Research Article

A Summary of Fire Frequency Estimates for California Vegetation before Euro-American Settlement

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ABSTRACT

California fire regimes have been altered from those that occurred prior to Euro-American settlement, and are predicted to continue to change as global climates warm. Inclusion of fire as a landscape-level process is considered essential to successful ecological restoration in many ecosystems, and presettlement fire regimes provide foundational information for restoration or "realignment" of ecosystems as climate change and land use changes progress. The objective of our study was to provide an up-to-date, comprehensive summary of presettlement fire frequency estimates for California ecosystems dominated by woody plants, and to supply the basis for fire return interval departure (FRID) mapping and analysis in California. Using the LANDFIRE Biophysical Settings (BpS) vegetation-fire regime types as a framework, we used literature review and the outcomes of regional expert workshops to develop twenty-eight presettlement fire regime (PFR) groups based on similarity of their relationships with fire. We then conducted an exhaustive review of the published and unpublished literature pertaining to fire return intervals (FRIs) observed prior to significant Euro-American settlement in the twenty-eight PFRs, and summarized the values to provide a single estimate of the mean, median, mean minimum, and mean maximum FRI for each PFR.

Much variability was evident among PFRs, with mean FRIs ranging from 11 yr to 610 yr, and median FRIs ranging from 7 yr to 610 yr; mean minimum FRIs ranged from 5 yr to 190 yr, and mean maximum FRIs ranged from 40 yr to 1440 yr. There was also high variability within many PFRs, and differences between minimum and maximum FRIs ranged from 32 yr to 1324 yr. Generally, median FRIs were lowest for productive drier forests such as yellow pine, dry and moist mixed conifer, and oak woodland (7 yr, 9 yr, 12 yr, and 12 yr, respectively). Median FRIs were highest for less productive woodlands such as pinyon-juniper (94 yr), high elevation types such as subalpine forest (132 yr), very dry types such as desert mixed shrub (610 yr), and productive moist forests such as spruce-hemlock (275 yr mean FRI). Our summary of California's presettlement fire regimes should be a useful reference for scientists and resource managers, whether they are seeking a general estimate of the central tendency and variability of FRIs in a broadly defined vegetation type, background information for a planned restoration project or a mechanistic model of vegetation-fire interactions, or a list of literature pertaining to a specific vegetation type or geographic location.

Keywords: California, fire frequency, fire history, fire return interval, FRID, presettlement fire regime

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INTRODUCTION

Fire is an important process in many of California's ecosystems, and it is becoming increasingly evident that fire regimes (including fire frequency, severity, extent, spatial patterning, etc.) have been greatly altered in some vegetation types by land use patterns and altered ecosystem processes associated with Euro-American settlement (i.e., after 1850) (Sugihara *et al.* 2006, Stephens *et al.* 2007, Skinner *et al.* 2009). Climatic variability at a variety of temporal scales has been shown to be associated with fire regime fluctuations in the past (Swetnam 1993). Anthropogenic climate change is a driver of current observed trends of increasing fire activity, and is predicted to continue to alter fire regimes and vegetation types in the future (Lenihan *et al.* 2003, Westerling *et al.* 2006, Miller *et al.* 2009, Gedalof 2011, National Research Council 2011). Consideration of fire as a landscape-level process is considered essential to facilitating ecological restoration or "realignment" (*sensu* Millar *et al.* 2007) efforts intended to increase ecosystem resilience in the face of climate change (North *et al.* 2009*a*). Restoration of narrowly defined historical conditions may no longer be a preferred management prescription in light of the uncertainty surrounding the effects of climate change on fire and other ecological processes. However, information on fire regimes before Euro-American settlement is of fundamental importance to modern and future management of many ecosystems in western North America (Millar *et al.* 2007; Wiens *et al.*, in press). Such historical information can help, among other things, to document the current status of fire in ecosystems and trends in fire activity and ecological effects over time; to encourage understanding of the underlying mechanisms that drive ecosystem response to changes in climate, fire, landscapes, and their interactions; and to provide data upon which models of "properly functioning" or "resilient" ecosystems might be built (Wiens *et al.*, in press).

Drawing comparisons between presettlement and current fire regimes can also assist land managers in prioritizing areas for ecological restoration. Fire return interval departure (FRID) analysis facilitates quantification of the difference between current and presettlement fire return intervals (FRIs), allowing managers to target areas at high risk of type conversion due to altered fire regimes (Caprio *et al.* 1997, Caprio and Graber 2000, van Wagtendonk *et al.* 2002). Robust estimates of the variability of presettlement FRIs in different vegetation types are a crucial part of FRID analysis, yet most fire history studies are highly localized, making it difficult to apply the results of individual studies to a regional-scale mapping and assessment effort.

Much work has been accomplished in documenting historical fire regimes in various vegetation types throughout California, and while several manuscripts summarize different subsets of this information, they are often either restricted to data derived from tree-ring studies, limited to forest vegetation types in a particular geographic region, or not intended to be comprehensive (e.g., Heyerdahl *et al.* 1995, Skinner and Chang 1996, Stephens *et al.* 2007). Thus, scientists and land managers currently lack a single source that summarizes all of the literature pertaining to presettlement fire regimes. The objectives of this paper are to provide an up-to-date comprehensive summary of presettlement fire frequency estimates for California ecosystems dominated by woody plants, and to provide the quantitative basis for fire return interval departure (FRID) mapping across California.

METHODS

Although the state of California is home to a high diversity of species, vegetation types, and fire regimes (Barbour *et al.* 2007), similarities among fire regimes and their effects on vegetation generally allow the organization of ecosystems into broad fire regime groups. Published efforts to categorize relationships between fire and vegetation in California include Agee (1993; northern California), Skinner and Chang (1996; Sierra Nevada), Stephenson and Calcarone (1999; southern California), Arno (2000; western US), Sugihara *et al.* (2006; statewide), Sawyer *et al.* (2010; statewide), and the LANDFIRE project (2010; Rollins 2009; entire US). Both the Sugihara *et al.* (2006) and Sawyer *et al.* (2010) efforts drew from a series of Joint Fire Science Program supported regional workshops held between 2000 and 2002 that reunited fire and vegetation experts from across the state and developed descriptions of fire regime characteristics for California vegetation communities. All of this information also fed the development of the LANDFIRE Biophysical Settings (BpS), which are potential natural vegetation (PNV) types linked to quantitative models of disturbance and succession (Rollins 2009). The disturbance-succession models for the California BpS types (which apply to the pre-Euro-American settlement period) were developed at a series of regional expert workshops sponsored by The Nature Conservancy in 2004 and 2005. After refinement and peer review, the BpS classification was finalized and mapped as part of the national LANDFIRE project (see Rollins 2009 and www.landfire.gov for details).

As an evolutionary outgrowth of the previous fire regime work cited above, the LANDFIRE Biophysical Settings represents the current state of the art for linking vegetation and pre-Euro-American settlement fire regimes across California. There are more than eighty individual BpS types mapped in California by LANDFIRE, but some are extremely uncommon, and many share similar fire regimes. Using the fire regime information provided for each BpS in the type description (LANDFIRE 2010), and referring to integrative vegetation and fire resources in the literature (see citations above, plus, e.g., Burns and Honkala 1990, Potter 1998, Barbour and Billings 2000, Barbour *et al.* 2007) and on the internet (e.g., the Fire Effects Information System [http://www.fs.fed.us/database/feis/]), we reduced the BpS list down to a smaller number of pre-Euro-American settlement fire regime groups (PFRs) that we subjectively considered sufficiently different to warrant retention. From our research, we also identified a number of PFRs that were not represented in the BpS classification. PFRs were designed to balance a reasonably small number of fire regime groups with sufficiently high discrimination in fire regime characteristics. We solicited peer review of the PFR list from 27 California fire and vegetation ecology experts and received responses from eleven. After adjustment, our final list included 28 PFRs.

For each PFR, we conducted an exhaustive review of the published and unpublished literature pertaining to mean, median, minimum, and maximum fire return intervals observed prior to significant Euro-American settlement (i.e., the middle of the nineteenth century). Sources included fire histories derived from dendrochronological and charcoal deposition records, modeling studies, and expert quantitative estimates. Priority was given to studies conducted in California, but sources from other states in western North America were included as appropriate for PFRs for which information was limited. When all sources were compiled, the average was taken of all mean, median, minimum, and maximum FRI values to yield a single mean, median, mean minimum, and mean maximum FRI estimate for each PFR. Thus, the minimum and maximum FRI estimates we provide for each PFR are not absolute minima and maxima, but typical mean values that would be expected across the geographical range of each PFR.

For conifer-dominated PFRs, most FRI values considered in this assessment were derived from small-scale (<4 ha) composite dendrochronological fire histories including records from multiple trees in a defined area, although some values were obtained from modeling or stand age-based studies (in the latter case, for PFRs characterized by stand-replacing fires). Composite FRIs often represent the fire history of a given area better than point FRIs (derived from a single tree) because some fire events fail to scar every recording tree within the fire perimeter, especially in regimes characterized by frequent low intensity fire (Collins and Stephens 2007, Falk *et al.* 2011). Furthermore, composite FRIs are more sensitive and better suited to analyzing changes in fire occurrence than point FRIs (Dieterich 1980, Swetnam and Baisan 2003). While there is some variability introduced by using composite FRIs from different-sized areas, they are less likely to underestimate presettlement FRI values than point FRIs.

RESULTS

Relationships between the PFRs and LANDFIRE BpS types are shown in Table 1; characteristic dominant woody species for each PFR are listed in Table 2. Four PFRs were not represented by any BpS types, due to their geographic rarity or their focus on single species. These were the "fire sensitive spruce or fir," the "big cone Douglas-fir," the "shore pine," and the "silver sagebrush" PFRs.

We derived fire frequency estimates for the 28 PFRs from 298 sources (Table 2). Most of our sources (213 of 298; 71.5%) were based on data collected in California. For the average PFR, 26.5% of sources were non-Californian, but seven PFRs had more than 50% of their sources from outside California (Table 2). These seven, which accounted for about two thirds of all of the non-California sources, are PFRs for which the dominant woody species are at the southern or western edge of their range in California, or are California endemics and very rare in the state (e.g., *Abies bracteata* [D. Don] D. Don ex Poit and *Picea breweriana* S. Watson in the fire sensitive spruce or fir PFR). Sixteen PFRs had ≤20% of their sources from outside California, and seven had exclusively California sources.

Derived mean, median, mean minimum, and mean maximum fire frequencies for each PFR are given in Table 2. Information on median FRIs was lacking for some PFRs, so median values were either taken from expert quantitative estimates of mean FRI (desert mixed shrub, semi-desert chaparral) or were not estimated (coastal fir, shore pine, spruce-hemlock). Because FRI distributions are often skewed (with more short or long intervals, depending on the PFR), median FRI values may be a better approximation of how often a given PFR burned than mean FRIs (Falk 2004).

Much variability is evident among PFRs, with mean FRIs ranging from 11 yr (dry mixed conifer and yellow pine) to 610 yr (desert mixed shrub), median FRIs ranging from 7 yr

Table 1. Relationship between Presettlement Fire Regime types (PFRs) and LANDFIRE Biophysical Settings (BpS) mapped in California. BpS types with "none" as PFR assignment are types for which we do not have sufficient data on presettlement fire regimes (e.g., non-woody vegetation, riparian types).

LANDFIRE Biophysical Setting	PFR
Inter-mountain basins aspen-mixed conifer forest and woodland	Aspen
Rocky Mountain aspen forest and woodland	Aspen
Columbia Plateau steppe and grassland	Big sagebrush
Inter-mountain basins big sagebrush shrubland	Big sagebrush
Inter-mountain basins big sagebrush steppe	Big sagebrush
Inter-mountain basins montane sagebrush steppe	Big sagebrush
Columbia Plateau low sagebrush steppe	Black and low sagebrush
Great Basin xeric mixed sagebrush shrubland	Black and low sagebrush
California coastal closed-cone conifer forest and woodland	Chaparral-serotinous conifers
California maritime chaparral	Chaparral-serotinous conifers
California mesic chaparral	Chaparral-serotinous conifers
California xeric serpentine chaparral	Chaparral-serotinous conifers
Klamath-Siskiyou xeromorphic serpentine savanna and chaparral	Chaparral-serotinous conifers
Mediterranean California mesic serpentine woodland and chaparral	Chaparral-serotinous conifers
Northern and central California dry-mesic chaparral	Chaparral-serotinous conifers
Southern California dry-mesic chaparral	Chaparral-serotinous conifers
North Pacific maritime dry-mesic Douglas-fir-western hemlock forest	Coastal fir
Baja semi-desert coastal succulent scrub	Coastal sage scrub
Northern California coastal scrub	Coastal sage scrub
Southern California coastal scrub	Coastal sage scrub
Inter-mountain basins curl-leaf mountain mahogany woodland and shrubland	Curl-leaf mountain mahogany
Colorado plateau blackbrush-mormon-tea shrubland	Desert mixed shrub
Inter-mountain basins greasewood flat	Desert mixed shrub
Inter-mountain basins mixed salt desert scrub	Desert mixed shrub
Inter-mountain basins semi-desert shrub-steppe	Desert mixed shrub
Mojave mid-elevation mixed desert scrub	Desert mixed shrub
Sonora-Mojave creosotebush-white bursage desert scrub	Desert mixed shrub
Sonora-mojave mixed salt desert scrub	Desert mixed shrub
Sonoran mid-elevation desert scrub	Desert mixed shrub
Sonoran paloverde-mixed cacti desert scrub	Desert mixed shrub
Mediterranean California dry-mesic mixed conifer forest and woodland	Dry mixed conifer
Northern rocky mountain foothill conifer wooded steppe	Dry mixed conifer
Sierra Nevada subalpine lodgepole pine forest and woodland	Lodgepole pine
Sierra Nevada subalpine lodgepole pine forest and woodland—dry	Lodgepole pine
Sierra Nevada subalpine lodgepole pine forest and woodland—wet	Lodgepole pine
Central and southern California mixed evergreen woodland	Mixed evergreen
Mediterranean California mixed evergreen forest	Mixed evergreen
Klamath-Siskiyou upper montane serpentine mixed conifer woodland	Moist mixed conifer
Mediterranean California mesic mixed conifer forest and woodland	Moist mixed conifer
California montane woodland and chaparral	Montane chaparral
Southern California oak woodland and savanna	Oak woodland

Table 1, continued.

LANDFIRE Biophysical Setting	PFR
California central valley and southern coastal grassland	none
California central valley riparian woodland and shrubland	none
California mesic serpentine grassland	none
California montane riparian systems	none
California northern coastal grassland	none
Inter-mountain basins montane riparian systems	none
Inter-mountain basins semi-desert grassland	none
Mediterranean California alpine dry tundra	none
Mediterranean California alpine fell-field	none
Mediterranean California subalpine meadow	none
North American warm desert riparian systems	none
North Pacific montane grassland	none
Pacific coastal marsh systems	none
California central valley mixed oak savanna	Oak woodland
California coastal live oak woodland and savanna	Oak woodland
California lower montane blue oak-foothill pine woodland and savanna	Oak woodland
Mediterranean California mixed oak woodland	Oak woodland
North Pacific oak woodland	Oak woodland
Columbia Plateau western juniper woodland and savanna	Pinyon juniper
Colorado Plateau pinyon-juniper woodland	Pinyon-juniper
Great Basin pinyon-juniper woodland	Pinyon-juniper
Inter-mountain basins juniper savanna	Pinyon-juniper
Mediterranean California red fir forest	Red fir
Mediterranean California red fir forest—Cascades	Red fir
Mediterranean California red fir forest—southern Sierra	Red fir
California coastal redwood forest	Redwood
Great Basin semi-desert chaparral	Semi-desert chaparral
Sonora-Mojave semi-desert chaparral	Semi-desert chaparral
North pacific hypermaritime sitka spruce forest	Spruce-hemlock
North Pacific lowland riparian forest and shrubland	Spruce-hemlock
North Pacific maritime mesic-wet Douglas-fir-western hemlock forest	Spruce-hemlock
Inter-mountain basins subalpine limber-bristlecone pine woodland	Subalpine forest
Mediterranean California subalpine woodland	Subalpine forest
Mediterranean California subalpine woodland	Subalpine forest
North Pacific maritime mesic subalpine parkland	Subalpine forest
Northern California mesic subalpine woodland	Subalpine forest
Sierra Nevada alpine dwarf-shrubland	Subalpine forest
Sierran-intermontane desert western white pine-white fir woodland	Western white pine
California montane Jeffrey pine(-ponderosa pine) woodland	Yellow pine
Mediterranean California lower montane black oak-conifer forest and woodland	Yellow pine
Northern Rocky Mountain ponderosa pine woodland and savanna—mesic	Yellow pine
Northern Rocky Mountain ponderosa pine woodland and savanna—xeric	Yellow pine

Table 2. Reference fire return intervals (FRIs) of pre-Euro-American settlement fire regimes (PFRs) considered in this analysis, and sources (citations on following pages, asterisks denote studies conducted wholly or mostly outside of California). Mean minimum and mean maximum are rounded to the nearest multiple of 5.

PFR	Characteristic dominant woody species	Mean	Median	Mean Min	Mean Max	Sources
Aspen	*Populus tremuloides* Michx, various conifers	19	20	10	90	1-7
Big sagebrush	*Artemisia tridentata* Nutt., *Purshia tridentata* (Pursh.) DC., *Chrysothamnus* spp.	35	41	15	85	2, 4, 7-22, 281-283
Bigcone Douglas-fir	*Pseudotsuga macrocarpa* (Vasey) Mayr, *Quercus chrysolepis* Liebm.	31	30	5	95	2, 23-26
Black and low sagebrush[1]	*Artemisia nova* A. Nelson, *A. arbuscula* Nutt.	66	53	35	115	2, 4, 12, 13, 21, 22, 27-31, 284
California juniper	*Juniperus occidentalis* Hook.	83	77	5	335	2, 13, 15, 18, 32
Chaparral and serotinous conifers	*Adenostoma* spp., *Arctostaphylos* spp., *Ceanothus* spp., *Quercus berberidifolia* Liebm., other shrubs; *Pinus attenuata* Lemmon, *P. muricata* D. Don, *Cupressus* spp., other serotinous conifers	55	59	30	90	2, 33-72
Coastal fir[1]	*Abies grandis* (Douglas ex D. Don) Lindl., *Pseudotsuga menziesii* (Mirb.) Franco	99	NA[2]	90	435	73-84
Coastal sage scrub	*Artemisia californica* Less.,*Baccharis pilularis* DC., *Eriogonum fasciculatum* Benth., *Salvia* spp., etc.	76	100	20	120	2, 25, 44, 47, 48, 71, 85-94
Curl-leaf mountain mahogany[1]	*Cercocarpus ledifolius* Nutt.	52	62	30	130	2, 4, 7, 14, 16, 18, 22, 95-98
Desert mixed shrub	*Atriplex* spp., *Sarcobatus vermiculatus* (Hook.) Torr., *Larrea tridentata* (DC.) Coville, *Coleogyne ramosissima* Torr., *Prosopis* spp., *Yucca* spp., *Ephedra* spp., *Opuntia* spp., etc.	610	610	120	1440	2, 99-108
Dry mixed conifer	*Pinus ponderosa, P. lambertiana* Douglas, *Calocedrus decurrens* (Torr.) Florin, *Abies concolor* (Gord. & Glend.) Lindl ex Hildebr., *Quercus kelloggii* Newberry	11	9	5	50	3, 6, 24, 68, 70, 71, 109-140
Fire sensitive spruce or fir[1]	*Abies amabilis* (Douglas ex Louden) Douglas ex Forbes, *A. bracteata, Picea engelmannii* Perry ex Engelm., *P. breweriana*	117	93	90	250	2, 22, 44, 141-157, 278-280, 285-297
Lodgepole pine	*Pinus contorta* Douglas ex Louden ssp. *murrayana* (Balf.) Engelm.	37	36	15	290	2, 3, 5, 6, 21, 68, 70, 112, 125, 127, 132, 158-172
Mixed evergreen	*Pseudotsuga menziesii, Lithocarpus densiflorus* (Hook. & Arn.) Rehder, *Quercus agrifolia* Née, *Q. chrysolepis, Umbellularia californica* (Hook.& Arn.) Nutt., *Arbutus menziesii* Pursh, *Acer macrophyllum* Pursh, *Taxus brevfolia* Nutt.	29	13	15	80	2, 23, 44, 74, 82, 127, 173-187
Moist mixed conifer	*A. concolor, Pseudotsuga menziesii, Calocedrus decurrens, Pinus ponderosa, P. lambertiana, P. contorta* ssp. *murrayana, Sequoiadendron giganteum* (Lindl.) J. Buchholz	16	12	5	80	2, 3, 6, 68, 70, 71, 98, 110-113, 116, 117, 119, 121-123, 125, 127-130, 132, 133, 136, 145, 147, 164, 168, 170, 183, 187-209

[1] PFRs for which >50% of sources are from outside California.
[2] Not applicable.

Table 2, continued.

PFR	Characteristic dominant woody species	Mean	Median	Mean Min	Mean Max	Sources
Montane chaparral	*Arctostaphylos* spp., *Ceanothus* spp., *Quercus vaccinifolia* Kellogg, *Prunus ilicifolia* (Nutt. Ex Hook. & Arn) D. Dietr., *Chrysolepis sempervirens* (Kellogg) Hjelmquist, other shrubs	27	24	15	50	2, 33, 58, 68, 209-211
Oak woodland	*Quercus douglasii* Hook & Arn, *Q. lobata* Née, *Q. wislizenii* A. DC., *Pinus sabiniana* Douglas ex Douglas	12	12	5	45	2, 44, 68, 127, 186, 212-225
Pinyon-juniper[1]	*Pinus monophylla* Torr. & Frém., *Juniperus* spp.,	151	94	50	250	2, 14, 16, 22, 71, 89, 226-233
Port Orford cedar	*Chamaecyparis lawsoniana* (A. Murray) Parl.	30	16	10	160	2, 98, 144, 147, 168, 173, 177, 187, 188, 205, 234-237
Red fir	*Abies magnifica* A. Murray, *A. concolor, Pinus montícola* Douglas ex D. Don, *P. murrayana*	40	33	15	130	2, 3, 6, 68, 110, 112, 119, 127, 132, 134, 162, 164, 168-170, 172, 181, 187, 238-248
Redwood	*Sequoia sempervirens* (Lamb. Ex D. Don) Endl.	23	15	10	170	2, 44, 74, 82, 174, 178, 179, 182, 186, 249-257
Semi-desert chaparral	*Adenostoma fasciculatum* Hook. & Arn., *Arctostaphylos* spp., *Cercocarpus betuloides* Nutt., *Eriogonum fasciculatum* Benth., *Purshia glandulosa* Curran, *Fremontodendon californicum* (Torr.) Coville, *Quercus john-tuckeri* Nixon & C.H. Mull, etc.	65	65	50	115	2, 258-261
Shore pine[1]	*Pinus contorta* Douglas ex Louden ssp. *contorta*	250	NA[2]	190	1025	78, 262, 277
Silver sagebrush	*Artemisia cana* Pursh	35	31	15	65	2, 10, 58, 263, 264, 298
Spruce-hemlock[1]	*Picea sitchensis* (Bong.) Carrière, *Tsuga heterophylla* (Raf.) Sarg., *Pseudotsuga menziesii*	275	NA[2]	180	550	75, 77, 80, 265-269
Subalpine forest	*Tsuga mertensiana* (Bong.) Carrière, *Pinus albicaulis* Engelm., *P. monticola, P. contorta* ssp. *murrayana, P. flexilis* James, *P. balfouriana* Balf., *P. longaeva* D.K. Bailey, *Abies magnifica*	133	132	100	420	2, 68, 98, 112, 143, 164, 165, 168, 172, 187, 199, 270-272
Western white pine	*Pinus monticola*	50	42	15	370	2, 6, 98, 112, 119, 127, 134, 147, 164, 166, 168-170, 172, 199, 245, 257, 273
Yellow pine	*Pinus ponderosa, P. jeffreyi, P. washoensis* H. Mason & Stockw., *P. lambertiana, Quercus kelloggii*	11	7	5	40	2, 3, 14, 21, 68, 70, 71, 113, 116, 117, 119, 127, 131, 132, 134, 165, 169, 189, 200, 224, 263, 274-276

[1] PFRs for which >50% of sources are from outside California.
[2] Not applicable.

1 Richardson and Provencher 2005
2 Sawyer *et al.* 2009
3 Van de Water and North 2010
4 Wall *et al.* 2001*
5 Riegel *et al.* 2006
6 Beaty and Taylor 2008
7 Miller *et al.* 2001*
8 Major *et al.* 2005
9 Zielinski and Provencher 2005
10 Medlyn and Kolden 2005
11 Winward 1991*
12 Miller and Rose 1999*
13 Young and Evans 1981
14 Gruell 1999*
15 Martin and Johnson 1979
16 Gruell *et al.* 1994*
17 Mensing *et al.* 2006*
18 Miller and Heyerdahl 2008
19 Sapsis 1990*
20 Bork 1984*
21 Norman and Taylor 2005
22 Kitchen 2010*
23 Sugihara and Borgias 2005
24 Safford and Keeler-Wolf 2005
25 Byrne 1978
26 Lombardo *et al.* 2009
27 Kolden and Medlyn 2005
28 Burkhardt and Tisdale 1976*
29 Kitchen and McArthur 2007*
30 Knick *et al.* 2005*
31 Loope and Gruell 1973*
32 Reeberg and Weisberg 2006
33 Sugihara *et al.* 2004
34 Foster 2006*a*
35 Syphard and Foster 2006
36 Beyers and Parker 2006
37 Keeler-Wolf *et al.* 2005
38 Syphard and Beyers 2006
39 Minnich 2006
40 Ne'eman *et al.* 1999
41 Vogl 1973
42 Conard and Weise 1998
43 Minnich 1989
44 Greenlee and Langenheim 1990
45 Keeley and Fotheringham 2001
46 Borchert 2008
47 Byrne *et al.* 1977
48 Mensing *et al.* 1999
49 Minnich and Chou 1997
50 Minnich 2001
51 Moritz *et al.* 2004
52 Moritz 2003
53 Zedler 1995
54 De Gouvenain and Ansary 2006
55 Wells *et al.* 2003
56 Mallek 2009
57 Stephens *et al.* 2004
58 Wright and Bailey 1982
59 Keeley 1982
60 Walter and Taha 1999
61 Wells and Getis 1999
62 Borchert and Foster 2006
63 Vogl *et al.* 1977
64 Keeley 1981
65 Florence 1987
66 Davis and Borchert 2006
67 Jackson 1977
68 Caprio and Lineback 2002
69 Zedler 1981
70 Minnich *et al.* 2000*
71 Stephenson and Calcarone 1999
72 Moir 1982*
73 Kertis *et al.* 2005*
74 Finney and Martin 1989
75 Long and Whitlock 2002*
76 Veirs 1980
77 Long *et al.* 2007*
78 Brown and Hebda 2002*
79 Long *et al.* 2010*
80 Long *et al.* 1998*
81 McCoy 2006*
82 Stuart 1987
83 Agee and Dunwiddie 1984*
84 Walsh *et al.* 2008*
85 Taylor 2006
86 Keeler-Wolf and Foster 2006
87 Hanes 1971
88 Westman 1982
89 Paysen *et al.* 2000
90 O'Leary 1990
91 Vogl 1976
92 Russell 1983
93 Talluto and Suding 2008
94 Keeley *et al.* 2005
95 Ross *et al.* 2005
96 Arno and Wilson 1983*
97 Erhard 2008*
98 Minckley *et al.* 2007*
99 Dingman and Esque 2005
100 Novak-Echenique 2005*a*
101 Novak-Echenique 2005*b*
102 Alford and Ambos 2005
103 Esque and McPherson 2005
104 Nachlinger 2005*
105 Thomas 1991
106 Wright 1986*
107 Brooks and Matchett 2006
108 Brown and Minnich 1986
109 Arabas *et al.* 2006*
110 Beaty and Taylor 2001
111 Beaty and Taylor 2009
112 Bekker and Taylor 2001
113 Caprio and Swetnam 1995
114 Everett 2008
115 Evett *et al.* 2007*
116 Fry and Stephens 2006
117 Gill and Taylor 2009
118 Keeler-Wolf 1991
119 Beaty and Taylor 2007
120 Hemstrom *et al.* 2008*a**
121 Wagener 1961
122 Kotok 1930
123 Show and Kotok 1924
124 Warner 1980
125 Caprio 2004*c*
126 Skinner *et al.* 2008*
127 Skinner and Chang 1996
128 Skinner *et al.* 2006
129 Skinner *et al.* 2009
130 Stephens and Collins 2004
131 Stephens *et al.* 2003*
132 Swetnam *et al.* 2001
133 Swetnam *et al.* 2009
134 Taylor 2000
135 Taylor 2004*
136 Taylor and Skinner 2003
137 Trouet *et al.* 2010*
138 Vaillant and Stephens 2009
139 Sherlock and Sugihara 2008
140 Gassaway 2005
141 Powell and Swanson 2005*
142 Simpson *et al.* 2005*
143 Swanson 2005
144 Borgias *et al.* 2005
145 Talley and Griffin 1980
146 Briles *et al.* 2005
147 Briles *et al.* 2008
148 Grissino-Mayer *et al.* 1995*
149 Touchan *et al.* 1996*
150 Wadleigh and Jenkins 1996*
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152 Hemstrom *et al.* 2008*b**
153 Toney and Anderson 2006*
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155 Schellhaas *et al.* 2001*
156 Anderson *et al.* 2008*
157 Allen *et al.* 2008*
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159 Caprio 2004*b*
160 Keifer 1991
161 Caprio 2002
162 van Wagtendonk 1995
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164 Daniels *et al.* 2005
165 North *et al.* 2009*b*
166 Pitcher 1987
167 Sheppard and Lassoie 1998
168 Skinner 2003
169 Stephens 2001
170 Taylor and Solem 2001
171 Caprio 2008
172 Hallett and Anderson 2010
173 Sugihara *et al.* 2005*a*
174 Veirs 1982
175 Hunter 1997
176 Atzet and Wheeler 1982*
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179 Greenlee 1983
180 Olson and Agee 2005*
181 Sensenig 2002*
182 Stephens and Fry 2005
183 Taylor and Skinner 1995
184 Wills and Stuart 1994
185 Atzet 1979*
186 Finney and Martin 1992
187 Atzet and Martin 1992
188 Reilly *et al.* 2005*a*
189 Bradley *et al.* 2005
190 Sherlock *et al.* 2005*a*
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198 Swetnam *et al.* 1990
199 Mohr *et al.* 2000
200 Moody *et al.* 2006
201 Drumm 1996
202 North *et al.* 2005
203 Phillips 2002
204 Scholl and Taylor 2010
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208 Stuart and Salazar 2000
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216 Davis 2006
217 Evens and Klein 2006*a*
218 Evens and Klein 2006*b*
219 Mensing 1992
220 Sugihara and Reed 1987
221 Anderson and Moratto 1996
222 McClaran 1988
223 Purcell and Stephens 1997
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225 Agee and Biswell 1978
226 Weisberg 2005
227 Arno 1985*
228 Gruell 1997*
229 Bauer 2006*
230 Bauer and Weisberg 2009*
231 Jamieson 2008*
232 Romme *et al.* 2009
233 Wangler and Minnich 1996
234 Reilly *et al.* 2005*b*
235 Zobel *et al.* 1982*
236 Agee *et al.* 1990*b**
237 Scher and Jimerson 1989
238 Atzet and White 2005
239 Safford and Sherlock 2005*a*
240 Safford and Sherlock 2005*b*
241 Barbour and Minnich 2000
242 Chappell and Agee 1996*
243 Bancroft 1979
244 Atzet and McCrimmon 1990*
245 Scholl and Taylor 2006*
246 Foster 1998*
247 Taylor 1993
248 Taylor and Halpern 1991
249 Sugihara *et al.* 2005*b*
250 Huff *et al.* 2005
251 Brown and Baxter 2003
252 Swetnam 1994
253 Fritz 1931
254 Hunter and Parker 1993
255 Jacobs *et al.* 1985
256 Norman 2007
257 Brown and Smith 2000
258 Provencher *et al.* 2005
259 Brooks 2005
260 Cable 1975
261 Brooks *et al.* 2007*
262 Parminter 1991*
263 Norman and Taylor 2003
264 Quinnild and Cosby 1958*
265 Acker *et al.* 2004
266 Whitlock *et al.* 2008*
267 Teensma *et al.* 1991*
268 Impara 1997*
269 Agee 1993*
270 van Wagtendonk *et al.* 2005
271 Richardson and Howell 2005
272 Short *et al.* 2005
273 Foster 2006*b*
274 Safford *et al.* 2005
275 McBride and Laven 1976
276 Taylor and Beaty 2005
277 Cope 1993
278 Uchytil 1991
279 Cope 1992*a*
280 Cope 1992*b*
281 Howard 1999
282 Johnson 2000
283 Tirmenstein 1999
284 Steinberg 2002
285 Sibold *et al.* 2006*
286 Veblen *et al.* 1994*
287 Buechling and Baker 2001*
288 Donnegan *et al.* 2001*
289 Kipfmueller and Baker 2000*
290 Suffling 1993*
291 Romme and Knight 1981*
292 Millspaugh and Whitlock 2003*
293 Brunelle and Whitlock 2003*
294 Brunelle *et al.* 2005*
295 Gavin *et al.* 2006*
296 Hallet and Hills 2006*
297 Brown *et al.* 1994*
298 Howard 2002

(yellow pine) to 610 yr (desert mixed shrub), minimum FRIs ranging from 5 yr (bigcone Douglas-fir, California juniper, dry mixed conifer, moist mixed conifer, oak woodland, and yellow pine) to 190 yr (shore pine), and maximum FRIs ranging from 40 yr (yellow pine) to 1440 yr (desert mixed shrub) (Table 2). There was also a great deal of variability within PFRs, as evidenced by differences between minimum and maximum FRIs ranging from 32 yr and 34 yr (montane chaparral and yellow pine, respectively) to 1324 yr (desert mixed shrub). FRI distributions ranged from unskewed distributions with little difference between mean and median FRIs (aspen, bigcone Douglas-fir, dry mixed conifer, lodgepole pine, montane chaparral, oak woodland, subalpine forest), to highly skewed distributions dominated by relatively short FRIs (coastal sage scrub), to highly skewed distributions dominated by relatively long FRIs (pinyon-juniper). Figure 1 graphically depicts the mean, median, mean minimum, and mean maximum FRIs for the 11 most widely distributed PFRs on Forest Service lands in California.

DISCUSSION

Our summary of California's presettlement fire regimes should be a useful reference for scientists and resource managers, whether they are seeking a general estimate of the central tendency and variability of FRIs in a broadly defined vegetation type, background information for a planned restoration project or a mechanistic model of vegetation-fire interactions, or a list of literature pertaining to a specific vegetation type or geographic location. A high degree of confidence can be placed in the validity of the FRI values for most conifer

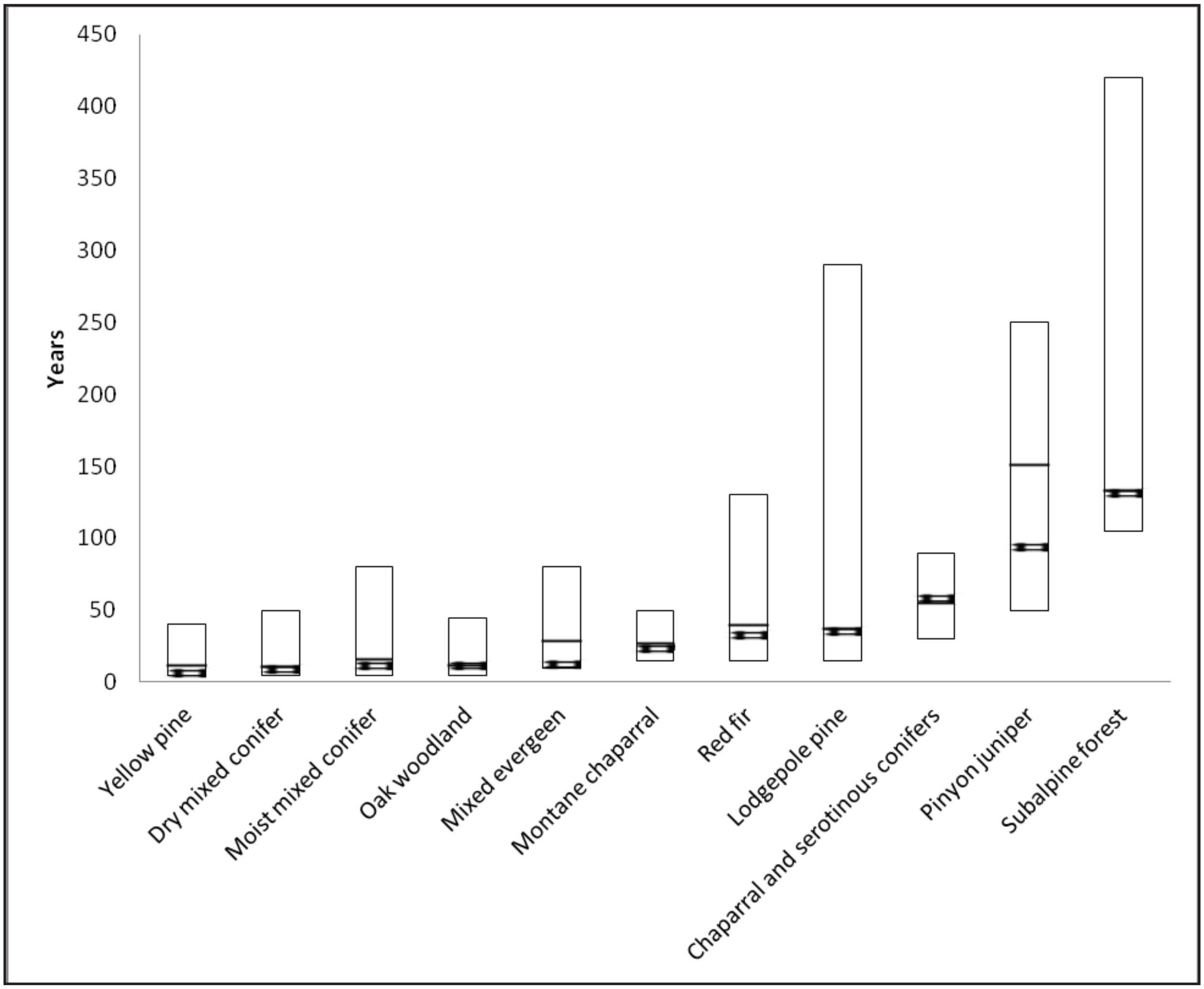

Figure 1. Fire return intervals (FRIs) for the 11 most widely distributed presettlement fire regime groups in California. Solid line is mean FRI, dotted line is mean median FRI, bottom of each bar is mean minimum FRI, top of each bar is mean maximum FRI.

PFRs, especially in the Sierra Nevada, due to the abundance of published dendrochronological studies. Less confidence is afforded to the FRI values of PFRs for which presettlement fire history is less well-studied, such as California juniper, desert mixed shrub, semi-desert chaparral, and silver sagebrush. For shrub-dominated PFRs in which presettlement fires are difficult to detect due to a lack of dendrochronological evidence, FRI values were derived from other types of data that may be less precise, such as charcoal in sediment cores, modeling, and expert quantitative evidence.

More research is needed in PFRs that currently have little quantitative fire history data available for California (see Table 2), or have high geographic variability in FRIs. The difficulties associated with obtaining high-resolution presettlement FRI data in shrub-dominated vegetation types categorically necessitates further study in most of these PFRs (e.g., big sagebrush, black and low sagebrush, chaparral, coastal sage scrub, curl-leaf mountain mahogany, desert mixed shrub, montane chaparral, semi-desert chaparral, silver sagebrush), and perhaps innovation of new or adaptation of existing fire history techniques. Similarly, PFRs dominated by tree species that are easily killed by fire (California juniper, coastal fir, fire sensitive spruce or fir, pinyon-juniper, shore pine, spruce-hemlock) require further study and application of techniques other than fire scar studies. The PFRs of limited geographical distribution in California (bigcone Douglas-fir, coastal fir, fire sensitive spruce or fir, Port Orford cedar, shore pine, spruce-hemlock, western white pine) are chronically understudied. Other PFRs (shore pine, desert mixed shrub, spruce-hemlock, California juniper, coastal fir, pinyon-juniper, western white pine, subalpine forest) are characterized by high geographic variability in fire frequency (high standard error of FRI statistics), requiring scientists and managers to carefully search for literature from local or similar areas.

Several interesting patterns in FRIs within and among different PFRs emerged from the body of fire history literature assessed for this article. For example, analyses of the correlation between fire scar sampling area and fire return interval revealed no trend of decreasing FRI with increasing sampling area for all PFRs pooled and most PFRs individually. Sampling area was significantly correlated with mean minimum FRI for the big sagebrush ($r = 0.867$, $P = 0.012$), Port Orford cedar ($r = -0.974$, $P = 0.026$), and red fir ($r = 0.742$, $P = 0.014$) PFRs. The trend of decreasing FRI with increasing sampling area for the Port Orford cedar PFR was consistent with established expectations (Baker and Ehle 2001, Swetnam and Baisan 2003), while the opposite trend for the big sagebrush and red fir PFRs may be indicative of the long minimum return interval, mixed severity, and stand replacement fire regimes that typify these vegetation types (Sugihara *et al.* 2006).

Ignitions by indigenous peoples were likely a large component of the presettlement fire record in some PFRs, such as redwood (Greenlee and Langenheim 1990) and oak woodland, and are difficult or impossible to definitively differentiate from lightning ignitions, although fire cause may be inferred from seasonality in some cases (Anderson and Moratto 1996). Some vegetation types in certain areas were probably maintained mostly by presettlement anthropogenic fire regimes, which may have resulted in vegetation type conversions in some parts of the landscape prior to Euro-American arrival. Widespread indigenous ignitions were probably uncommon in other PFRs, however, such as subalpine forest and desert mixed shrub (Anderson 2005). Regardless, no attempt is made in this assessment to differentiate between lightning and indigenous ignitions.

This paper provides background information for the FRID mapping products developed by the Forest Service's Pacific Southwest Region Ecology Program and Remote Sensing Lab (Safford *et al.* 2011; available at: http://www.fs.fed.us/r5/rsl/clearinghouse/r5gis/frid/). These annually updated maps provide information on geographic distribution of PFRs, and a number of different FRID statistics calculated using the California fire perimeters database (available at: http://www.frap.cdf.ca.gov/data/frapgisdata/select.asp). These map layers are useful for land and resource planning and assessment, as well as other natural resource applications such as fuels treatment planning, postfire restoration project design, management response to fire, and general ecological understanding of the historical and current occurrence of fire on the California national forests and neighboring jurisdictions.

Our process necessarily generalized across scales of both space and time. In general, and assuming all else is equal, areas with higher precipitation or less ignition within a given PFR would be expected to burn less often than drier areas with an ignition source (Agee 1993, Sugihara *et al.* 2006). A PFR in northwestern California therefore might be expected to support somewhat longer fire return intervals than the same PFR in southern California. A solution for this may be to use the median fire frequency as the preferred measure of central tendency for PFRs in parts of their range where vegetation is relatively more flammable, and the mean fire frequency where vegetation is relatively less flammable (at least where the median is shorter than the mean, which is the typical case). Patch sizes can also influence fire frequency, with small patches of mesic vegetation embedded in a matrix of drier vegetation having shorter fire return intervals than large patches of mesic vegetation, and vice-versa (Agee *et al*. 1990*a*). Obviously, where higher local accuracy is required, the reader should consult the primary literature (e.g., see the citations supporting Table 2).

Temporally, changes in vegetation on California landscapes since the middle of the nineteenth century can make comparisons between historical and contemporary conditions difficult. A good example is provided by the geographic distribution of the yellow pine PFR, which is dominated by ponderosa pine (*Pinus ponderosa* C. Lawson) and Jeffrey pine (*P. jeffreyi* Balf.). The Forest Service mapped vegetation on about 60 % of its California lands in the 1930s (Wieslander 1935). Modern vegetation mapping can be generalized to the same polygon resolution and compared with the 1930s maps to get a broad idea of landscape-level vegetation changes. After >75 years of fire exclusion, logging, and other anthropogenic change, the area occupied by the yellow pine PFR appears to have decreased by about two thirds in the central Sierra Nevada, with about two thirds of the loss due to infilling by shade-tolerant (mostly fire-intolerant) conifer species, for example from the genus *Abies* (Thorne *et al.* 2008; J. Thorne, University of California, Davis, USA, and H. Safford, USDA Forest Service, Vallejo, California, USA, unpublished data). The FRID mapping is often based on contemporary vegetation data, and these sorts of temporal changes cannot be properly accounted for. After completion of digitization of the 1930s vegetation maps, we hope to use them (where they are available) to update the geographic distribution of PFRs to allow a more accurate assessment of changes in fire frequency.

Although this study presents summarized estimates of presettlement fire frequency, it does not imply that contemporary fire should necessarily be applied at historical intervals, which may be neither feasible nor desirable in the context of altered anthropogenic influences and climatic conditions (Anderson and Moratto 1996; Millar *et al.* 2007; Wiens *et al.*, in press). Instead, the estimated presettlement FRIs are intended to serve as an assessment tool for comparison with current fire regimes and trends in those regimes, and to provide general guidelines for ecological restoration (or realignment) in vegetation types that are currently in jeopardy of type conversion due to fire frequencies that are outside the historical range of variation. In order to promote ecosystem resilience in the face of climate change and other uncertainties, efforts to restore fire to ecosystems should focus on the variability of fire frequencies (and other characteristics of the fire regime) that historically facilitated resilience, rather than applying fire to an ecosystem precisely at the mean or median interval.

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