California, pp. 431–443.
Stephens, S.L., Fry, D.L., Franco-Vizcaino, E., Collins, B.M., Moghaddas, J.J., 2007. Coarse woody debris and canopy cover in an old-growth Jeffrey pine-mixed conifer forest from the Sierra San Pedro Martir, Mexico. Forest Ecol. Manage. 240, 87–95.

Stokes, M.A., Smiley, T.L., 1977. An Introduction to Tree-Ring Dating. University of Chicago Press, Chicago, Illinois.

Stuart, J.D., 1987. Fire history of an old-growth forest of *Sequoia sempervirens* (Taxodiaceae) in Humboldt Redwoods State Park, California. Madrono 34, 128–141.

Stuart, J., Stephens, S.L., 2006. North coast California bioregion. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, California, pp. 147–169.

Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), 2006. Fire in California's Ecosystems. University of California Press, Berkeley, California, p. 596.

Sugnet, P.W., 1985. Fire history and post-fire stand dynamics of Inverness bishop pine populations. M.S. thesis. University of California, Berkeley, p. 82.

Swetnam, T.W., 1993. Fire history and climate change in sequoia groves. Science 262, 885–889.

Swetnam, T.W., Thompson, M.A., Sutherland, E.K., 1985. Spruce budworm handbook, using dendrochronology to measure radial growth of defoliated trees. In: USDA Forest Service Agriculture Handbook, p. 639.

Swetnam, T.W., Betancourt, J.I., 1990. Fire-southern oscillation relations in the Southwestern United States. Science 249, 1017–1020.

Taylor, A.H., 1993. Fire history and structure of red fir (*Abies magnifica*) forests, Swain Mountain Experimental Forest, Cascade Range, Northeastern California. Can. J. Forest Res. 23, 1672–1678.

Taylor, A.H., 2000. Fire regimes and forest change in mid and upper montane forests of the southern Cascades, Lassen Volcanic National Park, California, USA. J. Biogeogr. 27, 87–104.

Taylor, A.H., Halpern, C.B., 1991. The structure and dynamics of *Abies magnifica* forests in the southern Cascade Range, USA. J. Veg. Sci. 2, 189–200.

Taylor, A.H., Skinner, C.N., 1998. Fire history and landscape dynamics in a late successional reserve, Klamath Mountains, California, USA. Forest Ecol. Manage. 111, 285–301.

Taylor, A.H., Solem, M.N., 2001. Fire regimes and stand dynamics in an upper montane forest landscape in the southern Cascades, Caribou Wilderness, California. J. Torrey Bot. Soc. 128, 350–361.

Taylor, A.H., Skinner, C.N., 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecol. Appl. 13, 704–719.

Taylor, A.H., Beaty, R.M., 2005. Climatic influences on fire regimes in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA. J. Biogeogr. 32, 425–438.

USDA, 2006. Audit report, US Forest Service large fire suppression costs. US Department of Agriculture Office of Inspector General. Western Region Report No.08601-44-SF. Washington, DC, 47 pp.

van Wagtendonk, J.W., Fites-Kaufman, J., 2006. Sierra Nevada bioregion. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, California, pp. 264–294.

Vogl, R.J., Armstrong, W.P., White, D.L. Cole, K.L., 1988. The closed-cone pines and cypress. In: Barbour, M.G., Major, J. (Eds.), Terrestrial Vegetation of California, expanded ed. California Native Plant Society Special Publication Number 9. Sacramento, California, pp. 295–358.

White, D.E., Atzet, T., Martinez, P.A. McCrimmon, L.A., 2002. Fire regime variability by plant association in Southwestern Oregon. In: Proceedings of the Symposium Fire in California Ecosystems: Integrating Ecology, Prevention, and Management, November 17–20, 1997. San Diego, California. The Association for Fire Ecology Miscellaneous Publication No. 1, pp. 153–163.

Whitlock, C., Skinner, C.N., Bartlein, P.J., Minckley, T., Mohr, J.A., 2004. Comparison of charcoal and tree-ring records of recent fires in the eastern Klamath Mountains. Can. J. Forest Res. 34, 2110–2121.

Williams, J.E., DellaSala, D.A., 2004. Wildfire and conservation in the western United States. Conserv. Biol. 18, 872–873.

Wills, R., 2006. Central Valley bioregion. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, California, pp. 295–320.

Wills, R.D., Stuart, J.D., 1994. Fire history and stand development of a Douglas-fir/hardwood forest in northern California. Northwest Sci. 68, 205–212.

Wotowa, G., Trainer, M., 2000. The influence of Canadian forest fires on pollutant concentrations in the United States. Science 288, 324–328.