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Historical forest structure and fire in Sierran mixed-conifer forests reconstructed from General Land Office survey data

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Abstract. Dry forests of the western United States (ponderosa pine, dry mixed conifer) are often considered at risk of uncharacteristic severe fires, but recent research has found historically extensive severe fire. This has left divergent perspectives about how to restore dry forests, protect people and infrastructure from fire, and interpret the ecological effects of large fires, such as the 2013 Rim fire, a human-set 104,000 ha fire in the western Sierra Nevada Mountains. To help resolve this uncertainty, I used new methods to reconstruct historical forest structure and fire and test 11 hypotheses about them, using A.D. 1865–1885 General Land Office surveys, across 330,000 ha of Sierran mixed-conifer forests. The reconstructions show these historical forests were open and park-like in places, but generally dense, averaging 293 trees/ha; shade-tolerant trees and large trees were abundant, but smaller (<60 cm diameter) pines and oaks numerically dominated. These smaller trees, along with common understory seedlings and saplings and almost pervasive shrubs, created abundant ladder fuels. It is not surprising, given these conditions, that just 13–26% of historical Sierran mixed-conifer forests had only low-severity fire, with mixed-severity fire over 43–48%, and high-severity fire over 31–39% of the land area. The high-severity fire rotation was 281 years in the northern and 354 years in the southern Sierra, short enough to contribute to high levels of heterogeneity, including abundant areas and large patches (up to 9400 ha) of early-successional forest and montane chaparral, but long enough to allow recovery of old-growth forest over large land areas. Proposals to reduce fuels and fire severity would actually reduce, not restore, historical forest heterogeneity important to wildlife and resiliency. Sierran mixed-conifer forests are inherently dangerous places to live, which cannot be changed without creating artificial forests over large land areas. However, people can adapt to fires by channeling development to safer areas and modifying ignition zones near houses and communities to survive fire.

Key words: chaparral; dry forests; fire; forest structure; historical forests; land-survey data; mixed-conifer forests; old-growth forests, reconstruction; resilience; Sierra Nevada Mountains.

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INTRODUCTION

"...the departure of views begins with the relative certainty of fire frequency and spatial intensity in presettlement times. There is too little compelling evidence and incomplete rangewide research to conclude a precise pattern of fire frequency or severity in presettlement times. There were very probably areas that burned frequently (less than ten-year intervals), but some areas within the same vegetation type probably escaped burning for much longer periods and built up sufficient fuel loads to burn with high intensity...forest conditions were not

largely 'open or parklike,' in the words of John Muir; rather, there was a mix of dark, dense, or thick forests in unknown comparative quantities..."
(Alternative View: Sierra Nevada Ecosystem Project 1996 Volume 1:63)

Dry forests of the western United States could face increased drought, fire, and insect outbreaks in an altered condition because of past logging, livestock grazing, and fire exclusion, yet how to restore them is clouded by competing evidence and uncertainty about historical forests and wildfires, as is evident in the quote above. Evidence shows that some dry forests, which include ponderosa pine (*Pinus ponderosa*) forests and dry mixed-conifer forests with more firs (*Abies*, *Pseudotsuga*), were historically maintained in a relatively open, often park-like condition by low-severity fires (e.g., Covington and Moore 1994, Fulé et al. 2003). These fires periodically limited fuel buildup and large high-severity fires. However, paleoecological studies have revealed past high-severity fire in these forests (e.g., Pierce et al. 2004). Early scientific reports (Shinneman and Baker 1997, Baker et al. 2007) and aerial photography (Hessburg et al. 2007), tree-ring reconstructions (Ehle and Baker 2003), reconstructions from the General Land Office surveys in the late-1800s (Williams and Baker 2012*a*, *b*), and spatially-extensive age-structure analysis (Odion et al. 2014) present substantial evidence high-severity fire and dense forests were a significant part of historical forests. In the Sierra Nevada Mountains, the subject of this study, similar competing evidence led to both a main and alternative view of the role of fire and structure of historical forests after an extensive multi-author scientific study (Sierra Nevada Ecosystem Project 1996). The main view is above, and the alternative is in the initial quote.

Uncertainty about the structure of historical forests and role of high-severity fire has scientific and policy implications. Are sensitive species (e.g., spotted owls), endangered by uncharacteristic high-severity fires (Weatherspoon et al. 1992, Spies et al. 2006) or have these fires long provided early-successional vegetation favored for foraging (e.g., Bond et al. 2009)? Are high-severity fires increasing to unnatural levels (e.g., Adams 2013), threatening natural ecosystems as well as houses, or are these fires burning episodically at rates similar to historical rates (Baker 2012)? Is it restoration if these forests are extensively thinned to prevent high-severity fires, or will this reduce historically important high-severity fires and add to adverse effects of fire exclusion?

In a series of recent studies (Baker 2012, Williams and Baker 2012*a*, *b*, 2013), we used the General Land Office (GLO) surveys to help answer these questions. The surveys, mostly done in the late-1800s in the western U.S., laid out the public land-survey system as a grid of 1.6 km $\times$ 1.6 km section lines intersecting at section corners. Surveyors collected systematic data on tree attributes at corners and listed dominant trees and shrubs in order of abundance along section lines. These geographically precise data can be used, with new methods (Williams and Baker 2011), to accurately reconstruct forest structure (e.g., tree density) and fire severity across large land areas. Earlier use of the GLO data in the Sierra Nevada included analysis of tree sizes and forest composition (Fites-Kaufman 1997, Manley et al. 2000, Hyde 2002), analysis of changes in a burned chaparral area (Wilken 1967), and reconstruction of tree density (Maxwell et al. 2014).

I used GLO survey data to analyze 11 hypotheses (Table 1) about historical forest structure and fire in Sierran mixed-conifer (SMC) forests of the western Sierra Nevada, California. I supplemented survey data with 208 quotes from early scientific and agency reports about fire and forest structure (Appendix A). Hypothesis H_1, that historical SMC forests were somewhat open, is supported by studies that suggest historical SMC forests had low tree densities, and by early observations (Appendix A: Q112–Q134). North et al. (2009:9) indicate that "All reconstruction studies, old forest survey data sets, and 19th-century photographs (Gruell 2001, McKelvey and Johnston 1992) suggest that frequently burned forests had very low tree densities." McKelvey and Johnston (1992:237) said: "The stand structure at the turn of the century [A.D. 1900] was often quite open" and was "...one dominated by large, old, widely spaced trees..." (McKelvey and Johnston 1992:241). Early photographs of unlogged SMC forests support a generally open forest structure, except in the northern Sierra on cooler, moister sites (Gruell 2001). Scholl and Taylor (2010:375)

Table 1. Hypotheses about historical Sierran mixed-conifer (SMC) forest structure and fire.

Hypothesis	Description
H_1	Historical SMC forests were somewhat open, with moderately low tree densities (i.e., mean tree density <150 trees/ha).
H_2	Historical SMC forest composition was about half shade-intolerant pines (ponderosa pine, sugar pine) and oaks (California black oak, canyon live oak) and about half shade-tolerant white fir and incense cedar.
H_3	Historical SMC forests had mean basal areas of 33 m^2/ha.
H_4	Historical SMC forests were dominated by large trees (i.e., >50% of trees were >60 cm in diameter).
H_5	Historical SMC forests had relatively low abundance of small trees (i.e., <10% of area with understory trees).
H_6	Historical SMC forests had generally high shrub cover (i.e., >75% of area).
H_7	Low-severity fire historically characterized ≥85% of SMC landscapes, with <15% of area having other fire severities.
H_8	High-severity fire in historical SMC forests occurred with long fire rotations (i.e., >500 years).
H_9	Patches of contiguous high-severity fire area did not exceed 250 ha.
H_{10}	Historical northern Sierran forests differed in forest structure and fire from southern Sierran forests, based on the attributes tested in H_1–H_9.
H_{11}	Phases of Sierran mixed-conifer forests differed in forest structure and fire, based on the attributes tested in H_1–H_9.

also say: "Our reconstruction supports written descriptions of mixed-conifer stands as being low in density..." In contrast, Sudworth's (1900) early data suggest historical SMC forests averaged 229–235 trees/ha in the northern (Stephens 2000) and 278 trees/ha in the southern Sierra (Stephens and Elliott-Fisk 1998) for trees >30.5 cm. Early observations also support the idea that SMC forests were dense (Appendix A: Q135–Q147). Thus, evidence supports both the main view and the alternative in the initial quote.

Hypothesis H_2 suggests historical SMC composition had similar amounts of shade-tolerant and intolerant trees. McKelvey and Johnston (1992:235), said "Pines did not dominate the forests, either in numbers or in volume." In contrast, Scholl and Taylor (2010:375) found "a large proportion of large-diameter shade-intolerant and fire-tolerant pines and oak."

Regarding the basal area hypothesis, H_3, reported dominance by large trees suggests historical basal area and quadratic mean diameter were also moderately large. Basal area (BA) is the total cross-sectional area of tree stems, and quadratic mean diameter (QMD) is the diameter of the tree of mean basal area. Safford (2013) suggested a historical mean BA of 33.2 m^2/ha based on 13 reference values, and I thus use that as the hypothesis here. No specific estimate of historical quadratic mean diameter is available, thus a hypothesis is not posed.

Hypotheses H_4 and H_5 are that historical SMC forests were dominated by large trees, and small trees were lacking or rare. Based on data in Sudworth (1900), McKelvey and Johnston (1992:234) suggested that "...most stems exceeded 25 inches in d.b.h." and trees <28 cm (11 inches) "...were uncommon, though patches of very small regeneration appear to have been present." Sudworth's data also suggested to these authors that "sugar pine, Douglas-fir, and white fir occurred only as very large trees." Similarly, Scholl and Taylor (2010) found large-diameter trees were historically dominant. Gruell (2001:106) said that early photographs showed that SMC forests generally had "large trees either widely spaced or close together..." Early observations report old-growth with dominant large trees (Appendix A: Q112–Q117) and relatively few small trees, at least where fire was common (Appendix A: Q164, Q167–Q173).

Hypothesis H_6, that historical SMC forests had high shrub cover, is based on the observation that shrub cover declined after EuroAmerican settlement due to shading by increased conifer cover (Gruell 2001, North et al. 2009), intense early sheep grazing (Sudworth 1900, Leiberg 1902, Vankat and Major 1978, McKelvey and Johnston 1992), overbrowsing by deer, and a decline in fire-stimulated shrubs due to fire exclusion (Vankat and Major 1978). Early photographs (Gruell 2001:106–107) often suggested only "scattered understory trees or shrubs..." or "a patchy chaparral understory with numerous openings," or grassy or oak-dominated understories. Chang (1996) also suggested patchy and variable understory shrubs in historical SMC forests. Some early observations report loss of shrubs to livestock grazing (Appendix A: Q198–Q199) and a sparse understory by about 1900

(Appendix A: Q200–Q203).

Hypotheses H_7-H_9 about historical fire are based on the finding that SMC forests historically had a fire regime with "frequent, low-severity fires" and "a low incidence of high-severity, or stand-replacing fire" but with some uncertainty about the latter (Collins and Stephens 2012:7). This is supported by Chang (1996). Scholl and Taylor (2010) suggested fires were mainly low severity but patchy, allowing some shade-tolerant trees to reach the canopy. Upper-elevation SMC forests may have had perhaps 15% of total burned area in high-severity fire, but as "many small stand-replacing patches (<4 ha) and few large patches (>60 ha)" (Collins and Stephens 2010:937). Stephens et al. (2007) estimated about 5% high severity in historical SMC forests. These ideas are supported by early observations in some cases (Appendix A: Q14–Q27).

The last two hypotheses suggest SMC forests varied in structure and fire regime between north and south (H_{10}) and among compositional phases (H_{11}). Gruell (2001), for example, found that historical SMC forests were denser on cooler, moister sites in the northern Sierra.

Methods

Study area

The study focuses on Sierran mixed-conifer (SMC) forests in the lower/middle montane zone (Barbour and Minnich 2000) on the western side of the Sierra Nevada Mountains from south of Quincy and Blairsden (Fig. 1a) to near Miracle Hot Springs, California (Fig. 1d). This forest extends from about 300–1800 m elevation in the northern Sierra and from about 1200 to 2300 m elevation in the southern Sierra Nevada (Fites-Kaufman et al. 2007).

Major trees include ponderosa pine (*Pinus ponderosa* Lawson and C. Lawson), sugar pine (*Pinus lambertiana* Douglas), incense cedar (*Calocedrus decurrens* (Torr.) Florin), Sierra white fir (*Abies concolor* (Gord. & Glend.) Lindl. Ex Hildebr. var. *lowiana* (Gord. & Glend.) Lemmon), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and California black oak (*Quercus kelloggii* Newberry). About 25 other trees and large shrubs were used by surveyors as bearing trees (see Appendix B for taxonomic authorities). Ponderosa and Jeffrey pine (*Pinus jeffreyi* Balf.) can co-occur, especially at higher elevations and in the southern Sierra, but were poorly distinguished by surveyors, thus are both included in ponderosa. Although giant sequoias (*Sequoia gigantea* (Lamb. Ex D. Don) Endl.) also occur in small groves, GLO survey data are often too coarse to provide useful data about them, and they are thus not studied. Major shrubs include *Ceanothus integerrimus* (and *C. parvifolius* in the southern Sierra) at lower elevations and *C. cordulatus* at higher elevations, often both with *Arctostaphylos patula* or with *A. viscida* at lower elevations. Other common shrubs include *Prunus emarginata*, *Quercus vacciniifolia*, *Cornus nuttallii*, *Chrysolepis sempervirens*, *Ribes roezlii*, *Corylus cornuta* var. *californica*, and *Chamaebatia foliolosa*. Surveyors used many common names for shrubs (Appendix B).

I selected study areas in the northern and southern Sierra Nevada Mountains (Fig. 1) to address hypothesis H_{10}: that the two regions differed. Entering GLO survey data is laborious, and in each study area I completed about 25 townships or 230,000 ha. A township is a public-land survey-system unit about 9.6 km × 9.6 km containing 36 sections each about 1.6 km × 1.6 km. Townships were chosen that had early (pre-1890) surveys, high-quality surveyors (Appendix C), and to span the elevational and latitudinal range of SMC forests. Selection favored areas relatively undisturbed at the time of the surveys to provide reference information about historical forests. Thus, I included current national parks, wilderness areas, and other protected areas. This undisturbed condition was rarer in the north than the south.

To test hypothesis H_{11}, I divided study areas into compositional and roughly elevational phases (Barbour and Minnich 2000): (1) ponderosa pine-Douglas-fir, (2) Sierran mixed-conifer, and (3) white fir (Table 2). These phases best correspond with Society of American Foresters cover types mapped in CALVEG, a satellite-based mapping system created by the Pacific Southwest Region of the U.S. Forest Service (www.fs.fed.us/r5/rsl/projects/mapping). CALVEG has been shown to have reasonable accuracy (Franklin et al. 2000). Associated vegetation (e.g., California black oak, canyon live oak, chaparral, grasslands) was not assigned to these phases in CALVEG, but can occur in any phase.

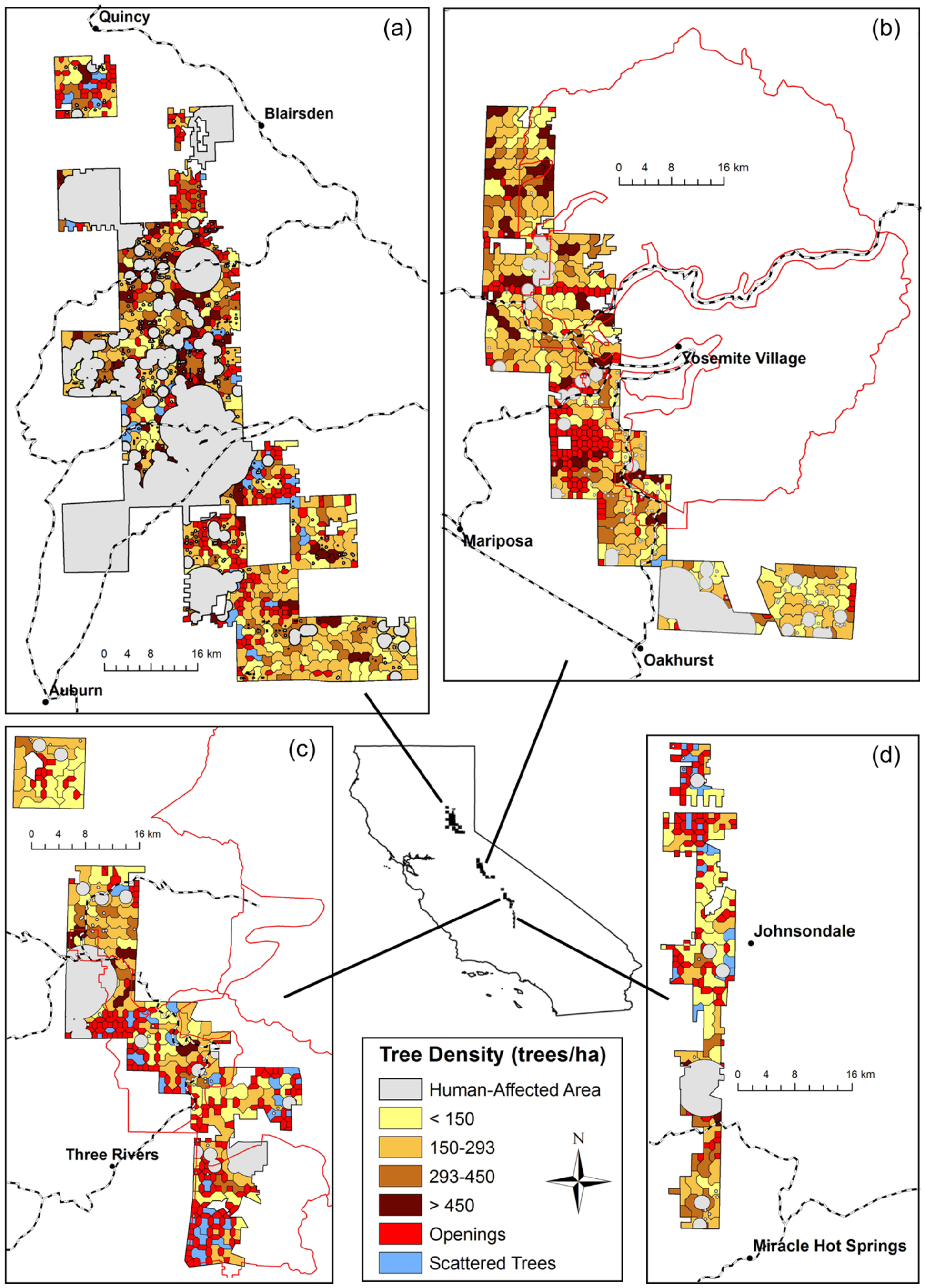

Fig. 1. Reconstructed tree density in Sierran mixed-conifer forests, excluding human-affected areas, in the: (a) northern Sierra Nevada, (b) southern Sierra Nevada on the western side of Yosemite National Park (red boundary), (c) southern Sierra Nevada on the western side of Sequoia-Kings Canyon National Parks (red boundary), (d) southern Sierra Nevada south of Sequoia-Kings Canyon National Park. Map scales differ among areas. This is based entirely on tree data at section corners, not section-line data. Openings are defined as corners where surveyors recorded no bearing trees. Scattered trees are defined as corners where surveyors recorded <50% of expected bearing trees. Major current roads are shown by black-and-white lines.

Table 2. Area in three phases of the Sierran mixed-conifer forest and the Society of American Foresters (SAF) cover types that occur in each phase. Note that these are before removal of human-affected areas.

Phase/SAF cover type (SAF No.)	Northern Sierra Nevada area (ha)	Southern Sierra Nevada area (ha)
Area in the three phases		
Ponderosa pine–Douglas-fir phase	75859	55924
Douglas-fir–tanoak–Pacific madrone (234)	359	5
Interior ponderosa pine (237)	18	16
Pacific Douglas-fir (229)	985	46
Pacific ponderosa pine (245)	18362	32180
Pacific ponderosa pine–Douglas-fir (244)	33308	63
California black oak (246)	7601	3942
Canyon live oak (249)	11339	10131
Hard chaparral (262)	3887	9541
Sierran mixed conifer phase	115037	103366
Sierra Nevada mixed conifer (243)	104249	83795
California black oak (246)	3302	4500
Canyon live oak (249)	1990	8306
Hard chaparral (262)	5496	6765
White fir phase	36284	58291
White fir (211)	31933	41412
Jeffrey pine (247)	2183	8671
California black oak (246)	68	1606
Canyon live oak (249)	18	1178
Hard chaparral (262)	2082	5424
Total area in the three phases	227180	217581
Area not in the three phases		
Miscellaneous minor types (207, 215, 217, 218, 221, 235, 238, 248, 250, 255, 256)	2056	3990
Non-forest (000)	6569	10746
Total area not in the three phases	8625	14736
Total study area	235805	235317

To include them in phases, I merged polygons of these other types with the phase that shared the polygon boundary or was closest.

The GLO surveys and their use in reconstructing historical forest structure

General Land Office (GLO) surveyors were required to record species, diameter, distance, and azimuth of two bearing trees on opposite sides of section-lines at quarter corners at the 0.8-km mark and four bearing trees, one per section, at section corners at the 1.6-km mark along section lines (USDI General Land Office 1881, 1894). Surveyors also recorded where they left forests and entered openings (e.g., grasslands, chaparral patches) and vice versa, and often also recorded entry and exit locations for areas of scattered trees or other conditions. Most surveyors used qualitative descriptors of forest density and tree size or the quality of timber (e.g., heavily timbered, dense forest, good timber). At the end of each section line, they were required to list dominant overstory trees or shrubs in order of abundance and do the same for understory trees and shrubs, also using density terms (e.g., dense, scattered).

Bearing-tree data at section corners and the section-line data constitute the GLO data used in the analysis. Bearing trees, typically >10 cm diameter, were measured accurately and selected with little bias, based on resampling at relocated section corners, and thus provide a valid statistical sample of dry forests (Williams and Baker 2010). Section-line data provide a statistically valid line-intercept estimate of percent cover (Butler and McDonald 1983).

Bearing-tree data can be used, with new methods we developed (Williams and Baker 2011), to reconstruct tree density, composition, basal area, quadratic mean diameter, and diameter distributions. Tree data are pooled to produce sufficient sample size. I pooled six contiguous corners (518 ha) for tree density, nine corners (777 ha) for composition, basal area, and quadratic mean diameter, and 12 corners (1036 ha) for reconstructing diameter distributions. In an extensive modern plot-based accuracy trial (Williams and Baker 2011), these levels of pooling led to the lowest relative mean absolute errors (RMAE) for tree density, varying from

14.4% to 23.0% among three states, and for basal area, varying from 21.0% to 25.4%. RMAE is 100 × (|GLO Survey estimate-plot estimate|)/plot estimate. Composition was 89–94% accurate and diameter distributions 87–88% accurate. GLO reconstructions thus approach the accuracy of tree-ring reconstructions of historical forest structure, which also have error (Scholl and Taylor 2010).

The new methods (Williams and Baker 2011) require field data to develop equations to estimate the Voronoi area of each tree and its crown radius from tree diameter (Williams and Baker 2011). A field assistant and I revisited 56 section corners in the study areas, spanning phases and a wide cross-section of stand structures. At each corner, we collected needed data for 2–4 of the nearest trees, aiming for 25–30 trees of each major species in the study area. For each tree, we measured diameter (at about 30 cm height, which is where surveyors likely measured diameter) using a caliper and crown radius using a densitometer and laser distance meter. The Voronoi area for the tree is the area of ground nearer to the subject tree than any other tree. We estimated this area by mapping, using the laser distance meter and a sighting compass, the location of each of at least six neighboring trees, with at least one per 90° of azimuth (Delincé 1986). In ArcGIS, I recreated the Voronoi polygon and measured its area. I then fit crown radius and Voronoi equations using regression (Minitab) for each major species, species groups (e.g., pines), and a pool of minor species (Appendix D). Bearing-tree data were then used with the equations to do reconstructions (Williams and Baker 2011). We also revisited about 100 section lines, where common names used by surveyors for trees and shrubs were cross-checked.

GLO survey data have some limitations. The fine-scale historical structure of SMC forests is often described as having highly clustered groups of trees separated by openings (North et al. 2009). The GLO survey data cannot discern this structure, as they are limited to scales exceeding a minimum three-corner reconstruction polygon of about 259 ha (Williams and Baker 2011). Surveyors did not all follow the instructions (e.g., USDI General Land Office 1881). Section-line descriptions or bearing trees can be missing, with no explanation, and some surveyors did not use density terms consistently. To offset this, I selected areas with high-quality surveys, analyzed and rated surveyor quality (Appendix C), then used the highest-quality records for specific analyses.

Some critiques of our GLO methods have appeared. Fulé et al. (2014) suggested some of our GLO methods were invalid. In response, we explained that our methods were extensively tested, validated, and shown to be accurate, and we added new corroboration (Williams and Baker 2014). Hagmann et al. (2013) suggested our GLO methods overestimated tree density in one area, but their inventory data, collected decades after surveys, omitted small trees and were collected in areas that had been logged (Odion et al. 2014). Maxwell et al. (2014) suggested surveyors were biased, but appeared unaware of Williams and Baker (2010) who found very low surveyor bias and error. Maxwell et al. also said GLO data are aggregated small point samples that could lead to misguided restoration, then used an aggregate of small point samples (185 small plots/transects in <0.1 ha) totaling <20 ha in a watershed of about 80,000 ha (a 0.025% sample) to guide restoration. Maxwell et al. had data for 1509 trees >100 years old in their 80,000 ha study area, thus one tree per 53 ha. GLO data provide 66% more tree data, with one tree per 32 ha. Maxwell et al. (2014:2) said "GLO estimates of forest structure and species composition lack sufficient detail to guide forest restoration management," but their sample of 1509 trees in 185 plots averages only 8 trees per plot, which seems to provide little detail to guide forest restoration management. Authors of some tree-ring studies thus appear to have overstated the merits of their methods relative to GLO methods, which often use similar tree sample sizes to produce comparable reconstructions with similar accuracy (Williams and Baker 2012*a*, Maxwell et al. 2014). Tree-ring methods could provide finer detail and higher accuracy if sample size was larger, but this would then be infeasible to replicate across large landscapes. Even the roughly 12,500 direct measurements of trees across 400,000 ha of GLO data would be challenging to replicate with tree-ring methods, and the evidence needed to use tree-ring methods has often disappeared, because of disturbance from land uses (Maxwell et al. 2014).

Separating EuroAmerican effects

The extended period of Indian influence on fire and forest structure in the study area had complex and heterogeneous effects, but ended abruptly in the middle 1800s (Parker 2002). The western Sierra experienced a gold rush beginning in 1848 and also early livestock grazing and logging (Beesley 2004). Mining impacted forests directly and also required logs for the mines, houses, and water systems. Since the study's focus is the pre-EuroAmerican historical forest, I used buffer analysis in GIS, with the survey data, to identify and exclude parts of the study areas where EuroAmerican land uses may have directly altered forests by the time of the surveys. As surveyors walked section lines, they recorded, in links from a section corner, where observed land-uses occurred, including point locations for small features (e.g., a building) and entry and exit locations for larger features (e.g., mining, farming). These features were mapped accurately, likely to within a few tens of meters. Early roads and mines often correspond closely with modern roads and abandoned mines visible on topographic maps. In the GIS, I assigned $\pm$50 links (20 m total length) as an extent for point features, so they would show up on maps and also as a rough estimate of extent.

A total of 2326 records of human uses in the northern and 389 in the southern Sierra was digitized. The number of sawmills identified by surveyors in the northern Sierra was 37. Beesley (2004) estimated 150 sawmills were in operation in the counties of the northern Sierra Nevada north of Sacramento between 1850 and 1900, thus it seems reasonable that about a fourth of those would have been operating in my study area. Features that represent the transportation system (i.e., roads, trails) or water system (i.e., ditches, reservoirs) may have been associated with specific mining or logging operations or other activities, but surveyors did not consistently record associations. These features also may have had multiple uses in many cases. Thus, I put them only in broad categories (i.e., transportation, water system).

I buffered all features to estimate the potential width of an "effect zone" (e.g., Forman and Deblinger 2000) in nearby forests, a zone adjoining the land use where trees may have been removed by mining, logging or other activities. Methods for estimating the effect zones for each land use and using buffers to spatially model the effect zones are given in Appendix E, along with detailed findings. I merged all estimated effect zones, then used the resulting map to erase affected areas, leaving a complementary area comparatively unaffected by EuroAmerican land uses. The merged map of buffered human effects covers 102,323 ha (39.5%) of the 235,805-ha northern Sierra Nevada area, leaving a 133,482-ha unaffected area (Fig. 1a), and in the southern Sierra covers 38,856 ha, leaving an unaffected area of 196,461 ha (Fig. 1b–d).

Reconstructing historical fire severity and fire rotation

Fire severity was reconstructed using three approaches: (1) structure-based evidence from a combination of tree sizes and tree density from survey tree data, (2) evidence from section-line descriptions of patches of chaparral and scattered trees, and (3) evidence from combined tree data and section-line data. In the first approach, reconstruction of fire severity is based on forest structure from combined small trees, large trees, and tree density, as used previously (Williams and Baker 2012*a*, 2013). I first intersected reconstructed tree-density (6-corner pools) with diameter distributions (12-corner pools) and used the 6-corner intersection. Fire-severity is based on calibration using 64 tree-ring reconstructions, where authors reconstructed forest structure and identified fire severity at the same locations (Williams and Baker 2012*a*). Low fire severity identified by authors corresponds with 6-corner polygons in which small trees were $\leq$46.9% of total trees, large trees were $>$29.2% of all trees, and tree density was $<$178 trees/ha. High fire severity occurs where small trees were $>$50.0% of total trees and large trees were $<$20.0% of total trees. Mixed severity corresponds with polygons between low and high.

The second approach uses evidence of high-severity fire shown by chaparral. Surveyors were required to record where they left forest and entered chaparral patches and vice versa. Chaparral patches are identified in section-line data by dominance by montane chaparral shrubs, primarily *Ceanothus integerrimus*, *C. cordulatus*, *Arctostaphylos patula* or *A. viscida*. Surveyors described 57% of chaparral section-line length as "dense." Montane chaparral dominates after high-severity fire in SMC forests (Cronemiller 1959, Nagel and Taylor 2005), which is strongly supported by early observations (Appendix A: Q57–Q78). Montane chaparral is favored after high-severity fire because the two *Ceanothus* and *A. patula* have fire-stimulated seed, persistent seedbanks, and can resprout after fire (Cronemiller 1959, Knapp et al. 2012). *Arctostaphylos viscida* is an obligate seeder, but its seed germination is not stimulated by fire (Kauffman and Martin 1991). *Ceanothus integerrimus*, *C. cordulatus*, and *A. patula* have refractory seed, but heat shock breaks dormancy imposed by a hard seed coat in *Ceanothus* and a chemical in charred wood or smoke does the same in *A. patula* (Keeley 1991). Thus, these shrubs are post-fire seed recruiters (Keeley 1991). Severe fires in SMC forests usually greatly increase montane chaparral shrubs. Mean shrub cover, for example, increased from 8.4% in a low-severity area to 17.2% in medium severity to 53.0% on a high-severity area of one fire (Crotteau et al. 2013). In five high-severity fires, shrub cover in 60% of plots was >60% (Collins and Roller 2013).

Not all chaparral originated after forest fires or is successional to forests, at least on century time-scales (Show 1924, Nagel and Taylor 2005). I estimated ~80% of chaparral area was successional to forests after these fires (Appendix F), which is similar to early estimates of two thirds to three quarters (Appendix A: Q95, Q98). The 20% not successional to forest either experienced another fire that maintained the chaparral (e.g., Appendix A: Q100–Q103) or was in an environmental setting unfavorable to forest (Appendix F). To approximately account for the 20% not successional to forest, I reduced chaparral area that indicates high-severity fire by 20%.

Unfortunately, surveyors did not record chaparral entry and exit locations for 27.7% of the area in the northern and 55.0% in the southern Sierra Nevada. These surveyors did not follow instructions (USDI General Land Office 1881, 1894), and instead described lines as having forest "and chaparral," providing no entry/exit locations or even the length of chaparral along section-lines. Thus, we know chaparral occurred on these lines, but not how much. To estimate missing chaparral, I divided documented chaparral area by the fraction of total unaffected area with chaparral entry/exit data. The added chaparral area occurred in areas mapped as low- or mixed-severity. As an approximation, I removed the hectares of added chaparral area from hectares of low- and mixed-severity areas in a manner that maintains their relative proportions.

Section-lines explicitly recorded as having scattered trees also likely represent high-severity fires. These lines typically also had one or more of the four main chaparral shrubs dominant in the understory, which was described as dense on about one-third of line-length. These lines also had many missing bearing trees, about 5% of line-length had understory seedling/sapling pines and 17% had understory oaks. These lines likely represent high-severity fires with more survivors and/or more post-fire trees than in chaparral patches. This pattern was also recorded many times in early observations (Appendix A: Q79–Q94, Q97). Slightly reduced dense shrubs with scattered small trees were reported 2–6 decades after high-severity fires in SMC forests (Merriam 1899, Show 1924, Cronemiller 1959, Wilken 1967, Conard and Radosevich 1982). This interpretation is also supported by comparison with maps by Leiberg (1902), described in the next section. In the northern Sierra Nevada, 100.0% of chaparral patches identified by surveyors were mapped later by Leiberg (1902) in his 75–100% burned category (high-severity fire). Similarly, 79.9% of patches with scattered trees were mapped later by Leiberg as high-severity fire.

In the third approach, combined tree- and section-line data were used to classify fire severity for forest openings (Fig. 1). An opening is a section corner lacking recorded bearing trees, and a corner with scattered trees had <50% of expected bearing trees. These are closely intermixed where they occur. Most surveyors in the southern (Appendix C), but not northern Sierra, used combinations of density terms for the overstory and understory in descriptions of section-lines containing these corners. A null hypothesis of random usage is rejected for both types of corners (Table 3). Indeed, 95% of corners with openings and 99% of corners with scattered trees had understories described as dense where

Table 3. Combinations of surveyor terms for forest overstories and understories at section corners that were openings or had scattered trees, and the corresponding reconstructed fire-severity. The test results for both openings and scattered trees were χ^2 (1, 472) = 110.6, $p < 0.001$.

Overstory density terms	Test and interpretation	Forest corners, openings: Understory dense/thick	Forest corners, openings: Understory not recorded	Forest corners, scattered: Understory dense/thick	Forest corners, scattered: Understory not recorded
Heavily timbered, good timber, very good timber, excellent timber	Observed	17.0	73.0	1.0	23.0
	Expected	59.5	30.5	19.0	5.0
	χ^2 contrib.	30.3	59.2	17.1	65.6
	Interpretation	Opening from moderate-severity fire in mature forest	Opening not from fire in mature forest	Opening from moderate-severity fire in mature forest	Opening not from fire in mature forest
Not recorded, scattered trees, scrubby trees	Observed	295.0	87.0	141.0	14.0
	Expected	252.5	129.5	123.0	32.0
	χ^2 contrib.	7.2	13.9	2.6	10.2
	Interpretation	Mid-successional after high-severity fire <30 years ago	Mid-successional from uncertain fire severity	Mid-successional after high-severity fire <30 years ago	Mid-successional from uncertain fire severity

overstory density was not described, thus was neither dense nor scattered, but still forested (Table 3). The dense/thick understories were almost entirely dominated by fire-stimulated *Ceanothus integerrimus* and *Arctostaphylos patula*, and nearly all also had understory trees, which were much less common in SMC forests in general.

I interpret this combination as a forest regenerated after high-severity fire that still retains the dense montane chaparral understory. The chaparral and scattered trees that identify high-severity fire in the second approach are similar but more fully forested. Trees regenerating in post-fire chaparral start overtopping shrubs within 8–10 years in the southern Sierra, and shrubs may reach the end of their lifespan after 35 years (Cronemiller 1959). Second-growth forests 30 years old may have 1000 or more trees/ha, averaging about 10–15 cm diameter (Dunning and Reineke 1933), also evident from early observations (Appendix A: Q96, Q99). Dense/thick understories seldom occurred in mature forests described as mature timber, but I used this as an indicator of mixed-severity fire. I left the other combinations as uncertain forest corners.

Fire rotation, the expected time to burn once across an area equal to a study area of interest, was calculated for high-severity fire as the period of observation divided by the fraction of the study area burned at high severity during that period (Baker 2009). The period of observation is based on the time needed to reach the size of a large tree. Tree growth is faster in the western Sierra Nevada, and I used <40 cm to define small trees and ≥50 cm to define large trees, in contrast to <30 cm and ≥40 cm, respectively, used in Arizona and Oregon (Williams and Baker 2012*a*). A 40-cm tree averaged about 120 years old in Arizona and 140 years old in the Blue Mountains of Oregon (Williams and Baker 2012*a*). In contrast, in the Sierra, a 50-cm tree was about 105–120 years old for sugar pine (Hodge 1906, Hall 1909), about 100–125 years for ponderosa pine (Hodge 1906, Hall 1909, Moore 1913), and about 100–155 years for white fir (Hodge 1906, Hall 1909, Moore 1913). I use 110 years as the average for a 50-cm tree, which is then used to reconstruct fire severity and estimate fire rotation for the 110-year period preceding the surveys, beginning about 1755–1775 and ending about 1865–1885 (Fig. 2).

Individual fires cannot be reconstructed from GLO data, but the area of contiguous patches that burned at high severity during the reconstruction period can be estimated from the final map of fire severity. I merged contiguous (touching) polygons of reconstructed high-severity fire and measured the area of each merged polygon. To avoid slivers and small polygons created by GIS operations, I omitted polygons <50 ha in area. I then constructed a binned histogram of patch sizes, and compared the

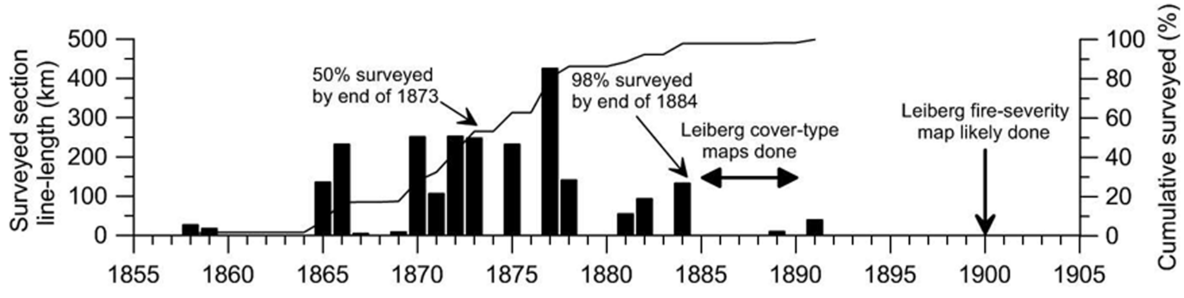

Fig. 2. Timing of Leiberg (1902) mapping relative to dates of surveys.

actual patch sizes to the hypothesized (H_9) 250-ha maximum.

Cross-validation

I compiled data from locations within or near the study area for which there are tree-ring reconstructions or early scientific inventories that report tree density or basal area, then used the GLO surveys to reconstruct tree-density and basal area for these same locations (Appendix G). Comparing these allows cross-validation of accuracy (Williams and Baker 2011). As a quantitative measure of the accuracy of the GLO estimates, I used RMAE, defined earlier.

Corroboration: Comparing the reconstructions to the Leiberg maps

A government scientist, John B. Leiberg, studied part of the northern Sierra Nevada about A.D. 1900, before national forests were established, to inventory and map forest structure (composition, timber volume, etc.) and threats to the forest (logging, fires, grazing, other human activities). I obtained digital versions of Leiberg's maps from the U.S. Forest Service's Pacific Southwest Research Station (www.fs.fed.us/psw/topics/ecosystem_processes/sierra/gis). Leiberg's study area overlaps 208,481 ha of my northern-Sierra study area, facilitating detailed comparison. However, after removing human-affected areas, the overlap area was 108,787 ha.

Between A.D. 1885 and 1890 (Fig. 2), Leiberg mapped cover types (e.g., chaparral), including five timber-volume categories (e.g., 2,000–5,000 board-feet/acre) in forests, across the 108,787-ha overlap area. The surveys in the overlap area were done in the 20 years before this cover-type map (Fig. 2). Near 1900, Leiberg also mapped 58,153 ha of burns, covering 53.5% of the overlap area, using four classes: (1) "5% to 25% of timber burned" on 23,484 ha (40.4%) of the overlap burn area, (2) "25% to 50% of timber burned" on 2,306 ha (4.0%), (3) "50% to 75% of timber burned" which did not occur in the overlap burn area, and (4) "75% to 100% of timber burned" on 32,363 ha (55.6%) of the overlap burn area (Leiberg 1902 Plate VII:18). Burned percentage refers to percentage of timber volume, thus the 75–100% burned category likely represents more than the 70–75% basal-area mortality often used as the minimum criterion for high-severity fire (e.g., Miller et al. 2009). In GIS, I overlaid and compared Leiberg's burns and cover-types, inside and outside burn areas, and overlaid Leiberg's burns on survey data.

The spatial error in the Leiberg maps is unknown. In the GIS maps, the total area of forest in the cover-type map is only 1.03 times (3% error) the area reported by Leiberg, and total chaparral area, foothill woodland area, and logged area have errors of only 2.3–6.7%. However, Leiberg's burn map may have one larger error. He reported in two places (Leiberg 1902:41, 186) that there were 715,440 acres that had $\geq$50% burned. In the GIS map of burns in Leiberg's whole study area, there are only 447,302 acres in the sum of the 50–75% and 75–100% burned categories. Much of the 50–75% category appears missing from the map. This is not a digitizing error; the printed map also has little area in this category. Thus, I focus on 5–25% and 75–100% burned categories.

Testing hypotheses

I used an initial alpha level of 0.05 for statistical tests, Bonferroni adjusted for multiple tests. I tested H_1 and H_3 using one-sample t-tests and H_2 using ANOVA. I tested H_4 to H_9 using null hypotheses and chi-square tests of counts. For H_4, I converted expected and actual percentages to counts (number of trees). For H_5 and H_6, which use section-line data, I converted expected and actual percentages to counts of the number of 1-km segments of section-line length. For H_7, which uses area data, I converted expected and actual percentages to counts of the number of 1000-ha areas. H_8 will be rejected if the actual value does not exceed the expected value of 500 years. H_9 was tested using a chi-square test with Yates' correction. I tested the null hypotheses of no difference between north and south (H_{10}) and among phases (H_{11}) using two-way ANOVAs with followup one-way ANOVAs and Tukey's multiple comparison procedure. H_{10} and H_{11} are tested along the way while testing corresponding hypotheses. I tested median tree densities using Kruskal-Wallis tests followed by a Bonferroni-corrected Mann-Whitney as a follow-up test. I compared diameter distributions using chi-square tests of counts in each 10-cm diameter class. Clipping with maps of phases produced some slivers, as pools of corners were not constructed to match boundaries of phases, thus I first omitted polygons <100 ha in area for 6-corner pools, <200 ha for 9-corner pools, and <300 ha for 12-corner pools, which still led to a large sample in each phase. Statistical testing used Minitab (Minitab, State College, Pennsylvania, USA).

Results

Historical forest density (H_1)

Hypothesis H_1, that historical SMC forests had mean tree densities that were low (i.e., <150 trees/ha), was rejected for all phases in both regions, except white fir in the north (Table 4), and rejected overall in the north and south, as well as pooled across regions and phases. I used an initial $\alpha = 0.05$, Bonferroni-corrected to $\alpha = 0.0055$, given nine planned tests, one per phase, one overall per region, and one for pooled data. Only 23% of area in the north and 33% in the south had a somewhat open, low-density condition with <150 trees/ha (Fig. 1).

Mean forest densities (Table 4) did not differ significantly between the northern and southern Sierra Nevada ($F = 1.23$, df = 1, 810, $p = 0.268$) or among the three phases ($F = 0.07$, df = 2, 810, $p = 0.935$), based on a two-way ANOVA, thus hypotheses H_{10} and H_{11} are rejected for this measure. Standard deviations did not differ significantly between north and south (Levene's test statistic = 0.21, $p = 0.645$) or among phases (Levene's test statistic = 0.13, $p = 0.874$). Reconstructed mean forest density across the study area thus can be pooled across the phases and regions, and was 293 trees/ha with a standard deviation of 477 trees/ha (Table 4).

Median forest densities, which ranged across phases and regions from 179 to 239 trees/ha (Table 4) are also useful, particularly because the distribution of tree densities was right skewed, with a long tail. About 16% of forest area exceeded 400 trees/ha and 3% had 1,000–9,000 trees ha. Indeed, 65% of the northern and 46% of the southern Sierra were dense, with >200 trees/ha, and 34% of the northern and 21% of the southern Sierra were very dense, with >300 trees/ha.

An initial $\alpha = 0.05$ was Bonferroni-corrected to $\alpha = 0.025$, given planned tests of medians, one for region, one for phase. Median forest density overall was significantly higher at 229 trees/ha in the north than the 191 trees/ha in the south ($H = 21.67$, df = 1, $p < 0.001$). Sample medians were 186 trees/ha in white fir, 208 trees/ha in ponderosa pine-Douglas-fir and 209 trees/ha in mixed-conifer, pooled across north and south. These were quite close, but not significantly different among the 3 phases ($H = 7.29$, df = 2, $p = 0.026$). If that test had instead been barely significant, the follow-up tests would have confirmed lack of significance. Thus, for medians, H_{10}, that regions differed, is not rejected, but H_{11}, that phases differed, is rejected.

Openings, which are section corners with no recorded bearing trees, and patches of scattered trees, which are corners with <50% of expected bearing trees, covered about 22% of each area (Table 4, Fig. 1). These corners are used in the fire-severity reconstructions.

Forest density was heterogeneous at a fine scale in both north and south (Fig. 1). Contiguous blocks of low-density forest (i.e., <150 trees/ha) seldom were >1,000 ha, although there was one larger area west of Johnsondale (Fig. 1d). Somewhat denser forests (150–293 trees/ha)

Table 4. Reconstructed areas, forest density, and forest composition in the parts of the northern and southern Sierra Nevada relatively unaffected by EuroAmerican land-uses, by phase and overall. Bearing trees were generally >10 cm diameter.

	Northern Sierra Nevada				Southern Sierra Nevada				
Variable	Ponderosa	Mixed conifer	White fir	Overall	Ponderosa	Mixed conifer	White fir	Overall	Pooled
Area (ha)									
Openings†	8981	9871	4417	23269	10602	15485	7014	33101	. . .‡
Scattered trees§	2006	3425	779	6210	1539	3819	1984	7342	. . .
Forested area¶	25478	55917	19291	100686	31649	65856	43865	141370	. . .
Total area	36465	69213	24487	130165	43790	85160	52863	181813	. . .
Percentage in openings/scattered	30.1	19.2	21.2	22.6	27.7	22.7	17.0	22.2	. . .
Forest density (trees/ha)									
Mean	331	346	263	318	260	277	308	275	293
SD	463	379	259	337	227	620	793	558	477
Minimum	71	55	55	55	85	47	47	47	47
First quartile	151	179	124	163	143	122	117	123	139
Median	213	239	204	229	201	191	179	191	206
Third quartile	362	378	314	360	288	275	277	278	312
Maximum	2880	2880	1989	2880	1932	9147	9147	9147	9147
n	83	170	65	234	117	231	145	314	548
t (mean = 150 trees/ha)	3.56	6.75	3.51	7.61	5.21	3.11	2.40	3.95	7.02
p	0.001	<0.001	0.001	<0.001	<0.001	0.002	0.018	<0.001	<0.001
Composition (%)									
Pines#									
Mean	32.9	30.2	30.5	30.2	48.9	48.4	45.5	46.3	. . .‡
SD	17.2	18.0	18.0	18.6	18.4	17.4	18.4	18.9	. . .
First quartile	22.0	17.6	15.0	17.2	38.1	36.4	33.3	34.6	. . .
Median	33.3	26.9	30.0	27.5	53.0	50.0	43.5	47.9	. . .
Third quartile	40.0	37.5	45.8	40.0	60.0	60.0	59.0	58.9	. . .
Maximum	100.0	100.0	68.4	100.0	100.0	87.0	90.0	100.0	. . .
Shade tolerant‖									
Mean	22.7	37.9	56.0	38.4	16.7	23.5	41.5	28.3	. . .
SD	16.8	22.4	23.2	24.2	11.1	16.1	20.8	20.3	. . .
First quartile	12.5	20.0	41.7	18.3	9.0	12.5	26.1	13.0	. . .
Median	18.6	34.8	54.2	34.9	14.8	21.7	41.7	25.0	. . .
Third quartile	29.8	52.1	71.4	53.9	22.8	30.4	55.6	42.1	. . .
Maximum	90.0	100.0	100.0	100.0	50.0	77.4	88.5	100.0	. . .
Oaks††									
Mean	42.1	30.4	10.9	29.1	32.6	25.3	9.3	22.4	. . .
SD	21.6	21.0	14.9	23.4	17.5	18.9	11.3	19.7	. . .
First quartile	30.4	10.6	0.0	5.1	20.8	9.1	0.0	5.1	. . .
Median	44.2	30.4	5.0	29.2	32.5	21.7	5.0	18.9	. . .
Third quartile	57.5	45.6	19.2	46.5	44.2	37.9	16.7	34.9	. . .
Maximum	100.0	80.0	66.7	100.0	73.9	100.0	52.4	100.0	. . .
Other species									
Mean	2.3	2.8	2.6	2.3	1.8	2.8	3.7	3.0	. . .
n	48	117	39	176	68	140	87	236	. . .

† Openings are defined as section corners or quarter corners at which surveyors recorded no bearing trees.
‡ An ellipsis (. . .) indicates that the value is undefined or was not estimated.
§ Scattered tree areas are defined by pools of corners in which <50% of expected trees were recorded by surveyors.
¶ Forested areas are defined by pools of corners in which ≥50% of expected trees were recorded by surveyors.
\# Pines include *Pinus jeffreyi*, *Pinus lambertiana*, *Pinus* spp. (recorded as just "pine" by surveyors), and *Pinus ponderosa*.
‖ Shade tolerant species include *Abies concolor*, *Calocedrus decurrens*, and *Pseudotsuga menziesii*.
†† Oaks include *Quercus chrysolepis*, *Quercus* spp. (recorded as just "oak" by surveyors), and *Quercus kelloggii*.

appear to cover the largest contiguous areas, perhaps up to about 2,500 ha, and often were peppered with 250–500 ha patches of very dense forests (>293 trees/ha). However, the northern half of the northern Sierra had a large area of contiguous very-dense forest, albeit interrupted by human-affected areas (Fig. 1a). At the township scale (9,328 ha), SMC landscapes nearly always had diverse tree densities, along with openings and scattered trees.

Cross-validation (Appendix G) showed the GLO reconstructions had low RMAE and were quite accurate. Estimates were rare and unusable for specific cross-validation for the ponderosa pine-Douglas-fir phase. In the mixed-conifer phase, four tree-ring reconstructions and four early inventories for specific comparison yielded a low overall RMAE of 5.2%. Another 13 general estimates were available. The mean of 21 specific and general estimates was 273 trees/ha, a 7% RMAE relative to the pooled GLO estimate of 293 trees/ha across SMC forests (Table 1). For the white fir phase, only one tree-ring reconstruction and one early-inventory estimate allowed specific comparison, for which GLO estimates had a mean RMAE of 14.2%. Combined with five other general estimates from early inventories, the overall general estimate for white fir was 292 trees/ha, only 0.3% less than the overall GLO estimate of 293 trees/ha for SMC forests.

Historical composition of pines, shade-tolerant trees, and oaks (H_2)

Regarding H_2, that historical SMC forests had about half shade-intolerant and half shade-tolerant trees, compositional trends are apparent in the reconstruction between the two regions and three phases in the percentage of trees that were shade-intolerant pines, shade-tolerant firs and incense cedar, and oaks (Table 4). Thus, the outcome for H_2 is complex.

Pines (primarily ponderosa pine and sugar pine) varied, among the six phases in the two regions, from about 30–33% of total trees in the north to about 46–49% of total trees in the south (Table 4). Two-way ANOVA showed that the mean percentage of trees that were pines did not differ significantly among the phases, when pooled across regions ($F = 0.97$, df = 2, 498, $p = 0.382$), but did differ significantly between north and south ($F = 107.74$, df = 1, 498, $p < 0.001$), with an average of 30.8% pines in the north and 47.8% pines in the south, pooled across phases.

The mean percentage of trees that were oaks (primarily California black oak and canyon live oak) varied from 9.3 to 42.1% among the six phases in the two regions (Table 4). Two-way ANOVA showed that the mean percentage of oaks, 29.1% in the north, was significantly higher than the mean of 22.4% in the south ($F = 7.52$, df = 1, 498, $p = 0.006$), and differed significantly among phases when pooled across regions ($F = 63.67$, df = 2, 498, $p < 0.001$). Follow-up tests showed mean percentages differed among phases in both the north ($F = 25.81$, df = 2, 203, $p < 0.001$) and south ($F = 39.98$, df = 2, 294, $p < 0.001$). The percentage of oaks was highest in the ponderosa pine-Douglas-fir phase in the north, where oaks were 42.1% of total trees, and was lowest in the white fir phase in the south, where oaks were 9.3% of total trees (Table 4).

Shade-tolerant trees (white fir, Douglas-fir, incense cedar) varied among the six phases in the two regions (Table 4). Two-way ANOVA showed that mean percentage of trees that were shade-tolerant, 38.4% in the north, was significantly higher than the mean of 28.3% in the south ($F = 51.92$, df = 1, 498, $p < 0.001$), and also differed significantly among phases ($F = 70.04$, df = 2, 498, $p < 0.001$). Followup tests showed mean percentages differed among phases in both the north ($F = 26.19$, df = 2, 203, $p < 0.001$) and south ($F = 48.50$, df = 2, 294, $p < 0.001$). The mean percentage of shade-tolerant trees was highest in the white fir phase in the north, at 56.0% of total trees, and lowest in the ponderosa pine-Douglas-fir phase in the south, at 16.7% of total trees (Table 4). Thus, hypothesis H_2 is rejected as a general pattern in historical SMC forests. Hypothesis H_{10}, that regions differed, and hypothesis H_{11}, that phases differed, are not rejected.

Historical basal area (H_3) and quadratic mean diameter

Reconstructed mean basal area varied from 27.9 to 40.5 m^2/ha among the six phases in the two regions (Table 5). An initial $\alpha = 0.05$ was Bonferroni-corrected to $\alpha = 0.00625$, given eight planned t-tests, one per phase and one overall in the two regions. Hypothesis H_3, that historical mean basal area equaled 33.2 m^2/ha, could not be rejected for any phase or for overall values in either region (Table 5). Two-way ANOVA showed that mean basal area was not significantly different between north and south ($F = 0.70$, df = 2, 497, $p = 0.404$), but was significantly different among phases ($F = 3.48$, df = 2, 497, $p = 0.032$). Followup tests showed that mean basal area did not differ among phases in the south ($F = 0.84$, df = 2, 294, $p = 0.433$), but did in the north ($F = 4.34$, df = 2, 202, $p = 0.014$). Basal area differed in the ponderosa pine-Douglas-fir phase and the white fir phase, but mixed-conifer did not differ from either. Hypothesis H_{10}, that historical SMC forests differed between north

Table 5. Reconstructed basal area and quadratic mean diameter in the parts of the northern and southern Sierra Nevada relatively unaffected by EuroAmerican land-uses, by phase and overall.

Variable	Northern Sierra Nevada				Southern Sierra Nevada			
	Ponderosa	Mixed conifer	White fir	Overall	Ponderosa	Mixed conifer	White fir	Overall
Basal area (m^2/ha)								
Mean	27.9	35.4	40.5	32.5	33.6	36.9	39.1	35.5
SD	15.5	21.4	22.0	20.0	19.4	26.4	30.8	25.6
Minimum	5.7	1.2	7.1	1.2	12.8	6.5	4.4	4.4
First quartile	16.2	20.4	25.7	18.7	23.1	24.4	22.4	21.7
Median	25.1	32.0	37.9	29.2	28.8	32.8	32.7	30.4
Third quartile	39.6	46.0	49.6	43.6	37.7	42.5	49.8	42.7
Maximum	61.2	120.6	120.6	120.6	146.9	246.3	246.3	246.3
n	48	116	39	175	68	140	87	235
t (mean = 33.2 m^2/ha)	2.35	1.09	2.08	0.97	0.17	1.66	1.79	2.34
p	0.023	0.279	0.044	0.355	0.866	0.099	0.076	0.020
Quadratic mean diameter (cm)								
Mean	47.6	50.6	58.9	49.8	58.1	60.8	63.3	59.3
SD	11.3	13.9	16.5	14.6	16.5	18.7	18.0	18.7
Minimum	22.0	24.6	35.9	22.0	29.6	22.0	34.6	22.0
First quartile	39.4	42.5	45.6	40.7	49.9	49.1	51.2	49.9
Median	46.4	49.2	57.9	48.6	56.0	58.3	59.1	57.0
Third quartile	55.7	57.5	67.0	57.9	65.2	71.3	74.8	70.6
Maximum	72.3	116.4	116.4	116.4	155.9	155.9	147.2	155.9
n	48	116	39	175	68	140	87	235

and south, is rejected for basal area, and H_{11}, that historical SMC forests differed between phases, is rejected in the north for basal area.

Cross-validation with tree-ring reconstructions and early-inventory estimates (Appendix G) was hampered by few estimates and potential problems with estimates. No tree-ring/inventory estimates are available for the ponderosa pine-Douglas-fir phase. In the mixed-conifer phase, specific comparisons are possible with five estimates, but three are from Sudworth (1900), whose estimates are atypical of historical forests (Bouldin 1999). Sudworth's estimates, which vary from 221-387 m^2/ha, are in the top 0.5% of reconstructed GLO estimates. I also suspect something is wrong with Sudworth's data. If Sudworth's data are left out, specific comparisons are not possible for the white fir phase, and the only specific comparisons are for the two in mixed-conifer, where RMAE is high, at 55.0%. However, the mean of four available general reconstructions and inventories is 33 m^2/ha for mixed-conifer (omitting Sudworth), compared to a pooled mixed-conifer mean of 36.2 m^2/ha, a 9.7% RMAE. Thus, cross-validation for basal area is limited by few reconstructions, and poor agreement with the two available ones, but has some general support for the overall study area. Basal area had only 21–25% RMAE in an extensive accuracy trial (Williams and Baker 2011).

Reconstructed quadratic mean diameter (QMD) ranged from 47.6 to 63.1 cm across the six phases in the north and south (Table 5). Two-way ANOVA showed that QMD was significantly different between north and south, when pooled across phases ($F = 34.92$, df = 2, 497, $p < 0.001$), and also differed among phases, when pooled across regions ($F = 6.06$, df = 2, 497, $p = 0.003$). A follow-up test identified significantly different groups: (1) white fir, mixed-conifer, and ponderosa pine-Douglas-fir phases in the south, all with the highest mean QMDs of about 58–63 cm and (2) ponderosa pine-Douglas-fir in the north, with the lowest mean QMD of 48 cm. A third group, containing the remaining two phases, white fir and mixed-conifer in the north, had intermediate QMD from 51 to 59, and its phases differed from groups 1 and 2, respectively.

Cross-validation with tree-ring reconstructions and early-inventory estimates (Appendix G) was also hampered by few estimates, after omitting Sudworth's data. No tree-ring/inventory estimates are available for specific comparisons for white fir or ponderosa pine-Douglas-fir phases. In the mixed-conifer phase, specific comparisons are possible with two estimates, where RMAE is

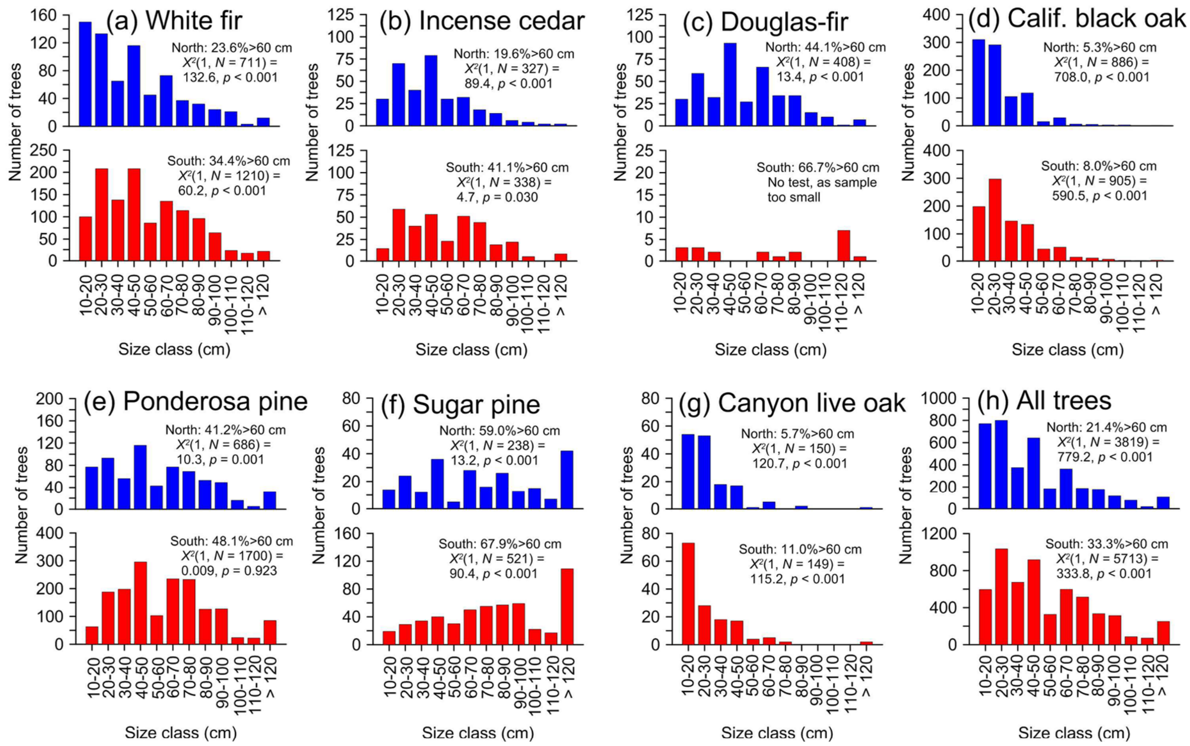

Fig. 3. Reconstructed diameter distributions for the northern (blue) and southern (red) Sierra Nevada. Note that y-axes are not always the same in the two areas. Omitted are trees only identified as "pine" or "fir" and species with <100 total trees in an area. Diameters were likely estimated at stump height (about 30 cm), thus are likely larger than at breast height (about 1.4 m). Also shown is the percentage of total trees that exceeded 60 cm diameter, and the result of the chi-square test of the null hypothesis that the number of trees >60 cm diameter equals the number of trees ≤60 cm diameter.

moderate, at 30.7%. The mean of four available general estimates is 48 cm for mixed-conifer, which compares well with a pooled mixed-conifer mean of 55.7 cm, a 16.0% RMAE. QMD also had only 12–16% RMAE in an extensive accuracy trial (Williams and Baker 2011).

Historical diameter distributions (H_4, H_5)

Regarding hypothesis H_4, the null hypothesis, that the number of trees ≤60 cm diameter equals the number >60 cm, is rejected for all trees in both north and south, except ponderosa pine in the south (Fig. 3e). In all cases, except sugar pine (Fig. 3f) <50% of trees were >60 cm diameter; overall, only 21% of trees in the north and 33% in the south were >60 cm diameter (Fig. 3). Percentages of trees >60 cm were higher in the south than north, across all species and in total. Hypothesis H_5, that historical SMC forests had low abundance of small trees, is also not supported. Trees ≤40 cm were 30.7% of all trees in the south and 41.1% of all trees in the north. Trees ≤20 cm were 11.2% of all trees in the south and 20.2% of all trees in the north.

Regarding hypothesis H_{10}, the northern and southern Sierra Nevada show some similarities and differences in diameter distributions. White fir, incense cedar, Douglas-fir, ponderosa pine, and sugar pine all show peaks in the 40–50 cm size class, relative to adjoining size classes; the peaks are more pronounced in the north. Sample sizes are so large that all species differed significantly ($p < 0.001$) in distributions between north and south, using chi-square. Size-classes contributing most to differences appear anecdotal in most cases (e.g., higher proportion of 60–80 cm incense cedar in the south than north; Fig. 3). However, there is a higher proportion of trees in

Table 6. Historical section-line length covered by understory trees and shrubs by region and phase.

Attribute	Northern Sierra Nevada				Southern Sierra Nevada			
	Ponderosa	Mixed conifer	White fir	Overall	Ponderosa	Mixed conifer	White fir	Overall
Understory trees in forests†								
Firs first (%)‡	1.3	0.5	2.7	1.1	0.2	1.3	3.2	1.6
Firs present (%)	24.1	16.5	22.6	18.4	32.9	50.8	67.7	51.5
Incense cedars first (%)	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.5
Incense cedars present (%)	24.0	12.7	18.1	15.6	17.1	26.7	47.9	30.3
Pines first (%)§	23.3	11.0	17.8	14.7	36.2	54.4	64.6	52.7
Pines present (%)	30.9	13.6	17.8	17.8	37.9	57.7	69.6	55.9
Oaks first (%)¶	18.3	25.8	15.3	20.1	18.3	9.1	2.7	9.2
Oaks present (%)	39.1	35.2	21.3	31.1	47.2	51.3	45.3	48.6
No trees present (%)	44.7	49.2	54.4	45.7	44.7	33.9	27.7	34.9
Any trees present (%)	43.1	38.1	36.8	36.5	55.3	66.1	72.2	65.1
Fraction of trees that were dense	0.16	0.37	0.60	0.35	0.48	0.59	0.39	0.37
Total line-length in sample (km)#	206.5	410.3	144.1	845.8	315.6	686.4	414.4	1521.2
Correction for missing data||	1.139	1.145	1.095	1.216	1.000	1.000	1.000	1.000
Understory shrubs in forests†								
Arctostaphylos first (%)	20.0	17.5	29.6	20.8	29.7	39.7	43.9	38.6
Ceanothus cordulatus first (%)	1.0	5.9	11.5	5.4	9.1	7.5	6.7	7.6
Ceanothus integerrimus first (%)	46.1	49.3	52.6	48.7	51.5	40.3	37.6	42.3
Corylus cornuta first (%)	2.7	2.8	0.2	2.3	0.4	1.4	1.0	1.0
Prunus first (%)	10.5	15.9	2.9	11.8	0.0	0.0	0.8	0.2
No shrubs (%)	7.3	2.2	0.0	3.4	3.1	1.9	2.2	2.1
Any shrub (%)	85.6	91.9	98.8	90.9	95.3	95.9	96.1	96.0
Fraction of shrubs that were dense	0.16	0.16	0.41	0.21	0.41	0.46	0.45	0.45
Total line length in sample (km)#	329.4	569.5	184.6	1122.4	311.7	687.9	414.6	1521.2
Correction for missing data||	1.076	1.063	1.013	1.060	1.016	1.023	1.017	1.019

† Surveyors were required to record understory trees and shrubs in order of abundance along the section line.
‡ Firs include *Abies concolor* and *Pseudotsuga menziesii*.
§ Pines include *Pinus ponderosa*, *P. jeffreyi*, and *P. lambertiana*.
¶ Oaks include primarily *Quercus kelloggii* and *Q. chrysolepis*.
# Section-line lengths in samples differ depending on the whether surveyors recorded the particular data (see Appendix C).
|| If a surveyor did not record information for an attribute, that could mean the attribute was truly lacking, which is how the percentages were calculated. However, this provides a low estimate, if the surveyor just neglected to record the information, in which case the data are missing. In this latter case, the correct percentage is obtained by applying the multiplier.

the smallest size class (10–20 cm) in the north than the south, particularly for white fir, incense cedar, California black oak, ponderosa pine, and all trees, but canyon live oak is an exception (Fig. 3). Incense cedar, Douglas-fir, ponderosa pine, and sugar pine all appear to have few trees in the smallest size class (10–20 cm). Both sugar pine and ponderosa pine had quite a few trees exceeding 120 cm, but sugar pine stands out for its large trees (Fig. 3).

Section-line data and understory trees and shrubs (H_5 and H_6)

Hypothesis H_5, that historical SMC forests had relatively low abundance (i.e., <10%) of small trees, is not supported by section-line data in either the northern (χ^2 (1, $N = 1122$) = 877.2, $p < 0.001$) or southern Sierra (χ^2 (1, $N = 1521$) = 5132.4, $p < 0.001$). Instead, understory trees were abundant on 36.5% of area in the north and 65% in the south (Table 6) and 35–37% of these areas had dense understory trees. Among phases, the percentage with trees of any species was highest in ponderosa pine-Douglas-fir in the north, and white fir in the south.

Hypothesis H_6, that historical SMC forests had high shrub abundance is supported, as the null hypothesis that the percentage of shrub cover was not greater than 75% is rejected in the northern (χ^2 (1, $N = 1122$) = 343.2, $p < 0.001$) and in the southern Sierra (χ^2 (1, $N = 1521$) = 1748.9, $p < 0.001$). Overall, 91% of section-line length in the north and 96% in the south had shrubs (Table 6); 41% of these occurrences in the north in the white fir phase and 41–46% in the south in the three phases were described as dense shrubs (Table 6). Only 16% of the other two phases in the north had dense shrubs. *Ceanothus integerrimus* was most abundant in both north and south, followed by *Arctostaphylos patula/viscida*, then *Ceanothus cordulatus* (Table 6).

Table 7. Reconstructed fire severity and fire rotation for the unaffected area in the northern and southern Sierra Nevada.

Landscape component	Northern Sierra Nevada		Southern Sierra Nevada	
	Area (ha)	Area (%)	Area (ha)	Area (%)
Uncertain fire components left out	17716		9376	
Forest corners–openings	14279		8343	
Forest corners–scattered trees	3437		1033	
Reconstructed fire components	115766	100.0	187085	100.0
Low-severity fire	14546	12.6	49492	26.4
Mixed-severity fire	55858	48.2	79446	42.5
Mixed-severity forest area	55858	48.2	78643	42.0
Forest corners–openings	0	0.0	803	0.5
High-severity fire†	45362	39.2	58147	31.1
High-severity forest area	10656	9.2	5171	2.7
Forest lines–chaparral	14075	12.2	13443	7.2
Forest lines–scattered trees	20631	17.8	14141	7.6
Forest corners–openings	0	0.0	18509	9.9
Forest corners–scattered trees	0	0.0	6883	3.7
Total unaffected area (ha)	133482		196461	
High-severity fire rotation (years) ‡		281		354

† High-severity components include all the areas reconstructed as high-severity fire. These include: (1) the structure-based model with survey tree data to reconstruct high-severity forest area, (2) chaparral patches, which are high-severity areas reconstructed from section-line data, (3) forest lines–scattered trees, which are also reconstructed from section-line data, (4) forest corners–openings, which are forest corners lacking bearing trees that also have dense shrubs in the understory, and (5) forest corners–scattered trees, which are forest corners missing >50% of bearing trees. See text for details on these reconstructions.

‡ Calculated as 110 years/(percentage/100) using the percentage of the area within which fire components were reconstructed.

Historical fire severity (H_7–H_8)

Hypothesis H_7, that low-severity fire characterized ≥85% of historical landscapes is rejected for both the northern (χ^2 (1, $N = 116$) = 555.0, $p < 0.001$) and southern Sierra (χ^2 (1, $N = 187$) = 329.1, $p < 0.001$). Exclusive low-severity area covered only about 13% of the northern and 26% of the southern Sierra Nevada (Table 7, Fig. 4). Hypothesis H_8, that the high-severity fire rotation in historical SMC forests was >500 years is not supported for either the northern (281 years) or southern Sierra Nevada (354 years; Table 7). North and south differed substantially in their historical fire regime (Table 7) thus hypothesis H_{10} is supported for fire.

Within each region, percentages varied among phases (Fig. 5), but are inconsistent, thus the outcome for hypothesis H_{11} is complex. Somewhat more low severity was found in the white fir phase and slightly more mixed severity in the mixed-conifer phase in each region. In the north, the greatest high severity was in white fir, but in the south, it was in the ponderosa pine-Douglas-fir phase. Corresponding fire rotations varied among the six phases in two regions from 223 years in white fir in the north to 542 years in white fir in the south (Fig. 5).

Contiguous fire areas (H_9)

There is some spatial pattern to reconstructed fire severities (Fig. 4). Mixed-severity fire covered a little less than half of both the north and south (Table 7) and formed the matrix within which were found smaller areas of high- and low-severity fire (Fig. 4). Contiguous areas of low-severity fire were rare in the northern Sierra Nevada, and usually only a few hundred hectares in extent, except along its southern border (Fig. 4a). In the southern Sierra Nevada, several contiguous areas of low-severity fire of 3,000 to 6,000 ha occurred (Fig. 4b–d).

Large patches of contiguous high-severity fire occurred historically in the north (Fig. 4a) and south (Fig. 4b–d). Patch-size distributions were similar between north and south (Fig. 6), with most patches <1000 ha. Ten in the north and eight in the south were >1000 ha, two each in north and south were >4000 ha. The largest were 8050 ha in the north and 9400 ha in the south. Thirty-six of 75 patches in the north and 25 of 70 patches in the south were >250 ha. The hypothesis (H_9), that all patches of contiguous high-severity fire were <250 ha, was rejected for the north (χ^2 (1, $N = 75$) = 36.6, $p < 0.001$) and south (χ^2 (1, $N = 70$) = 29.7, $p < 0.001$).

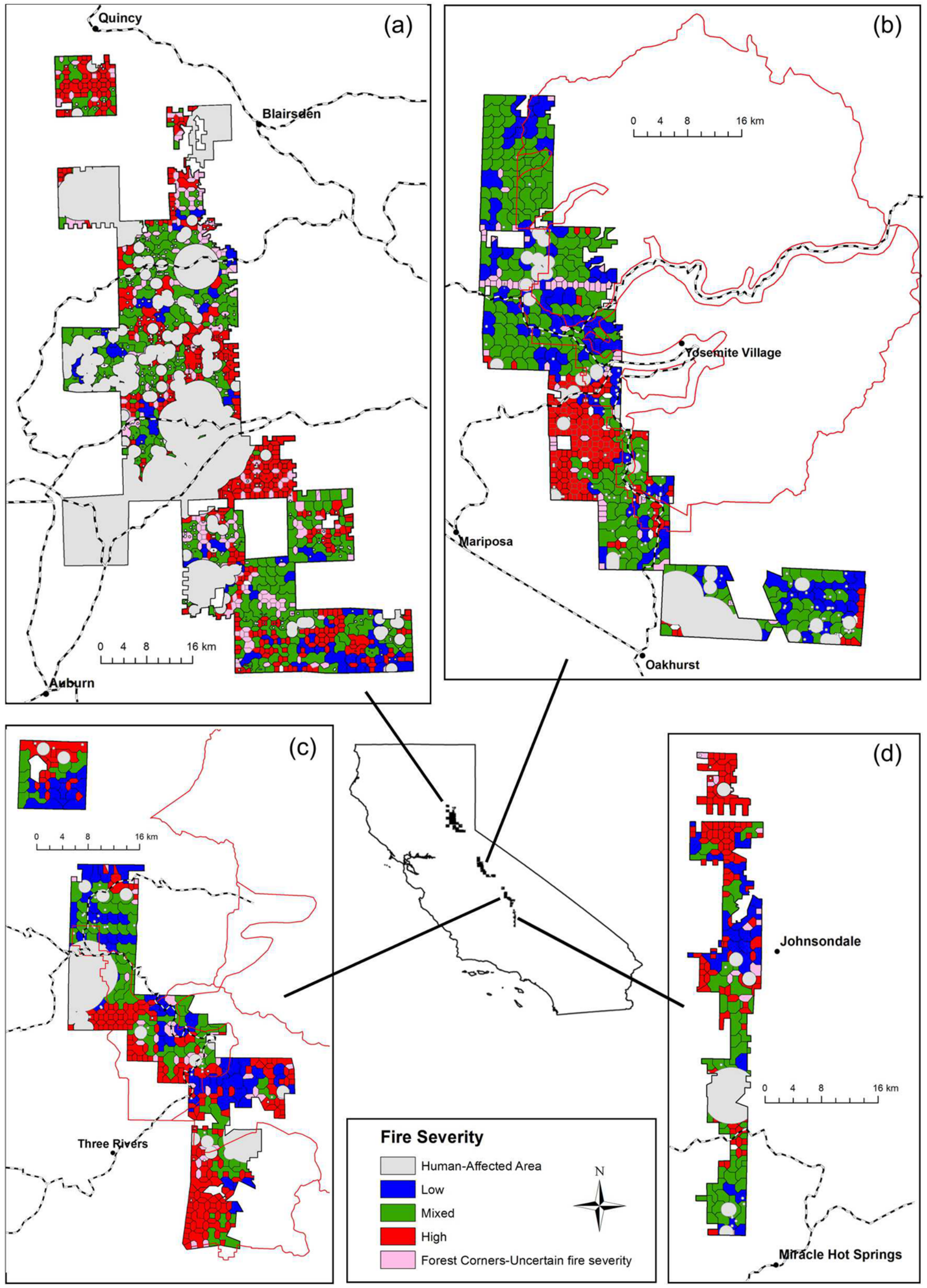

Fig. 4. Reconstructed fire severity in Sierran mixed-conifer forests, excluding human-affected areas, in the: (a) northern Sierra Nevada, (b) southern Sierra Nevada on the western side of Yosemite National Park (red boundary), (c) southern Sierra Nevada on the western side of Sequoia-Kings Canyon National Parks (red boundary), (d) southern Sierra Nevada south of Sequoia-Kings Canyon National Park. Note that map scales differ among the areas.

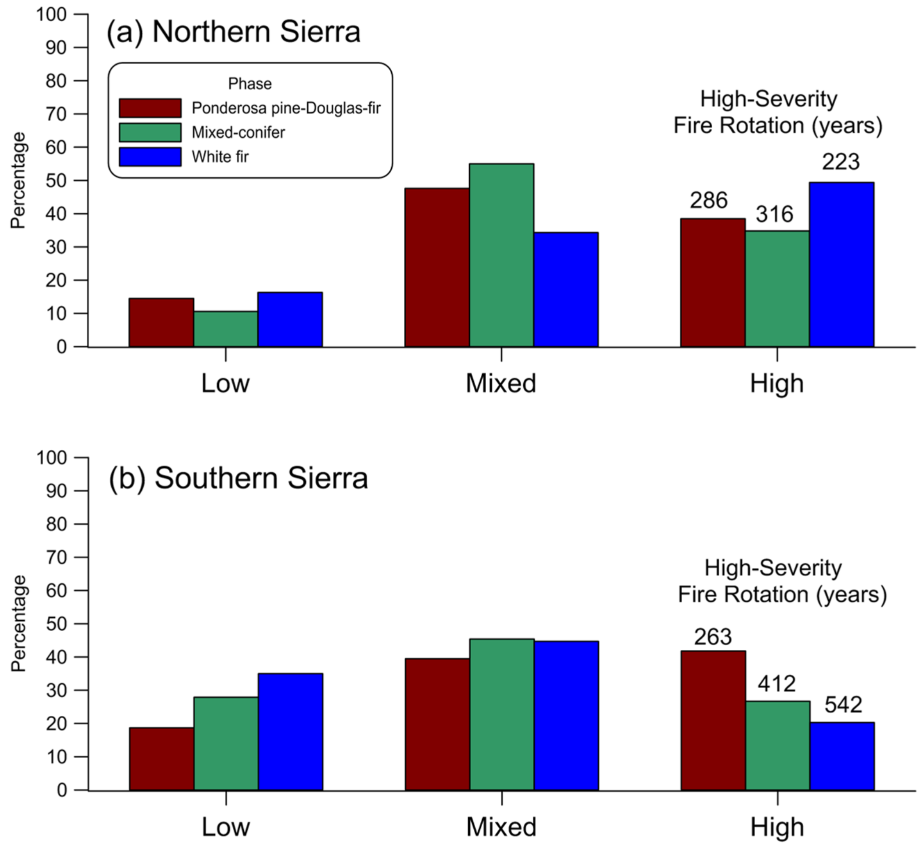

Fig. 5. Percentages of reconstructed fire area by fire severity among the three phases of Sierran mixed-conifer forests, and high-severity fire rotations, in: (a) the northern Sierra Nevada and (b) the southern Sierra Nevada.

Corroboration and new findings from comparison with Leiberg's (1902) maps

Leiberg's burn categories appear reliable, as they are consistent with expected effects of different fire severities, as can be seen by comparing cover types inside versus outside burn areas across his maps (Fig. 7). Percentages in all categories are, as expected, reduced inside the 75–100% burned category relative to outside the burns, except chaparral, which is greatly increased (Fig. 7a). Also as expected, the area inside the lower severity 5–25% burned category has only slightly elevated area in chaparral and <2,000 board-feet/acre (Fig. 7b). The 25–50% category covers insufficient area, and the 50–75% category does not occur.

The areas mapped by Leiberg in the 75–100% burned category on about 32,360 ha of the overlap area in 1900 are also consistent with high-severity fires. First, the areas in the 75–100% burned category were mapped in 1885–1890 as 42.4% chaparral (13,707 ha), 19% forest (6,306 ha) having <2,000 board-feet/acre, 25% forest (8,020 ha) having 2,000–5,000 board-feet/acre, and only 13% forest (4,177 ha) having >5,000 board-feet/acre (Fig. 7a). These areas thus mostly had no timber or low timber volume, as mature forests had >10,000 board-feet/acre. Some or all this area had likely already burned at high severity by 1885–1890. Second, the chaparral area in this 75–100% burned category (13,707 ha) was 90.4% forested (12,391 ha) at the time of the surveys 1–25 years prior to Leiberg's mapping (Fig. 2); only 9.5% of it was chaparral that reburned. Third, areas of chaparral are a strong indicator of high-severity fire in forests. Leiberg says: "There can not be the slightest doubt that every acre of chaparral represents so much ground once

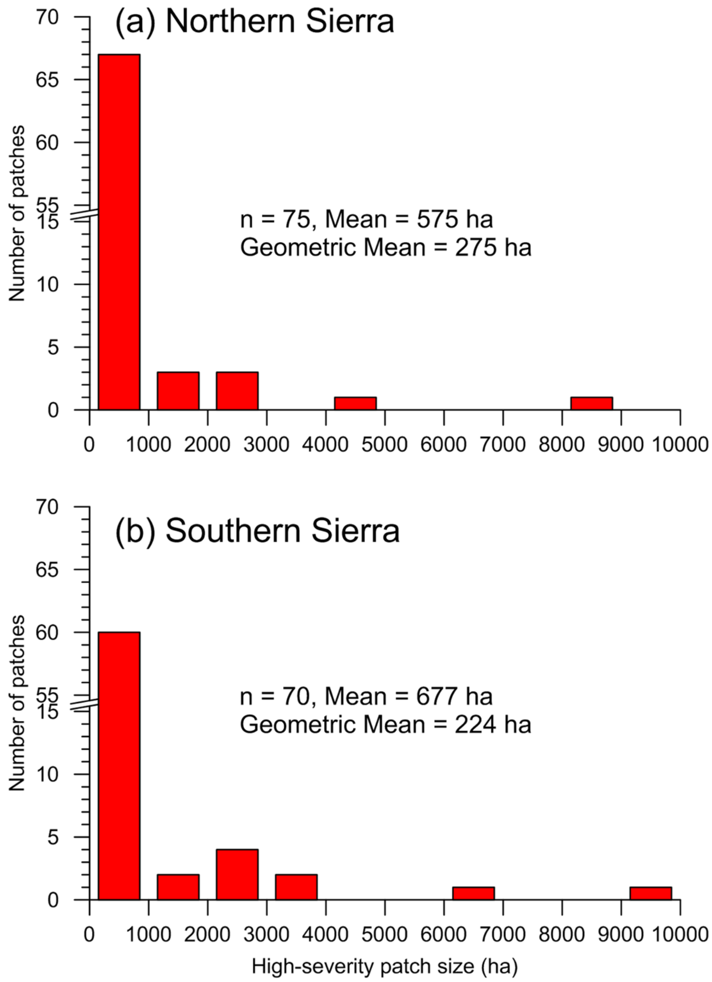

Fig. 6. Size distribution of contiguous patches of high-severity fire in the (a) northern Sierra Nevada and (b) southern Sierra Nevada. The distribution was truncated at the low end at 50 ha, to avoid small polygons created by clipping and other GIS operations.

forested, denuded by fire, then overgrown with brush" (Leiberg 1902:43). The chaparral in the 75–100% category was also 87% of total chaparral Leiberg mapped in the overlap area, thus chaparral was concentrated in this high-severity category.

When the Leiberg 75–100% burned category from 1900 is compared to the survey section-line data from 1865–1890, it is clear that high-severity fire burned 18,769 ha of mature forest after the surveys (Fig. 8). Surveyors described 58% (201 km) of the 346-km section-line length in the 75–100% burned category as "heavily timbered," "good timber," or "excellent timber," thus mature forest. The 58% is a line-intercept estimate of the area ($0.58 \times 32{,}360$ ha $=$ 18,769 ha) of mature forest that burned. This occurred 8.8% (1650 ha) in the ponderosa pine phase, 63.0% (11,827 ha) in mixed-conifer, and 28.2% (5,294 ha) in white fir. Section lines listed the first tree or shrub (the dominant) as: 58% pine, 20% white fir, 10% chaparral, 9% oak, and 3% Douglas-fir, thus high-severity fire was favored in pine-dominated parts of all phases.

The remaining 145 km of the 346-km section-line length (13,500 ha) in the 75–100% burned category is also consistent with high-severity fire, but in younger forests. This area was described by surveyors as having: (1) scattered and/or scrubby trees, (2) poor, fair, or medium timber, or

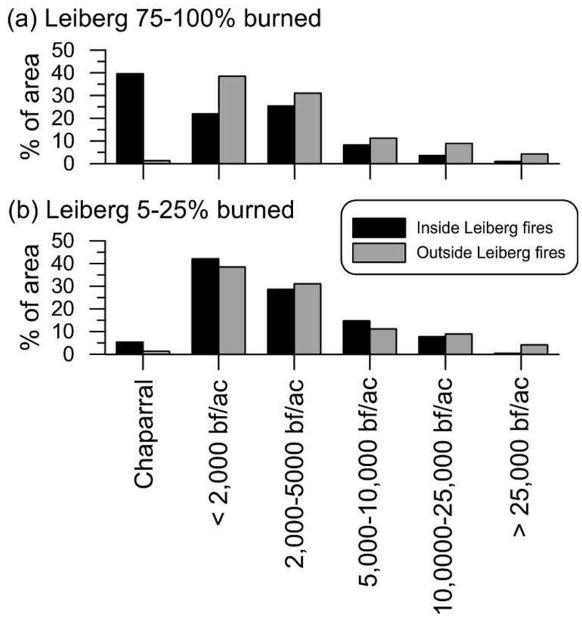

Fig. 7. Percentage of land area, by cover type and timber volume, as mapped by Leiberg in 1885–1890 inside and outside burns mapped by Leiberg (1902) about 1900, for two severities of fire: (a) 75–100% burned, (b) 5–25% burned.

(3) was not specifically described, thus was unremarkable but likely not mature timber. This area likely burned mostly before, rather than after the surveys, and had recovered for at least 16 years (1884–1900), and more likely for at least 20–35 years, if not much longer, before the 1900 Leiberg fire map. Leiberg indicates his mapping of fires extended back to the early 1800s.

Leiberg did not provide sufficient mapping detail to be able to fully determine patch size, but the 18,769-ha high-severity area that burned mature forest is concentrated in two contiguous, roughly 8,000 ha areas (Fig. 8). This underestimates patch size for the high-severity area as a whole, as it is only for the mature forest, but adds evidence that hypothesis H_9, that patches of contiguous high-severity fire area did not exceed 250 ha, is rejected.

Discussion

Historical forest structure

Historical SMC forests were on average denser than other dry forests in the western United States. The mean density of 293 trees/ha exceeds mean densities reconstructed from GLO data (Williams and Baker 2012*a*, 2013) for northern Arizona and the Blue Mountains, Oregon (142–167 trees/ha), and the Colorado Front Range (217 trees/ha), but is similar to the 275 trees/ha mean for dry mixed conifer forests in Oregon's eastern Cascades (Baker 2012). Cross-validation shows that mean tree density is reconstructed with low error, averaging <10% RMAE in nine comparisons, better than the 11.4% mean RMAE in five comparisons in northern Arizona (Williams and Baker 2011). The cross-validation also validates tree-ring reconstructions and early inventories (Appendix G). In addition, dense forests were often described by early observers (Appendix A: Q135–Q147). Thus, tree-ring reconstructions, early scientific reports and the GLO reconstructions concur that historical SMC forests were dense to very dense on average, not on average open and park-like as in the main view in the introduction.

Somewhat open, park-like forests with <150 trees/ha did occur, but only on 23% of the northern and 33% of the southern Sierra Nevada. These open forests were often described by early observers (Appendix A: Q118–Q134). Dry forests in the eastern Oregon Cascades were similar to the northern Sierra Nevada, with 25% of the landscape having <143 trees/ha (Baker 2012), but other dry forests had a larger percentage of low-density forests (Williams and Baker 2012*a*, 2013). These open, park-like forests are a striking, ecologically important component of historical SMC landscapes that warrants protection and restoration. However, reconstructions from these areas (e.g., Scholl and Taylor 2010), which my reconstruction also validates, are atypical of most historical SMC forest landscapes, which averaged almost twice as dense.

Relative to other dry-forest landscapes, historical SMC landscapes generally had much higher proportions of dense forest. The 65% of the northern and 46% of the southern Sierra that was dense (>200 trees/ha) contrasts with 45% in the Colorado Front Range, 29% in Oregon's Blue Mountains, and 15–17% in northern Arizona (Williams and Baker 2012*a*, 2013). Very dense forest (>300 trees/ha) was 34% of the northern and 21% of the southern Sierra Nevada, similar to the Eastern Oregon Cascades, with ≥25%

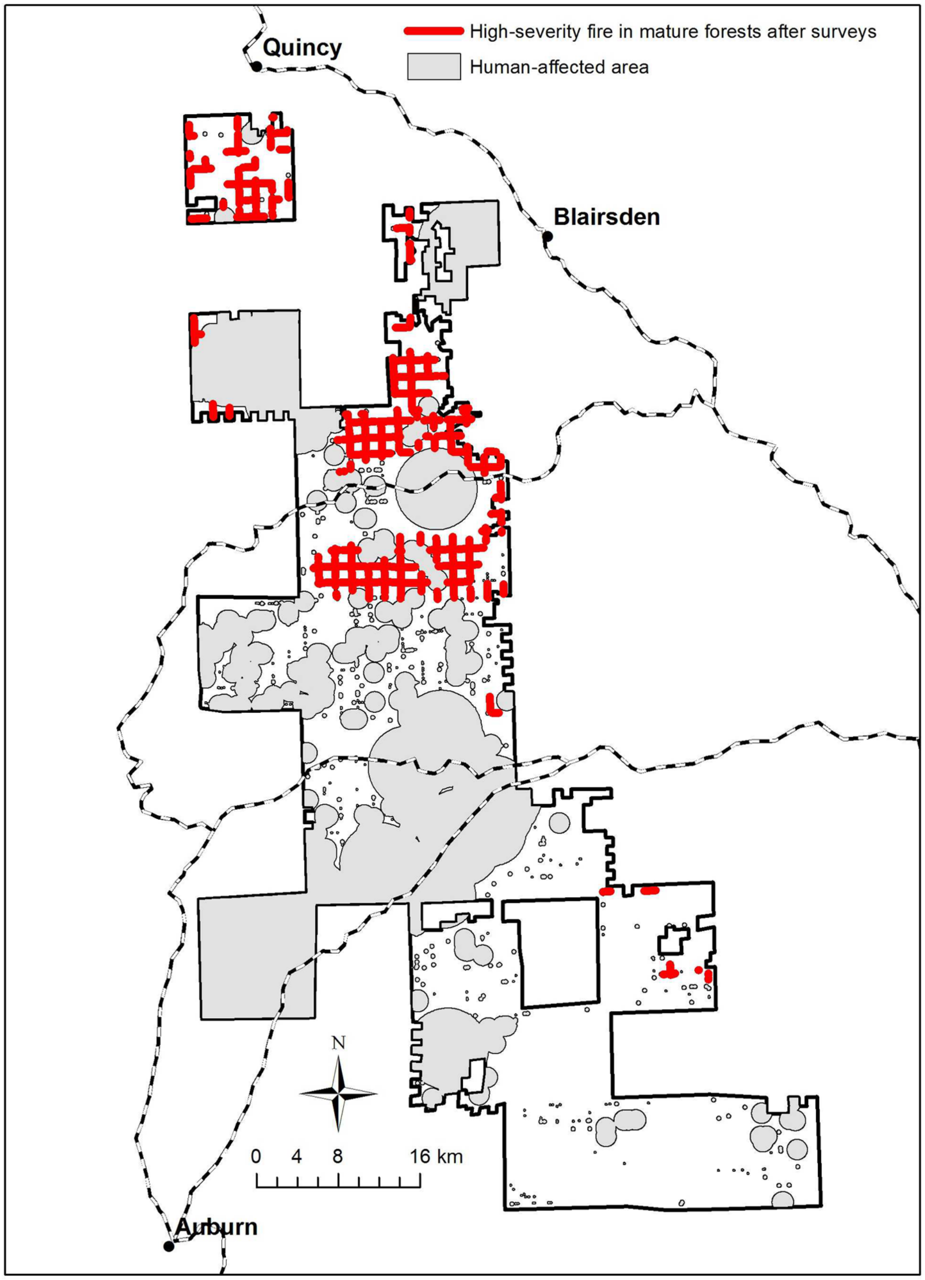

Fig. 8. Areas of mature Sierran mixed-conifer forest burned at high severity after the surveys and before Leiberg's mapping. The Leiberg 75–100% burned category from 1900 was overlain on the survey section-line data from 1865–1890. Section lines shown in red were described by surveyors as "heavily timbered," "good timber," or "excellent timber," thus mature forest, in 1865–1890 before Leiberg mapped these areas in 1900 as severely burned.

(Baker 2012), but greater than in northern Arizona, which had 7–10% with >250 trees/ha (Williams and Baker 2013).

Historical SMC forests were more heterogeneous in tree density than other dry-forests reconstructed with GLO data. The coefficient-of-variation of tree density was 162.8%, about three times as large as in dry-forest landscapes of northern Arizona (Williams and Baker 2013). At a township scale, patches of low- or very-dense forest were peppered across broader expanses of generally dense forest (Fig. 1). Variability is from variation in fire severity and associated post-fire succession, and variation in environment, from open rocky slopes with scattered trees (Appendix A: Q148–Q159) to north-facing or higher-elevation moister slopes with denser forests (Appendix A: Q143–Q147). This historical variability supports its recent focus in ecological restoration programs (van Wagtendonk and Lutz 2007, North et al. 2009, Collins et al. 2011).

Historical basal area appears to have been similar across SMC forests and comparatively large for dry forests, with a mean between 28-41 m^2/ha, averaging 33–36 m^2/ha in the two regions (Table 5). Reconstructed means do not differ significantly from the hypothesized mean of 33.2 m^2/ha from a sample of reference data (Safford 2013). This is about three times the mean historical basal area on the Coconino Plateau in northern Arizona (Williams and Baker 2013). The relative consistency in this attribute of forest structure in SMC forests likely reflects a combination of environmental constraints and limitation by wildfires and other disturbances. Overall means for basal area have reasonable accuracy relative to means of tree-ring reconstructions and inventories, with 7.0% RMAE in mixed-conifer.

Historical quadratic mean diameter varied over a limited range (means of 48–63 cm) among phases and regions (Table 5), with a low coefficient-of-variation (24–32%) compared to other attributes. QMD was higher than the 40.1 cm reconstructed for ponderosa pine forests on the Coconino Plateau, Arizona (Williams and Baker 2013). QMD had RMAE of 30.7% at two sites with specific comparisons, but general comparisons show a 16.0% RMAE in the study area overall, comparable to the 12–16% RMAE in the accuracy trial (Williams and Baker 2011).

The results show that historical SMC forests were not dominated by trees >60 cm diameter (dbh), as often suggested (McKelvey and Johnston 1992, Gruell 2001, Scholl and Taylor 2010). Northern Sierran forests overall had only 21% and southern Sierran forests only 33.3% of trees >60 cm (Fig. 3). These included oaks, but conifers >60 cm were only 29% of 9532 total trees. Two early observations suggested SMC forests were multi-aged (Appendix A: Q113–Q114). Large trees, although not numerically dominant, were a key feature of historical SMC forests.

The results show that historical SMC forests were instead numerically dominated by smaller trees and also had abundant seedlings and saplings beneath these small trees. Trees 10–50 cm in diameter were 61% of 9532 total trees (Fig. 3). Since an average 50-cm diameter tree was roughly 110 years old, SMC forests were numerically dominated by relatively smaller and younger trees. Section-line data show that additional smaller understory tree-regeneration (<10 cm diameter) was likely present across most forests but abundant on 37% of the northern and 65% of the southern Sierra and more than a third of this regeneration was dense. Early reports indicate that fires could reduce or eliminate seedlings and saplings (Appendix A: Q160, Q168–Q174), but also stimulated abundant post-fire recruitment (Appendix A: Q163, Q166). Some areas lacked understory trees, but most contained abundant or even very dense understory trees, varying among species and with environment and fire (Appendix A: Q160–Q197). SMC forests had understory tree abundance similar to dry forests in eastern Oregon (Baker 2012, Williams and Baker 2012*a*), but much more than in the Colorado Front Range or northern Arizona, which had only 1–10% of area with understory trees (Williams and Baker 2012*a*, 2013).

The results show that historical SMC forests had nearly ubiquitous and often abundant shrubs, more than in other dry western forests. Shrubs were present on 91% of forest area in the north and 96% in the south, and were dense on 41–46% of shrub area in the south and the white fir phase in the north (Table 6). By about A.D. 1900, overgrazing had substantially reduced shrub cover (Vankat and Major 1978; Appendix A: Q198–Q199), thus sparse understories at this time could reflect overgrazing (Appendix A: Q200–Q203). However, denser forests reportedly had fewer shrubs (Appendix A: Q205–Q206). Both fire and canopy openings favored denser shrubs (Appendix A: Q205, Q208). The eastern Cascades, Oregon, had shrubs on 71% of forest area (Baker 2012). The Blue Mountains, Colorado Front Range, and northern Arizona had shrubs on only 0.3–18.0% of forest area (Williams and Baker 2012*a*).

I hypothesize that the peak in diameter distributions in the 40–50 cm class for several trees in both the northern and southern Sierra (Fig. 3) reflects elevated recruitment after regional drought and/or moderate and high-severity fires in the late-1700s to early-1800s. Extreme elevated temperatures (Scuderi 1993) occurred in 1779 and 1786–1805, which also had large areas burned in both Yosemite (Scholl and Taylor 2010) and Sequoia National Parks (Swetnam et al. 2009) SMC forests. Elevated ponderosa pine and sugar pine recruitment is evident in age structures in Yosemite after this period (Scholl and Taylor 2010; Fig. 6). The peak is not likely surveyor bias, as that would require similar bias across most of 35 surveyors. Relocated bearing trees also document little bias in bearing-tree selection (Williams and Baker 2010).

Historical fire severity

Other droughts are documented in the western Sierra during the period of the fire-severity reconstruction, which begins about 1755–1775 and ends about 1865–1885. Major periods of drought and high temperature occurred during 1764–1794 and 1806–1861 (Graumlich 1993) as well as 1856–1865 and 1870–1877 (Herweijer et al. 2006). These warm, dry periods increased after the preceding Little Ice Age, but continued into the 20th century (Herweijer et al. 2006). Thus, the reconstruction period and modern period may both have had climate favoring fire.

The hypothesis that low-severity fire nearly exclusively maintained dry-forest landscapes is rejected for historical SMC forests, as only 13–26% of these landscapes had only low-severity fire over the 110 years preceding the surveys. However, early reports suggest that high-severity patches did occur, associated with low-severity fires in these areas, and often were small (Appendix A: Q18–Q26, Q71, Q72, Q74, Q75). Show and Kotok (1924) reported that 15 early low-severity fires in the pine region (including the western Sierra) had an average of about 15% high-severity fire, but in small patches. Early reports that suggested low-severity fires were mostly the only fires (Appendix A: Q14-Q16, Q41–Q43) likely reflect the limited data they had available. The low percentage of exclusive low severity (13–26% of study areas) is shared with mixed-conifer forest in Oregon's eastern Cascades (Baker 2012). Low-severity fire was more common in the Blue Mountains (Williams and Baker 2012*a*) and northern Arizona (Williams and Baker 2012*a*, 2013). The hypothesis that low-severity fire exclusively maintained entire dry-forest landscapes has been rejected for all areas with spatially-extensive reconstructions (Baker 2012, Williams and Baker 2012*a*, 2013). Dry-forest landscapes in the western US were instead most strongly influenced by mixed- and high-severity fire, as also shown by Odion et al. (2014).

Mixed-severity fire was the dominant fire severity in SMC forests, found on 48% of the northern and 43% of the southern Sierra. Leiberg (1902) first documented the extent of mixed-severity fires in SMC forests (Appendix A: Q29, Q32–Q40). He described in detail the diversity of forest structures left behind and created by a mixture of fire severities: (1) chaparral patches and "lanes" often with surviving individual trees and tree groups or larger patches of surviving trees, (2) severely-thinned forests often with heavy chaparral understories, (3) scattered young trees regenerating in the chaparral, if observed 5–20 years after the fire, and (4) remnant denser unburned or lightly burned patches of forest often directly adjacent to the chaparral (Appendix A: Q35, Q39, Q94). Show and Kotok (1924) described this same suite (Appendix A: Q106), but did not recognize it as mixed-severity fire. Mixed-severity fire in SMC forests is most similar to dry forests in the eastern Cascades of Oregon (Baker 2012) and Washington (Hessburg et al. 2007), and Oregon's Blue Mountains (Williams and Baker 2012*a*), which had 43–59% mixed-severity.

In the Sierra, high-severity fire was somewhat more prominent in the north, found across 39% of these landscapes and 31% of the southern Sierra, lower than in the Colorado Front Range and on northern Arizona's Black Mesa (Williams and Baker 2012*a*), similar to the 30% in dry mixed-conifer in the eastern Cascades of Washington (Hessburg et al. 2007), but higher than in other areas. The high-severity rotation of 281 years in the north is similar to the 271-year rotation in dry forests in the Colorado Front Range and the 278-year rotation in the central region in Oregon's Eastern Cascades (Baker

2012). The 354-year rotation in the southern Sierra is a little longer, but not as long as the 435-year rotation overall in Oregon's eastern Cascades or the 828-year rotation in Oregon's Blue Mountains (Williams and Baker 2012*a*). High-severity fire likely was often a component of mixed-severity fires rather than independent, but extended at times as contiguous patches over large areas (Fig. 6).

Dry western forests were considered resistant to high-severity fire because understory fuels were kept low by frequent fires (Covington and Moore 1994). If so, fires could not have burned at high severity in the Sierra Nevada during a period of intense overgrazing by livestock in the late-1800s, when understory fuels were reduced. Comparison of survey data and Leiberg's data show that high-severity fire burned about 18,770 ha of mature forest after the surveys (Fig. 8). Moreover, the idea that low-severity fire kept understories free of fuels is not applicable to most SMC forests, which had pervasive ladder fuels in understory shrubs and small trees, that were often dense over large areas. Also, historical tree densities averaged 293 trees/ha, not including smaller understory trees. Calibration with fire severities from tree-ring reconstructions shows that forests this dense did not have a low- to moderate-severity fire regime (Williams and Baker 2012*a*), also shown by simulation analysis (Johnson et al. 2011).

The idea that low-severity fire kept fuel loads low and prevented high-severity fires is also behind the modern notion that historical high-severity fires did not produce patches exceeding a few hundred hectares (e.g., Collins and Stephens 2010). However, the reconstructions show that contiguous areas of historical high-severity fire commonly exceeded 250 ha and reached as high as 9400 ha. Show and Kotok (1924) also reported chaparral areas produced by fire over contiguous areas >2000 ha (Appendix A: Q95). In the Colorado Front Range, historical high-severity patch sizes had a geometric mean of 171 ha for patches >20 ha (Williams and Baker 2013). I found means only a little higher (Fig. 6) for patches >50 ha. Maximum historical patch size in Colorado was 8331 ha, similar to the maxima of 8050 ha in the northern and 9400 ha in southern Sierra, as well as the 8000-ha patches in Leiberg's maps (Fig. 8).

Extensive historical mixed- and high-severity fire and associated diverse forest structures are now well-established as characterizing much of the historical dry forest across the western US (Baker 2009, Williams and Baker 2012*a*, Odion et al. 2014), including in the western Sierra Nevada. This finding from spatially extensive GLO studies and spatially extensive analysis of forest age structures (Odion et al. 2014) is also well corroborated by early scientific accounts, early primary observations and photographs, paleo-ecological studies, and other age-structures (synopses in Baker 2009, Odion et al. 2014, Williams and Baker 2014). The alternative view of SMC forests in the 1996 Sierra Nevada Ecosystem Project Final Report to Congress, excerpted in the introductory quote, was supported by Leiberg's detailed study in 1902, and is again now that spatially extensive data are available from GLO survey data. Historical SMC forests were not largely open or park-like, but instead were mostly dense or very dense, high-severity fire was common, and mixed-severity fires and topography fostered very heterogeneous forest structure.

Contrasting historical forest structure and fire: northern and southern Sierra Nevada

The northern and southern Sierra and the phases had similarities and differences in historical fire and forest structure. North and south did not differ in mean tree density or basal area, had similar amounts of mixed-severity fire, similarly high understory shrubs, and heterogeneous landscapes with a matrix of dense forests interrupted by patches of low-density forest and very dense forest. Northern forests had less open, low density forest, about 50% more dense and very dense forest, and higher median tree density than southern forests. They were slightly dominated by shade-tolerant trees with equal accompanying oaks and pines, whereas southern forests were almost half pines, nearly a third shade-tolerant trees, and less than a fourth oaks. Southern forests had more trees >60 cm, and a higher quadratic mean diameter, fewer 10–20 cm trees, but almost twice as much coverage by understory trees and dense shrubs. I suggest this may reflect more fire in the southern Sierra Nevada nearer the time of the surveys. The northern Sierra had a quarter more high-severity fire and a high-severity fire rotation about one quarter shorter than in the southern Sierra, which had about twice as much area of exclusive low-severity fire. Larger amounts of dense forest, more shade-tolerant trees and oaks, and smaller trees are congruent with more high-severity fire and less low-severity fire in the northern Sierra. In both regions, oaks declined by almost three quarters from the ponderosa pine-Douglas-fir phase to the white fir phase, whereas shade-tolerant trees roughly doubled. Neither mean nor median tree densities differed among phases.

Limitations

Although I explicitly spatially controlled for EuroAmerican effects in the reconstruction of the historical fire regime in the northern Sierra Nevada (Appendix E), it remains possible that high-severity fire was elevated somewhat by EuroAmericans in this area. The spatial control is for fixed locations (e.g., sawmills), but people moving through these landscapes could set fires that spread over larger areas. Another limitation is the relatively short period for the fire-severity reconstructions, 110 years, which is less than the estimated rotations. Thus, it is likely that the estimates are imprecise. However, modern data for comparison (e.g., Hanson and Odion 2014) also are limited, typically to <30 years. It is an unfortunate reality that analysis and comparison of fire severity is limited by short periods of record. Another limitation is that the amount of high-severity fire and the fire rotation for high-severity fire do not include the high-severity parts of mixed-severity or low-severity fires, as they cannot be separated and measured. Thus, the high-severity fire rotation was likely shorter than my estimates. All reconstructions of historical forests that provide reference data have limitations, but their limitations increase with the passing of time since EuroAmerican settlement. The GLO-based reconstructions are nearly all for 1865–1884, with a median of 1873 (Fig. 2). This is not ideal, as EuroAmerican land uses expanded rapidly after 1848 (Beesley 2004), 17–36 years before the surveys (median 25 years). However, the GLO reconstructions provide the earliest spatially extensive reconstructions.

Other methods of reconstructing historical forests have limitations as well. First, detailed tree-ring reconstructions of forest structure (Appendix G), are unfortunately few for SMC forests ($n = 5$) relative, for example, to northern Arizona where > 100 reconstructions are available across large land areas (e.g., Abella and Denton 2009). Second, tree-ring reconstructions are typically limited to current old forests in protected areas, where evidence of historical forests is relatively undisturbed and best preserved. Forests that may have originated after mixed- and high-severity fires in the early to middle-1800s, which may be denser and <150 years old today are often not studied, leading to a sampling bias against younger, denser historical forests and mixed- and high-severity fire. This explains why Mallek et al.'s (2013) estimates of historical mixed- and high-severity fire are too low. Finally, later inventories (e.g., Collins et al. 2011) and the VTM plots from the 1930s (Keeley 2004) provide significantly diminished evidence about historical forests, since they took place 60–90 years after the 1848 EuroAmerican expansion.

Management Implications

Fuel-reduction programs will not restore historical fire, forest structure, or resiliency

The reconstructions show that the historical fire regime in SMC landscapes included low- to moderate-severity fire, likely at modest intervals, combined with mixed-severity fires, at longer intervals, which included substantial high-severity fire. The low- to moderate-severity component of the fire regime included many small high-severity patches. These fires did not keep fuels at low levels, as forests were dominated numerically by smaller trees (<50 cm diameter) and abundant shrubs commonly considered ladder fuels. SMC forests thus were not generally resistant to the mixed-severity fires, but instead: (1) burned completely and became chaparral across contiguous patches or lanes, or (2) were severely thinned by them, leaving scattered surviving trees or tree groups, often with dense chaparral understories, or (3) were thinned less severely and developed an open, park-like structure with large, old trees.

This old-growth structure may have conferred some resistance to higher fire severity, but these stands, too, were at best incompletely resistant (Hessburg et al. 2007), as demonstrated by the large area of mature forest that burned after the surveys. Given that high-severity fire rotations were about 280–350 years, which is the mean expected time between stand-replacing fires at any point in SMC landscapes, there was ample time for full recovery of old-growth forests across large areas. Moreover, mixed- and high-severity fires often left surviving trees and tree groups that became older emergent trees in recovering forests. Although these forests were likely not very resistant to mixed- and high-severity fires, tree and shrub regeneration after these fires was abundant (Appendix A) and forest resilience was thus historically very high.

Episodic recovering early-successional forests from mixed-severity fire had many ecological benefits (DellaSala et al. 2014). As an example, I analyzed whether SMC oaks, thought to be declining recently due to fire exclusion, were damaged or favored by these fires. I found oak concentrations favored in areas burned by mixed-severity fires before the surveys (Appendix H), which is also supported by early observations (Appendix A: Q64, Q76–78, Q84, Q90).

A current agency focus on lowering fuel loads so that only low-severity fires occur is not supported by the findings of this study. Agency proposals (North et al. 2009, North 2012) seek to lower fuel loads, remove most small trees and shrubs, and create and maintain low-density forests with large fire-resistant trees, low fuel loads, and nearly homogeneous low-severity fire, which this study shows were atypical of historical SMC forests. For example: "Mixed-conifer resilience might be best ensured by (1) reducing fuels such that if the forest burned, the fire would most likely be a low-severity surface fire..." (North et al. 2009:v). However, this study shows that a mix of fire severities historically created and maintained SMC forests.

Moreover, lowering fuel loads to eliminate all but low-severity fires will not restore the high levels of heterogeneity that characterized historical SMC forests. Multiple authors agree that more intense fires are needed (Schmidt et al. 2006, van Wagtendonk and Lutz 2007, Collins et al. 2011). However, agency proposals appear conflicted. For example, North et al. (2009:20; Fig. 9) use the 2007 Moonlight Fire to illustrate desirable landscape heterogeneity they suggest should be created. However, just 31% of Moonlight's burned area was from low-severity fire, 25% was from moderate-severity, and 43% was from high-severity fire (http://www.mtbs.gov). The desirable heterogeneity from the Moonlight fire cannot be created with the mostly low-severity fire that North et al. (2009) also recommend, or with mechanical thinning which does not mimic habitat structures (e.g., snags, down logs, chaparral patches) created by moderate- and high-severity fire. Reducing fuels to eliminate moderate- and high-severity fires would, if successful, reduce the historical landscape-level heterogeneity that provided wildlife habitat and conferred resiliency to drought, insect outbreaks, and fires (Millar et al. 2007).

Working with nature to restore historical fire, forest structure, and resilience

What is needed to restore SMC fire regimes so that these landscapes remain as resilient as they were historically? First, the higher-severity component of SMC fire regimes may still be functioning, but its rate (fire rotation) is deficient. Historical high-severity fire rotations of 281 years in the northern and 354 years in the southern Sierra (Table 7) are both shorter than estimated high-severity rotations for 1984–2010 of 461 years for the lower montane and 893 years for the mid-upper montane, using data from Monitoring Trends in Burn Severity (http://www.mtbs.gov; Hanson and Odion 2014). This suggests a deficit in high-severity fire in recent relative to historical landscapes. Lack of significant trend from 1984–2010 in high-severity fire proportion or annual area of high-severity fire (Hanson and Odion 2014) indicates the deficit was not being reduced through 2010 by increased high-severity fire. The percentage of total burn area that burned at high severity between 1984–2010 varied from year to year (Hanson and Odion 2014), but likely averaged close to, or only a little less than the 31–39% reconstructed for historical forests (Table 7), so it did not appear to be in deficit or surplus through 2010.

Some are concerned that recent high-severity patch sizes are uncharacteristically large and damaging in dry western forests (Stephens et al. 2013, Fulé et al. 2014). However, these articles surprisingly presented no patch-size data (Williams and Baker 2014). Hanson and Odion (2014) found that maximum annual patch sizes across

27 years (1984–2010) in Sierran montane forests included one year of about 8,000 ha, a few years with 3,000–7,000 ha and many years with 1,000-ha maximum patch sizes. These are the sizes Fule et al. mention, but they are very similar to reconstructed historical patch-sizes (Fig. 6). Also, Williams and Baker (2012*b*) found that recent patch-size distributions for high-severity fire in the Colorado Front Range did not differ from historical distributions, except for a recent deficit in the largest sizes. Thus, the data suggest that the only restoration need regarding high-severity fire through 2010 was to remedy a deficit in the rate (fire rotation) of high-severity fire. The 2013 Rim fire added several thousand hectares that will offset some of the deficit in high-severity burned area, help restore landscapes, and maintain their resilience.

The low- to moderate-severity part of the historical fire regime may need restoration and maintenance in two ways. First, the rate (fire rotation) at which these fires burn is likely not matching the historical rate, but it is still unresolved what the historical rate was. Past estimates derived from the widespread composite-fire-interval method (e.g., North et al. 2012) suggest much more low-severity fire than actually occurred, due to methodological flaws in this method (Baker and Ehle 2001, Dugan and Baker 2014). Available direct estimates of overall fire rotation compiled by Mallek et al. (2013) are better, but have a sampling bias toward low-density mature forests that makes them unreliable for the whole SMC landscape, which was denser. Mallek et al.'s conclusion that lower-severity fires are burning at lower rates than historically may be valid, but valid evidence is very limited. New landscape (Farris et al. 2010) and plot-based methods (Dugan and Baker 2014) can produce valid and accurate estimates, but many more are needed.

Second, small high-severity patches from low- to moderate-severity fires provide tree-regeneration sites, abundant shrub cover, dead snags, and important wildlife habitat that likely are deficient relative to historical forests. The reconstructions from section-line data (Table 6) show that fire-stimulated understory shrubs (*Ceanothus*, *Arctostaphylos*) and understory trees that provided ladder fuels essential to maintain the high-severity component of the low-severity fire regime were historically abundant. These fuels were substantially reduced by overgrazing by domestic livestock in the late-1800s and further reduced by fire exclusion that removed the fire stimulus that maintains these shrubs (Vankat and Major 1978). Mis-directed fuel-reduction programs are removing more of these fuels, which likely need to be increased, not reduced.

Fire is the logical choice for restoring historical fuels. However, previous work in Yosemite National Park showed that prescribed fires were typically ignited in shoulder seasons, and were lower in fireline intensity and fire severity than wildfires or wildland fire-use fires (van Wagtendonk and Lutz 2007). Low-intensity prescribed fires will not restore a substantial component of small high-severity patches, as they seldom increase fire-stimulated shrubs (e.g., Collins et al. 2009). In contrast, wildfires from 1974–2005 in Yosemite averaged about 37% low severity, 44% moderate severity, and 19% high severity, excluding unchanged areas, which is much more similar to the historical distribution of 26% low-, 43% mixed-, and 31% high severity fire (Table 7) than are fire-severity distributions for prescribed or wildland fire-use fires (van Wagtendonk and Lutz 2007). Wildfires thus were most restorative. Wildland fire-use, or multi-objective fires managed for specific goals, may help, but also may be insufficient unless allowed to create more high-severity patches, something that managers likely can accomplish.

Protecting people and infrastructure

Sierran mixed-conifer forests have likely long been subject to severe fires, and the plants and animals that live in them have remarkable capabilities to thrive both after these fires and in the interludes between them. It is us who have perhaps not had sufficient time to adapt to the rather fiery wild nature that characterized historical Sierran mixed-conifer forests. Extensive property damage, loss of human life, and ignitions by people are symptoms of this lack of adaptation. Perhaps adaptation has not occurred because the public has heard that the problem largely lies in the forest and can be fixed because it is an artifact of past mis-directed forest management.

However, the reconstructions and early scientific reports both show that these forests are inherently dangerous places to live, and will remain so if restored. Even low-intensity fires often blew up into small high-severity patches, and episodically fires became very severe and unstoppable over thousands of hectares. Even if society did not want to restore Sierran mixed-conifer forests and instead just wanted to prevent severe fires, this study shows fuel-reduction programs in wildlands are unlikely to work well. The understory fuels targeted in contemporary fuel-reduction programs were very extensively reduced in the late-1800s by overgrazing, yet high-severity fire still burned thousands of hectares of mature forest at high intensity.

The focus instead can be where it is essential and effective, which is to make our homes fire-safe through fuel reduction in home-ignition zones (Calkin et al. 2014), and reduce ignitions by people. Communities can also create growth boundaries, and rearrange their land uses to place ball fields, parks, wetlands, canals, irrigated crops and other low, open, less-flammable land uses on the outskirts (Baker 2009). In public forests, Smokey the Bear is still needed. About half the burned area in the 20 largest fires in California was from ignitions by people (www.fire.ca.gov). Closure of public forests during severe droughts is sensible. We can also reduce accidental ignitions by people in forests by redirecting development away from forests (Syphard et al. 2007) and by creating passive fire-safe features in places where people recreate, camp, stop, and drive, as well as near infrastructure (e.g., powerlines). People and wildfire can coexist in dangerous dry western forests if we accept that historically dominant and ecologically essential mixed-severity fires inherently have overwhelming physical power that requires us to adapt (Calkin et al. 2014).

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Supplemental Material

Appendix A

Table A1. Early observations (into early 20th century) about fire and forest structure in Sierran mixed-conifer forests of the Western Sierra Nevada and nearby areas. Observations are arranged by topic. Phrases in brackets [ ] are my insertions for clarification. Note that the assignment of individual quotes to different fire severities is necessarily imprecise.

Source	Location	Quote	Interpretation
Fire causes			
Leiberg (1902:41)	Northern Sierra	Q1: "Here, as elsewhere in the West, lightning is popularly supposed to be the cause of many fires. It is within the bounds of possibility that fires might originate in this manner, but it is not likely to happen very often. Most of the fires which have burned in this region can be traced to human agencies."	Lightning a rare cause, mostly people
Leiberg (1902:85)	Middle Fork of the Feather River	Q2: "The fires which have so extensively decimated the forest in the region under consideration are in most cases due to human agency. Possibly some have been caused by lightning, but lightning as an agency in the starting of forest fires is probably here, as elsewhere in the West, a convenient scapegoat upon which to throw the sins of the careless or maliciously inclined hunter, prospector, or sheepman, to whose presence most of the fires can be ascribed."	Lightning a rare cause, mostly people
Leiberg (1902:41)	Northern Sierras	Q3: "The belief is generally held that the sheep herders fired the country in all directions and have been responsible for most of the fires of recent years. However that may be, all the fires observed during the last summer closely followed the sheep camps."	Sheep herders caused fires
Sudworth (1900:555)	Southern Sierra	Q4: "But, carefully considered, there is a close relationship between the origin of many forest fires and sheep grazing . . . the writer's observations in the region under consideration show that a large number of fires are due to the presence of sheep herders. Some of these fires were due to carelessness and some were purposely set. . . . These fires proceed from neglected camp fires, from purposely fired fallen timber, and also from the deliberate setting of fires in high chaparral."	Sheep herders caused fires
Flintham (1904:37)	Southern Sierra	Q5: "Extensive sheep grazing in the past has caused serious damage in the Sierras. The mountains were formerly overgrazed, and the spread of fires set to renew and extend the pasture and browse for the huge bands . . . has left its mark in the damage to the forest."	Sheep herders caused fires
California State Board of Forestry (1888:124)	Northern Sierra	Q6: "The fires have been set in years past by Indians to drive or herd their game. Sheepherders set many fires wantonly, also campers, and travelers generally. Railroad engines occasionally fire the dry leaves and weeds along their lines, which escape to the woods, but generally much vigilance is used on the part of workmen to prevent such accidents. Rarely lightning ignites a tree, at least certain forest fires are reported to be caused by lightning."	Sheep herders caused fires; Railroads did not cause fires; Lightning a rare cause
California State Board of Forestry (1886:43)	Amador, Calaveras, Tuolumne, and Mariposa Counties	Q7: ". . . I think it can be safely affirmed that at an elevation of three thousand five hundred to five thousand feet (the region of the sawmill post and shake business) the people are reasonably careful to prevent fires, because it would be injurious to them, as the woods always contain logs, wood, shakes, and posts that would be destroyed in any extensive fire above this elevation. . . The stock men (cattle and sheep) are charged with deliberately firing the forest so as to clear underbrush and afford a crop of grass for the ensuing year."	Livestock grazing caused fires; Logging did not cause fires

Table A1. Continued.

Source	Location	Quote	Interpretation
Cooper (1906:34–35)	Whole Sierra	Q8: "Lumbered areas, owing to the brush and slash upon them, have offered particularly favorable conditions for severe fires. So great is the danger that fire almost invariably follows lumbering, and to it many of the after effects of lumbering, such as the presence of chaparral, the entire absence of young growth, etc., may be traced. The worst feature, perhaps, of such fires is the destruction of standing trees which might otherwise serve to seed up the area."	Logging caused fires
Flintham (1904:35)	Southern Sierra	Q9: "The heavy slash from logging generally left on the ground exposes the cut-over areas to greatest danger from fires, which have frequently swept over them, and often far beyond into areas of virgin timber..."	Logging caused fires
Show and Kotok (1924:5–6)	Whole Sierra	Q10: "The written historical records of the period, though extraordinarily meager on this question, indicate that the early miner was the cause of many forest fires ... there is evidence that these early prospectors found themselves hampered by brush and young growth, and adopted the practice of setting fire to the woods in order to facilitate their search for gold-bearing outcrops."	Mining caused fires
Leiberg (1902:63–64)	North Fork of the Feather River	Q11: "The burned region west of the river corresponds exactly to the extent of the auriferous areas where mining has been carried on since 1850. The tracts more severely burned east of the river are not situated in a very rich mineral region, but connect directly with burned tracts adjoining the placer grounds east of Spanish Peak. On its face the evidence would seem to warrant the conclusion that the fires which have ravaged the basin most extensively followed in the steps of miners and prospectors of the early days. The correctness of this conclusion is further strengthened by the fact that the big burns throughout the country examined lie contiguous or very close to much of the richest mineral ground."	Mining caused fires
Flintham (1904:38)	Southern Sierra	Q12: "Mining... Generally carried on on the lower foothill slopes below the lower line of the forest, the prospecting in various regions has occasioned practically no modification to the forest, except where locally the stand in the pine belt has been culled for mine timbers."	Mining did not cause fires
Leiberg (1902:41)	Northern Sierra	Q13: "The only older burns which give any clues to their age are those which stretch in a line from northwest to southeast through the central district of the region. They are marked by the occurrence of large tracts covered with chaparral. Most of these areas are situated contiguous to placer camps, worked from the earliest times, and might be regarded as having been burned over by fires spreading from such camps. In some instances this most likely happened, but a large proportion of the chaparral tracts was denuded of forest so long ago that nearly all the stumps have decayed. Hence the fires which overran them probably date back to the early part of the last century."	Mining did not cause older fires
Low- to moderate-severity fire			
Sudworth (1900:557)	Southern Sierra	Q14: "The fires of the present time are peculiarly of a surface nature, and with rare exception there is no reason to believe that any other type of fire has occurred here... The tree roots are for the most part buried deep in the crevices of bare rock, in gravel, sand, or shale, over which surface fires run annually without the slightest direct injury to the roots. Barring the debris left from timber-cutting, the only food for these fires is the scanty fall of pine and fir needles, irregular patches of low conifer seedlings and chaparral. In general, these materials limit the fires to surface burning."	Fires were low severity

Table A1. Continued.

Source	Location	Quote	Interpretation
Sterling (1904*a*):4	Southern Sierra	Q15: "In the virgin timber fires do comparatively little damage and are easily controlled. It is seldom that the flames reach up into the foliage, even in stands of fir, but usually run along through the litter as a ground fire, often burning deep into the humus and smouldering for days."	Fires were low severity
Hodge (1906:61)	Whole Sierra	Q16: "In virgin timber ground fires are the rule, and it is seldom the flames reach up into the foliage of large trees, even in stands of fir. Where there is little undergrowth, such fires are easily controlled, since they have only the litter of the forest floor for fuel. They often burn deep into the humus, however, and may smoulder for days."	Fires were low severity
Hodge (1906:61)	Whole Sierra	Q17: "Wherever dense undergrowth exists, as along the lower edge of the timber belt, the fires are naturally more severe, and more difficult to control, and individual trees and clumps are occasionally killed."	Fires were low to moderate severity
Leiberg (1902:65)	North Fork of the Feather River	Q18: "There are many such chaparral tracts throughout the yellow-pine type of forest, both east and west of the river, but most of them are small, rarely exceeding 5 to 10 acres."	Fires were low to moderate severity
Leiberg (1902:84)	Middle Fork of the Feather River	Q19: "The damage has not been very extensive, probably not over 5 per cent of the original stand of timber. The red and white fir has suffered the most; the yellow pine the least. Here and there a sugar pine has been burned at the base and lies prostrate, while on occasional small spots varying in size from 3 to 50 square rods [up to about 0.13 ha] the timber has been consumed, and brush has taken the place of the forest."	Fires were low to moderate severity
Leiberg (1902:94)	South Fork of the Feather River	Q20: "Throughout the forested region there are many spots, 3 to 10 square rods in extent, burned clean of timber. . . If all such places were taken into account, the amount of badly burned forest in the South Fork of Feather River Basin would probably swell to two or three times the figures above given."	Fires were low to moderate severity
Leiberg (1902:106)	North Fork of the Yuba River	Q21: "From Woodville Creek eastward to Canyon Creek, surface fires of moderate intensity have run through most of the heavy timber, destroying perhaps 4 to 6 per cent and leaving behind wide patches of heavy underbrush to mark their paths."	Fires were low to moderate severity
Leiberg (1902:137)	Yuba River Basin	Q22: "The destruction in the woodlands has been light . . . while in the forested areas it may run up to 5 or 8 per cent. The badly burned tracts have been swept by fires within recent years. They occur as small scattered patches in different portions of the wooded and forested areas. . ."	Fires were low to moderate severity
Leiberg (1902:95)	South Fork of the Feather River	Q23 "South of the river fires in the yellow-pine forests have not been so abundant nor so widespread as north of the stream, but enough have been burned there to clearly leave their impress . . . the loss in the yellow-pine types is probably about 8 per cent."	Fires were low to moderate severity
Leiberg (1902:64)	North Fork of the Feather River	Q24: "The most extensive fire within recent years in the yellow-pine areas burned in the northern portion of French Creek Basin, killing much oak, but not many conifers."	Fires of low to moderate severity top-killed oaks
Leiberg (1902:106–107)	South Fork of the Feather River	Q25: ". . .the western edge of the large and destructive burns are met near Lexington Hill and Union Hill. Here the yellow-pine type of forest joins that of the Shasta fir, and the fires burning in the latter have spread into the regions of the former, destroying especially the white and red [Douglas-fir] firs. The forest shows the work of the fire in thin stands and numerous patches of dense brush without timber, covering 4 to 50 square rods of ground."	Fires of low to moderate severity killed white fir and Douglas-fir

Table A1. Continued.

Source	Location	Quote	Interpretation
Fitch (1900*b*:572)	Yosemite area	Q26: "...one [a fire] continuing for several weeks burned over a large area. No particular damage was caused, however, to the larger timber with the exception of cedar and fir trees in certain localities, the sugar and yellow pine generally appearing to escape unhurt, although a great amount of dead and fallen timber had accumulated upon the ground."	Fires of low to moderate severity killed incense cedar and white fir
Show and Kotok (1924:29)	Whole Sierra	Q27: "The influence of fire in the California pine region, in interrupting the normal development of the forest and in perpetuating the intolerant species through its selective action, is fundamentally the same as in the Pacific Northwest, but by the gradual diminution of the tolerant white fir and incense cedar, which are easily killed by fire. The intolerant pines, with their ability to resist fire, are established under conditions unfavorable to their competitors."	Fires of low to moderate severity killed incense cedar and white fir
Moderate and mixed-severity fire			
Sudworth (1900:557)	Southern Sierra	Q28: "There is evidence that a much older forest than is represented in the present growth once existed here and that much of this growth has been gradually destroyed by fire. A very few of these trees—yellow pine, sugar pine, and white fir—are occasionally met with now. They are nearly twice as old as the oldest recent growth and could not well have disappeared through any other agency than fire. What the character of the older fires was is impossible to state."	Forests with two age-classes suggest past moderate-severity fire
Leiberg (1902:62)	North Fork of the Feather River	Q29: "…growth generally open, except along the bottoms of creeks, where heavy brush growths have followed fires and 15 to 20% of the standing red fir [Douglas-fir] has been damaged."	Fires were moderate severity in Douglas-fir
Leiberg (1902:165)	Middle Fork of the American River	Q30: "In the lower and middle portions of the Long Canyon drainage… All of the timber in this drainage is set in heavy underbrush. It has been greatly damaged throughout by successive fires, and most of the incense cedar, as well as much of the sugar pine, is hollow or rotten at the core in consequence."	Fires were moderate severity
Show and Kotok (1924:13)	Whole Sierra	Q31: "One of the most striking features brought out in Table 3 is that in every fire but one [of 15 early large fires in the pine region] a certain percentage of the burned area shows heavy loss from heat killing, heavy loss here being defined as the outright death of 50 per cent or more of the merchantable timber on any area … with a general (weighted) average for all of 15.3 per cent … this loss, it should be noted represents the complete or nearly complete wiping out of small patches of the stand rather than a uniformly distributed loss over the entire area."	Fires were mixed severity with about 15% high severity in small patches
Leiberg (1902:156)	North Fork of the American River	Q32: "The region showing the most extensive devastation by fire begins on the western slopes leading up to Monumental Hill and continues to the head of the basin. Every slope and canyon radiating from the group of ridges of which that point forms the culminations has been visited by fire. At the lower elevations, where the yellow-pine type is the prevailing forest, the damage has been largely confined to the red [Douglas-fir] and white firs, amounting to 15 or 20 per cent."	Fires were mixed severity with about 15–20% high severity in Douglas-fir and white fir
Leiberg (1902:116)	Middle Fork of the Yuba River	Q33; "In the western area of the basin north of the river the woodlands and forest have been swept by fire throughout, but as the forest is of the yellow-pine type the damage has not been extensive except as regards the white-fir, which has suffered severely, probably 20–25 per cent in the aggregate having been destroyed."	Fires were mixed severity with about 20–25% high severity in white fir
Leiberg (1902:94–95)	South Fork of the Feather River	Q34: "In the region around Lumpkin fires have burned through most of the heavy forest existing there. A large amount of white and red fir [Douglas-fir] has been destroyed—partly consumed, partly fire killed, and still standing."	Fires were mixed severity with high severity in white fir and Douglas-fir

Table A1. Continued.

Source	Location	Quote	Interpretation
Leiberg (1902:171–172)	Middle Fork of the American River	Q35: "In the valley of Long Canyon 20 to 30 per cent of the timber has been destroyed... Everywhere the undergrowth, where the timber has not been wholly destroyed, has more than quadrupled in density, while on some of the southern slopes, like the ridges between Long Canyon and Rubicon River, soil aridity has followed to such an extent that the chaparral is scarcely able to obtain a foothold. All the areas around French Meadows tell the same tale and show the same picture of scattered broken stands of timber set in dense undergrowth, or separated by lanes of chaparral. All the way down the main canyon of the Middle Fork of the American River there is a succession of these fire glades, alternating with heavy stands which serve to indicate the former density of the forest. All the slopes of Duncan Canyon from its head down show the same marks of fire—dead timber, dense undergrowth, stretches of chaparral, thin lines of trees or small groups rising out of the brush, and heavy blocks of forest surrounded by chaparral. North of Duncan Peak and connecting with the burns on the northern slopes of North Fork of American River Canyon the forest has been burned out in narrow lanes and patches. In some places brush has replaced the timber, in other localities the ground has been too rocky, soil aridity has set in, and low shrubs or coarse weeds thinly cover the ground."	Fires were mixed severity with about 20–30% high severity in lanes and patches
Leiberg (1902:130)	South Fork of the Yuba River	Q36: "In the central area extensive surface fires have run through the timber north of the river, destroying about 25 per cent of it; south of the river only 4 or 5 per cent."	Fires were mixed severity with about 25% high severity
Leiberg (1902:168)	Middle Fork of the American River	Q37: "Duncan Canyon: Yellow pine, 10 to 20 per cent; scattered sugar pine; red [Douglas-fir] and white fir, 60 to 75 per cent; incense cedar, oak, and occasional Shasta firs; small blocks of timber growing on rocky ground, separated by lanes of brush growth ... damaged by fire to the extent of 25 to 30 per cent."	Fires were mixed severity with about 25–30% high severity
Leiberg (1902:169)	Middle Fork of the American River	Q38: "...North Fork of the Middle Fork... Yellow pine, 30 to 40 per cent; balance red fir, white fir, incense cedar, and oak; open scattered stands growing on steep, rocky ridges and in the narrow bottoms of deep canyons; damage by fire, 35 to 40 per cent."	Fires were mixed severity with about 35–40% high severity
Leiberg (1902:156–157)	North Fork of the American River	Q39: "South of the river at the head of the basin the fires have burned out patches of timber in the midst of heavy stands, thinning the forest in other localities, the damage amounting to 35 per cent. Thence westward there is a line of heavy burns following the main canyon. The fires ate their way through what originally has been a heavily forested tract along the upper slopes of the canyon, completely burning up wide blocks of timber and greatly thinning what they did not wholly destroy; the damage has been about 30 per cent. From Red Point westward to the woodlands the forest is fire marked nearly throughout, small stands, especially of red [Douglas-fir] and white fir, having been burned out here and there, the destruction in isolated localities amounting to 50 or 60 per cent, while the average is approximately 5 per cent, as near as can be judged at this time, as most of the fires burned long ago and their traces have been obliterated to some extent by subsequent logging operations."	Fires were mixed severity with about 30–60% high severity, over both wide areas and in small patches

Table A1. Continued.

Source	Location	Quote	Interpretation
Leiberg (1902:41)	Northern Sierra	Q40: "It is estimated that the areas badly burned—that is, those on which 50 per cent or more has been destroyed—comprise 715,440 acres [this includes moderate- and high-severity fire], and of this amount there are 213,730 acres, in tracts larger than 80 acres, on which the destruction has been total [this is the high-severity part]. If the many small lots of badly burned forest which are scattered throughout the still growing stands were taken into the account, the figures given above would be considerably increased."	Fires of moderate and high severity covered more than 290,000 ha
High-severity fire			
Sudworth (1900:558)	Southern Sierra	Q41: "The instances in this region where large timber has been killed outright by surface fires are comparatively rare. Two cases only were found, and are shown on the accompanying map... One of these burns involved less than an acre, and the other included several hundred acres. They are exceptional cases, and the killing of the trees is accounted for by the fact that long protection from fire and from all but cattle grazing had resulted in the accumulation of much fallen timber, considerable humus in depressions and on benches, and a dense undergrowth of brush and seedlings. The fires burned deep enough to badly injure the surface roots, which resulted in subsequent death of the timber."	High-severity fire was rare, occasionally up to 100–200 ha
Show and Kotok (1924:31)	Whole Sierra	Q42: "Extensive crown fires, though common in the forests of the western white pine region, are almost unknown in the California pine region. Local crown fires may extend over a few hundred acres, but the stands in general are so uneven-aged and broken and have such a varied cover type that a continuous crown fire is practically impossible."	High-severity fire was rare, occasionally up to 100–200 ha
Kotok (1933:4020)	Eldorado County	Q43: "...complete wiping-out of the original coniferous forests representing the climax types, never extended over large areas during the Indian period. In contrast, with the advent of white man, lumbering, grazing, and an enormous increase in fires (in a 75-year period) brought rapid retrogression."	High-severity fire historically rare, became common after EuroAmerican settlement
Show and Kotok (1924:13)	Whole Sierra	Q44: "A dense, closed stand of timber, on the other hand, will more readily develop a true crown fire. Such fires are the rule in dense, even-aged second-growth stands where there is an uninterrupted tree canopy."	High-severity fire likely in dense second growth
Show and Kotok (1924:27)	Whole Sierra	Q45: "With summer fires, these dense groups of reproduction, even in sapling and pole stages, are peculiarly susceptible to crown fires, just as the larger second-growth stands are."	High-severity fire likely in dense second growth
Show and Kotok (1924:Plate V Figure 2)	Whole Sierra	Q46: "Although crown fires are rare in old stands, in the California pine region, they often develop from light burns in second growth. When this occurs, the result, as in this case, is disastrous."	High-severity fire likely in dense second growth
Show and Kotok (1924:31)	Whole Sierra	Q47: "Existing second-growth stands [established after logging in 1850–1870] are typically even-aged and fully stocked, have a continuous, unbroken canopy, and are consequently susceptible to the most destructive type of forest fire."	High-severity fire likely in dense second growth
Show and Kotok (1924:32)	Nevada City area	Q48: "Rock Creek Fire, 1910... This fire burned a strip, 3 ½ miles long and 1 ¼ miles wide through the center of a practically continuous tract of 40-year old second-growth western yellow pine...The total burned area was 2,840 acres [1150 ha]... A cruise of the burn showed that on more than 75 per cent of the total area all trees were killed, except occasional isolated clumps. This fire spread through the crowns, utterly destroying the timber on all slopes and exposures, and resulted in the reversion of the burn to a worthless brushfield... The destruction by this single fire was almost complete and far exceeds anything known in the virgin forests either in this particular locality or any other part of the pine region."	High-severity fire in 1910 in second-growth ponderosa pine

Table A1. Continued.

Source	Location	Quote	Interpretation
Hall (1909:29)	Plumas National Forest	Q49: "The most destructive fire in 1908 occurred on the western edge of the Forest, mostly outside. It was started in the foothill type outside of the Forest and ran up a ways into the Forest burning over in all outside and inside some 10,000 acres . . . in the timber destroying everything in its central path, even large timber."	High-severity fire in 1908 over a large area
Hall (1909:29)	Plumas National Forest	Q50: "On private land near Quincy, a very bad fire burned over some sixty acres of mostly thick stands of pure yellow pine almost completely killing every one and killing nearly all of the large mature trees."	High-severity fire of about 60 ha in dense ponderosa pine
Hodge (1906:39)	Whole Sierra	Q51: "The leaves also are very inflammable, and crown fires in this species [white fir] are not uncommon."	High-severity fire common in white fir
Leiberg (1902:117)	Middle Fork of the Yuba River	Q52; "South of the Middle Fork Canyon the region of the yellow-pine forest is fire marked and damaged very much as in the corresponding areas north of the river, to a point just beyond Bloomfield. From here on, eastward to Shands, the timber is composed largely of white fir, probably to the extent of 60 per cent, and long swaths have been burned in all directions through these stands of low fire-resisting capacity."	High-severity fire in white fir in long swaths
Leiberg (1902:156)	North Fork of the American River	Q53: "East of Monumental Hill the forest is burned to the extent of 75 per cent on all the ridges at the head of Granite Canyon, Big Valley, and in general everywhere in the watershed as far east as Onion Creek. The fires have raged alike in the Shasta-fir and yellow-pine forest, here burning long lanes clear of timber, there destroying large blocks of forest, leaving behind isolated trees or small groups fire scarred or half consumed, and covering, as a sequel, ridge and slope with matted brush growths. At the head of the canyon the fires burned out the timber in spots here and there, and doubtless are responsible for the grassy tracts and thin, scattered stands of forest which characterize the slopes of the main range."	High-severity fire in ponderosa pine burned lanes, wide areas, and small patches
Leiberg (1902:144)	Bear River Basin	Q54: "In the forests fires have been more destructive. Considerable of the old growth has been burned. . ."	High-severity fire in old growth
Leiberg (1902:156–157)	North Fork of the American River	Q55: "South of the river at the head of the basin the fires have burned out patches of timber in the midst of heavy stands, thinning the forest in other localities, the damage amounting to 35 per cent. Thence westward there is a line of heavy burns following the main canyon. The fires ate their way through what originally has been a heavily forested tract along the upper slopes of the canyon, completely burning up wide blocks of timber and greatly thinning what they did not wholly destroy."	High-severity fire across wide areas
Leiberg (1902:41)	Northern Sierra	Q56: "It is estimated that the areas badly burned—that is, those on which 50 per cent or more has been destroyed—comprise 715,440 acres [this includes moderate- and high-severity fire], and of this amount there are 213,730 acres [86,530 ha], in tracts larger than 80 acres, on which the destruction has been total [this is the high-severity part]. If the many small lots of badly burned forest which are scattered throughout the still growing stands were taken into the account, the figures given above would be considerably increased."	High-severity fire on more than 86,530 ha
High-severity fire led to chaparral, oak, scattered surviving trees and tree groups, and recovering forests			
Leiberg (1902:41)	Northern Sierra	Q57: "The only older burns which give any clues to their age are those which stretch in a line from northwest to southeast through the central district of the region. They are marked by the occurrence of large tracts covered with chaparral. . .a large proportion of the chaparral tracts was denuded of forest so long ago that nearly all the stumps have decayed. Hence the fires which overran them probably date back to the early part of the last century."	High-severity fire led to chaparral

Table A1. Continued.

Source	Location	Quote	Interpretation
Leiberg (1902:43)	Northern Sierra	Q58: "An increase in density and extent of brush growth below the 7,300-foot level is here an unfailing consequence of fires. In the yellow-pine type of forest and in the woodland it grows to larger proportions, and here and there, where the timber has been totally destroyed, it forms patches of pure growth…there can not be the slightest doubt that every acre of chaparral represents so much ground once forested, denuded by fire, then overgrown with brush. At the head of Slate Creek, and near Howland Flat, in the western portion of Sierra County, chaparral identical with these growths elsewhere in the region is now in the process of formation on tracts which were covered with forest to within twenty years ago."	High-severity fire led to chaparral
Leiberg (1902:65)	North Fork of the Feather River	Q59: "Elsewhere [outside the woodland belt below SMC forests] a brush growth close enough to be called chaparral is invariably a sequel to the total destruction of the forest on any area below the highest subalpine elevations."	High-severity fire led to chaparral
Hodge (1906:14–15)	Whole Sierra	Q60: "Patches of pure chaparral without trees occur throughout the Sierras, particularly at the higher elevations. They almost invariably occupy situations that are capable of producing timber, and their origin lies in forest fires."	High-severity fire led to chaparral
Cooper (1906:30)	Whole Sierra	Q61: "In many portions of the State where fires have been exceptionally bad this process has gone so far that the tree growth has been entirely replaced by chaparral."	High-severity fire led to chaparral
Hodge (1906:39)	Whole Sierra	Q62: "The white fir forest is usually extremely dense, containing little undergrowth. When it is destroyed by fire, however, it is usually seeded up promptly to chaparral."	High-severity fire in white fir led to chaparral
Leiberg (1902:84)	Middle Fork of the Feather River	Q63: "Bush-covered tracts occur everywhere in the basin, but chaparral proper is found only where the forest has been destroyed by fire… In yellow-pine forests the brush is chiefly a thin undergrowth scattered among the growing trees, except on ground where the forest has been wholly or partially destroyed by fire, when it forms true chaparral."	High-severity fire led to chaparral
Leiberg (1902:118–119)	Middle Fork of the Yuba River	Q64; "Where fires have swept through the lower areas of the yellow-pine forest and consumed the timber, a heavy growth of manzanita … has followed as a sequel… In the upper areas of the yellow-pine forest, especially where white fir constituted the principal species, heavy masses of brush growth composed of species of ceanothus, scrub oak, and manzanita … for a chaparral cover on the denuded or partially denuded tracts."	High-severity fire led to chaparral
Leiberg (1902:156)	North Fork of the American River	Q65: "From the western limits of the forested regions to Emigrant Gap the traces of fire are more obvious. Partly or wholly dead timber seared by fires and the brush growths following in their wake exist in every canyon and on every ridge."	High-severity fire led to chaparral
Leiberg (1902:171)	Middle Fork of the American River	Q66: "Between Big Meadow and French Meadows 60 to 70 per cent of the timber has been destroyed, and the underbrush has, in consequence, become so dense that no living thing larger than a mouse can make its way through it."	High-severity fire led to chaparral
Hall (1909:11)	Plumas National Forest	Q67: "In type 'B' [SMC forests] the chief, if not only agent, acting to form temporary types is fire, killing off the timber and allowing invasion of brush. This temporary type is more apt to occur and last longer on the hot southern and western slopes than elsewhere, because there reproduction of trees is more difficult and slower."	High-severity fire led to chaparral
Show (1924:83)	Northern Sierra	Q68: "Perhaps the most striking characteristic of the timber region of northern California … is the very large area occupied by brushfields. The brushfields, for the most part, are the result of fires which have destroyed the timber and allowed the brush to occupy the ground; in round numbers 1,500,000 acres are now in this condition. Of this million and a half acres probably 75 per cent is restocking naturally, scattered individuals and groups of trees having survived the fires of the past, and can be depended on to take care of themselves…"	High-severity fire led to chaparral

Table A1. Continued.

Source	Location	Quote	Interpretation
Boerker (1915:15)	Northern Sierra	Q69: "Unlike the chaparral regions of southern California, this brush is only a temporary type and is, in most cases, the result of fire having destroyed the forest cover. Not a small part of our brush areas may be attributed to 'light burning' which was practiced for many years by Indians and more recently by stockmen. In most cases, in from 5 to 10 years after the fire has consumed the timber, the brush takes possession of the land; the length of time depending upon the severity of the fire, the presence of brush plants in or near the fire area, and other conditions."	High-severity fire led to chaparral
Flintham (1904:4)	Southern Sierra	Q70: "This denudation of the forest has been occasioned by fire and lumbering. In the Southern Sierras the spread of fires over the mountains, mainly since the settlement of the State, has thinned and injured the valuable timber stand, and has removed the protective forest cover from considerable areas of the upper and lower watersheds of the streams, allowing imperfect cover of chaparral to gain permanent possession . . . lumbering . . . has produced the same result though generally over much more restricted areas."	High-severity fire led to chaparral
Flintham (1904:32–33)	Southern Sierra	Q71: "The most noticeable effect of the fire in the fir forests is the denudation of the cover—the opening of areas in the forest. . . There result within the forest small open spots, in which dead stubs of the fire-killed timber stand . . . and frequently on the upper slopes and crests of ridges great areas of openings, which fire or death following upon it have completely denuded of the cover formerly occupying the site as evidence from charred logs and occasional stubs or trees left standing. The areas opened in the fir stand after the fire, more especially the denuded crests of the ridges and the divides, have generally been overgrown by a specially dense and heavy chaparral of species occurring as undergrowth under the stand at this altitude. . . Fire and chaparral extension have stood to each other throughout the Sierras in the relation of cause to effect. The encroachment of the chaparral has uniformly followed fires, and has been uniformly inimical to the forest cover. . ."	High-severity fire led to chaparral
Flintham (1904:166)	Southern Sierra	Q72: "However, denudation of the forest cover has been confined to relatively small areas, and has led to no serious deterioration of any section of the mountains from excessive erosion or other injurious agency, because the removal of the forest cover does not imply complete opening of an area but generally its recovering with a dense chaparral growth. . .	High-severity fire led to chaparral
Leiberg (1902:95)	South Fork of the Feather River	Q73: "The young growth is in thickset stands with little underbrush. Here and there it is broken . . . by hillsides formerly nearly deforested by fires and now covered with a close growth of manzanita."	High-severity fire led to chaparral with manzanita
Leiberg (1902:132)	South Fork of the Yuba River	Q74: "In the yellow-pine forest, especially in the restocking where patches have been burned clean, a chaparral springs up 3 to 5 feet high, composed almost exclusively of manzanita."	High-severity fire led to chaparral with manzanita
Leiberg (1902:145)	Bear River Basin	Q75: "Small brush-covered patches of ground occur here and there in the eastern portion, having followed as a sequel to fires in the yellow-pine forest. The brush consists chiefly of manzanita."	High-severity fire led to chaparral with manzanita
Leiberg (1902:157)	North Fork of the American River	Q76: "All along the Blue Canyon and Canyon Creek drainage a large proportion of the reforestation consists of scrubby oak instead of the coniferous species of trees which formerly constituted the timber in these localities. The extensive and heavy stands of brush which have here come as a sequel to fires show no sign of being replaced with tree growth. . . All the higher slopes of Monumental Hill are covered with dense chaparral, which will not be replaced by forest for a century or more."	High-severity fire led to oak and chaparral

Table A1. Continued.

Source	Location	Quote	Interpretation
Kotok (1933:4019–4020)	Eldorado County	Q77: "In reconstructing the ecological changes in this county due to fire the following major retrogressions have been noted: The *Pinus ponderosa* with its usual understory of *Quercus kelloggii* changes to one of *Quercus kelloggii* with scattered pine… The pure *Pinus ponderosa* type passes to a *Ceanothus integerrimus*, *Arctostaphylos viscida* association… In the mixed-conifer type…infrequent fires will favour the pines against the firs, arresting the succession to the fir climax. Repeated fires will invariably reduce the high coniferous forests to sprouting shrub associations."	High-severity fire led to oak and chaparral
Leiberg (1902:124)	South Fork of the Yuba River	Q78: "The forest has been extensively ravaged by fires and is almost everywhere badly choked with underbrush. Up to 4,500-foot level there are large quantities of oak mixed with it; above that altitude the oak soon thins out and disappears."	High-severity fire led to oak and chaparral
Leiberg (1902:59)	North Fork of the Feather River	Q79: "On the slopes of Clermont Hill, south of American Valley, the forest is thin and scattered, and is composed largely of small red fir [Douglas-fir], being set on rocky ground among great masses of undergrowth."	High-severity fire led to small trees in dense chaparral
Leiberg (1902:77)	Middle Fork of the Feather River	Q80: "A few miles west of Lumpkin the forest rapidly begins to thin out… The stands … have been extensively thinned by the ravages of repeated fires. In much of this section the timber is set in thick brush, which has, as elsewhere, increased enormously as a sequel to the fires."	High-severity fire led to thin forests in dense chaparral
Leiberg (1902:77)	Middle Fork of the Feather River	Q81: "But the thin stands of timber, especially on the northern exposures of the canyon [Middle Fork] declivities above the point where Cascade Creek enters, are largely due to fires and the consequent development of dense chaparral."	High-severity fire led to thin forests in dense chaparral
Leiberg (1902:78)	Middle Fork of the Feather River	Q82: "From Buckeye south … a large percentage of the fir has been damaged by recent fires, and nearly all of it stands in thick growths of underbrush."	High-severity fire led to thin forests in dense chaparral
Leiberg (1902:95)	South Fork of the Feather River	Q83: "Northeast of Lumpkin … the basin of the South Fork shows, by the uniform thinning of the forest and the abundance of chaparral, ample evidence of widespread fires."	High-severity fire led to thin forests in dense chaparral
Leiberg (1902:100)	North Fork of the Yuba River	Q84: "The yellow-pine forest, as it follows up the lateral canyons…is mostly thin and small… The larger proportion consists of red fir [Douglas-fir], here and there white fir, incense cedar, and oak, generally set in thick underbrush, the result of many and severe fires."	High-severity fire led to thin forests in dense chaparral
Leiberg (1902:165)	Middle Fork of the American River	Q85: "The forest on the slopes and in the canyon of Rubicon River below the mouth of Grayhorse Canyon is extremely thin… On the southern declivities the forest occurs as isolated blocks of thin growth standing in heavy underbrush on bowlder-[sic] strewn slopes. Yellow pine forms 25 to 40 per cent; white fir most of the remainder"	High-severity fire led to thin forests in dense chaparral
Leiberg (1902:80)	Middle Fork of the Feather River	Q86: "…small quantities of yellow pine and red fir [Douglas-fir] in canyons, all of poor quality and generally small size; set in dense chaparral…"	High-severity fire led to small trees in dense chaparral
Leiberg (1902:81)	Middle Fork of the Feather River	Q87: "Region around Mount Jackson and Grizzly Peak: Chiefly white fir, some small and stunted yellow pine, occasional bunches of Shasta fir; all in thick chaparral … much damaged by repeated fires."	High-severity fire led to small trees in dense chaparral
Leiberg (1902:77)	Middle Fork of the Feather River	Q88: "From Mount Ararat west to Buckeye the forest occurs in more or less isolated stands surrounded by chaparral."	High-severity fire leaves unburned patches in dense chaparral
Leiberg (1902:82)	Middle Fork of the Feather River	Q89: "Region around Franklin Hill: Chiefly yellow and sugar pine, red and white fir in less quantities; timber of fair quality and size: forest broken by patches of chaparral."	High-severity fire leaves unburned patches in chaparral

Table A1. Continued.

Source	Location	Quote	Interpretation
Leiberg (1902:103)	North Fork of the Yuba River	Q90: "Goodyears Creek drainage: In the lower area, yellow and sugar pine, red [Douglas-fir] and white fir, incense cedar and oak scattered as small trees, thin lines or small groups in dense chaparral…"	High-severity fire led to thin forests and scattered trees or patches in dense chaparral
Leiberg (1902:164)	Middle Fork of the American River	Q91: "The forest is mostly yellow-pine, not having been logged; the stands are thin and scattered, everywhere broken by tracts of chaparral or rocky exposures with little soil and hardly any tree growth."	High-severity fire led to thin forests and scattered trees in dense chaparral
Leiberg (1902:156)	North Fork of the American River	Q92: "East of Monumental Hill the forest is burned to the extent of 75 per cent on all the ridges at the head of Granite Canyon, Big Valley, and in general everywhere in the watershed as far east as Onion Creek. The fires have raged alike in the Shasta-fir and yellow-pine forest, here burning long lanes clear of timber, there destroying large blocks of forest, leaving behind isolated trees or small groups fire scarred or half consumed, and covering, as a sequel, ridge and slope with matted brush growths. At the head of the canyon the fires burned out the timber in spots here and there, and doubtless are responsible for the grassy tracts and thin, scattered stands of forest which characterize the slopes of the main range."	High-severity fire in ponderosa pine led to chaparral, scattered individual trees or patches, and grassy areas
Leiberg (1902:165)	Middle Fork of the American River	Q93: "The middle portion of the main canyon of Middle Fork of American River…Close-set stands alternate with thin lines of trees or scattered individuals rising out of heavy undergrowth."	High-severity fire led to thin forests and scattered trees or patches in dense chaparral
Leiberg (1902:171–172)	Middle Fork of the American River	Q94: "In the valley of Long Canyon 20 to 30 per cent of the timber has been destroyed… Everywhere the undergrowth, where the timber has not been wholly destroyed, has more than quadrupled in density, while on some of the southern slopes, like the ridges between Long Canyon and Rubicon River, soil aridity has followed to such an extent that the chaparral is scarcely able to obtain a foothold. All the areas around French Meadows tell the same tale and show the same picture of scattered broken stands of timber set in dense undergrowth, or separated by lanes of chaparral. All the way down the main canyon of the Middle Fork of the American River there is a succession of these fire glades, alternating with heavy stands which serve to indicate the former density of the forest. All the slopes of Duncan Canyon from its head down show the same marks of fire—dead timber, dense undergrowth, stretches of chaparral, thin lines of trees or small groups rising out of the brush, and heavy blocks of forest surrounded by chaparral. North of Duncan Peak and connecting with the burns on the northern slopes of North Fork of American River Canyon the forest has been burned out in narrow lanes and patches. In some places brush has replaced the timber, in other localities the ground has been too rocky, soil aridity has set in, and low shrubs or coarse weeds thinly cover the ground."	High-severity fire led to thin forests and unburned patches in dense chaparral, along with some areas of herbaceous vegetation
Show and Kotok (1924:42–43)	Whole Sierra	Q95: "Estimates made after years of study of brush fields indicate that about two-thirds of their area is reproducing sufficiently to establish eventually a commercial forest. The extent to which tree reproduction is taking place depends naturally on the number and distribution of seed trees available, for regeneration can be counted on to a distance of only a few hundred feet from seed trees. Smaller brush fields, generally speaking, are restocking in a satisfactory manner. It is chiefly in the very large brush areas of 5,000 acres [2024 ha] or more … that complete restocking will be a matter of several tree generations, or of planting."	Forest recovery in chaparral after high-severity fire

Table A1. Continued.

Source	Location	Quote	Interpretation
Show and Kotok (1924:43)	Whole Sierra	Q96: "The amount of reproduction present in the brush fields to-day is very much greater than would seem on superficial examination, for in many places the young trees are just beginning to break through the brush canopy and to become easily visible. This condition is wholly the result of 15 to 20 or 25 years of fire exclusion."	Forest recovery in chaparral after high-severity fire
Moore (1913:22)	Plumas National Forest	Q97: "The brush, particularly on the drier sites, appears to assist rather than to hinder reproduction. In the yellow pine-incense cedar type the brush areas are not extensive and generally contain scattering trees, particularly yellow pine. The brush here does not form a complete covering, but leaves spots of exposed rocky soil. . .In the mixed conifer type the brush areas, though extensive, generally contain scattered old yellow pine and sugar pine individuals which have resisted the fire. The brush here forms a nearly complete canopy hindering, though not entirely preventing the reproduction of yellow pine. Sugar pine, because of its greater tolerance, comes up well through the thinner places in the brush."	Forest recovery in chaparral after high-severity fire
Show (1924:83)	Northern Sierra	Q98: "Perhaps the most striking characteristic of the timber region of northern California . . . is the very large area occupied by brushfields. The brushfields, for the most part, are the result of fires which have destroyed the timber and allowed the brush to occupy the ground; in round numbers 1,500,000 acres are now in this condition. Of this million and a half acres probably 75 per cent is restocking naturally, scattered individuals and groups of trees having survived the fires of the past, and can be depended on to take care of themselves. . ."	Forest recovery in chaparral after high-severity fire
Boerker (1915:15)	Northern Sierra	Q99: "Unlike the chaparral regions of southern California, this brush is only a temporary type and is, in most cases, the result of fire having destroyed the forest cover. . . In most cases, in from 5 to 10 years after the fire has consumed the timber, the brush takes possession of the land; the length of time depending upon the severity of the fire, the presence of brush plants in or near the fire area, and other conditions. After the brush has established itself, if seed trees are nearby, seedlings will get started and fight their way through the brush. It takes from 15 to 30 years for a seedling to get large enough to overtop the brush . . . if the stand of saplings becomes dense enough, the brush underneath will be killed for lack of sunlight and a forest cover will begin to form. This is nature's very slow process of reestablishing a forest cover. If there are no seed trees near the burned area, it is only a matter for conjecture how long it will take a forest to reestablish itself."	Forest recovery in chaparral after high-severity fire
Show and Kotok (1924:36)	Whole Sierra	Q100: "Further, the gradual thinning of the forest allows the invasion of brush and other inflammable cover so that succeeding surface fires more readily develop into disastrous crown fires."	Chaparral fires are also high severity
Show and Kotok (1924:43)	Whole Sierra	Q101: "Fires in the brush fields . . . are of serious moment, not because they destroy merchantable timber, but because at one stroke they may sweep the new forest from thousands of acres and even destroy the scattered seed trees that are necessary to maintain the forest type."	Chaparral fires are also high severity
Show and Kotok (1924:43)	Whole Sierra	Q102: "Not only do fires in brush attain a greater average size than in timber, but for equal areas of timber land and brush land nearly seven times as many acres of brush land are being burned each year as timber."	Chaparral fires are larger and more frequent than forest fires
Show and Kotok (1924:44)	Whole Sierra	Q103: "Recent studies have shown . . . that fires in brush are far more difficult to control than those in virgin forest, and attain a much larger average size. Once started, also, they are likely to sweep into adjoining timber stands with an intensity that results in wiping out the immediately adjoining timber belt, thus extending the brush fields themselves. Fires in brush fields are typically crown fires and partake of the nature of crown fires in timber."	Chaparral fires are also high severity, larger, and expand into forest

Table A1. Continued.

Source	Location	Quote	Interpretation
Repeated fires led to chaparral: the attrition theory			
Show and Kotok (1924:29)	Whole Sierra	Q104: "On such as burn as the Ham Station fire . . . not only was a certain percentage stripped of timber, but this area as a whole is reverting to brush, and the brush will in turn increase the intensity of subsequent fires. . . Another example . . . is the Howard fire. . . This area has been subject for many years to repeated forest fires and by this process of attrition has been reduced in density, thereby increasing the amount of undergrowth. The latest fire on this area, which has caused tremendous damage, is the logical and inevitable result of previous fire history. All such examples lead to the same conclusion: *Fire in forest areas invariably breeds still more serious fires*."	Attrition theory of chaparral formation by repeated fires
Show and Kotok (1924:78)	Whole Sierra	Q105: "Fires in the virgin forests of the California pine region rarely are catastrophes, for they do not wipe out at one stroke the entire stands over a large area. Indeed, they are generally distinguished by the fact that much of the damage is relatively inconspicuous and not immediately evident. But a study of the fires of the past and those of the present shows unmistakably that attrition is the inevitable concomitant of repeated fires. This wearing down of the forest is remarkably exhibited in all its varied stages in the California pine region to-day, from the well-stocked areas of mature timber to the nontimber-producing chaparral. The fire-scarred virgin forest, the broken, patchy timber stand of no present merchantability; the brush fields with scattered, isolated trees, and small groups of trees; the continuous brush fields occupying potential timberland and restocking only slowly; and finally, pure brush or chaparral, the end product, are but the different chapters of the story of attrition."	Attrition theory of chaparral formation by repeated fires, but consistent with high-severity fire leaving scattered trees and unburned patches of forest in dense chaparral
Show and Kotok (1924:41–42)	Whole Sierra	Q106: "The most convincing proof that the brush fields are the result of fire is that within a comparatively short distance there may be found all the gradations from a stand of merchantable virgin timber to a stand of brush with no living trees. . . Other evidence that the brush fields were formerly timberland, and have reverted to their present condition chiefly through fires, may be summarized as follows: 1. In the largest brush fields occur scattered patches or islands of virgin forest in naturally protected spots, where our knowledge of present fires shows that timber would be least susceptible to complete destruction. Also living stands of old-growth virgin timber are found immediately adjacent to brush fields and occupying similar sites. 2. Scattering living trees and snags, bearing the evidence of many fires, are not unusual in even the largest brush fields. Even in brush fields with no standing trees or snags a careful search nearly always reveals burnt remnants of tree trunks, stumps, or hollows formed by the complete burning out of stumps. 3. Repeated burnings are shown in charred remains of brush found in brush fields. 4. The woody species occurring as underbrush in the virgin forest are the same as those constituting the cover of adjacent brush fields, and brush is known to sprout after fires in which conifers have been destroyed. 5. Reproduction of coniferous species becomes established in the brush fields wherever seed trees are present and fires are absent.	Attrition theory of chaparral formation by repeated fires, but consistent with high-severity fire leaving scattered trees and unburned patches of forest in dense chaparral
Sterling (1904*a*:3)	Southern Sierra	Q107: "Here, as in the northern Sierras, the prevalence of chaparral over large areas suitable for timber growth, and undoubtedly once under forest cover, is due to repeated fires which gradually killed the seed trees and destroyed all young growth."	Attrition theory of chaparral formation by repeated fires

Table A1. Continued.

Source	Location	Quote	Interpretation
Greeley (1907:108)	Southern Sierra	Q108: "The third unfavorable feature of the west Sierra Forest is the area, large in aggregate, on which the stand is very open or has disappeared entirely. This is the effect mainly of intermittent fires which have swept the lower timber belt since early Indian times. The usual fire of this region, like the ground fires of the southern pineries, removes leaf litter and humus and kills young growth, but simply scorches the butts of larger trees. Its worst effect is the dense coppice of ceanothus, manzanita, bear clover, and other chaparral species which sprout so rapidly and thickly after a fire that the slower seedling reproduction of the Sierra conifers is largely precluded. Each successive fire leads to a denser growth of brush and harder conditions of reproduction of pine, fir, or cedar. In time, the older timber succumbs to scorching and weakening at the butt and the forest passes gradually into chaparral. All through this forest one is impressed by the enormous acreage which at some time has been forested and is capable of growing pine timber, but which is now barren or nearly barren of tree growth. Even on the forested areas, much of the stand is open and irregular. Not one-third of the productive capacity of this belt of forest land is now being utilized, and with dense patches of chaparral locking reproduction there is but little prospect of natural betterment."	Attrition theory of chaparral formation by repeated fires
Hodge (1906:64)	Whole Sierra	Q109: "The reversion of timber land to chaparral through repeated fires which kill the reproduction and eventually the seed trees, is one of the serious problems in the commercial forests."	Attrition theory of chaparral formation by repeated fires
Moore (1913:22)	Plumas National Forest	Q110: "The brush areas . . . are almost without a doubt the result of repeated fires."	Attrition theory of chaparral formation by repeated fires
Sterling (1904*b*:211–212)	Northern Sierra	Q111: "If an artificial grouping were made it would throw the chaparral into two types or classes: (1) that which has *evidently* always been in possession, (2) that which has taken possession since lumbering and fire removed or thinned the forest growth. In the one case natural causes, mainly fire, are responsible. . .In both cases the chaparral covers the sites of former forests. The first mentioned type is found mainly on the higher elevations, seldom below 4,000 feet and the best examples above 6,000, often in tracts of great extent along the summits and slopes of main ridges, and in smaller areas on lateral ridges. The second type of chaparral mentioned is found at lower elevations, and invariably in the path of lumber operations. The high brush covered ridges described as type (1) show external evidence of having been timbered; and old residents affirm that it has always been brush land because too high or too poor to produce timber. Examination, however, usually reveals the presence of old stubs and charred logs among the densest chaparral, often entirely covered with soil; while the soil conditions are as good as in the adjoining timber. From the surrounding forest blackened stubs and occasionally a decrepit tree extend out into the chaparral. These burned stubs and trees, as retreating outposts of the forest, show that timber once grew where brush now hold full sway. Each succeeding fire reduces these evidences of former timber growth, kills a few more trees along the disputed boundary, and extends the line of chaparral farther back into forest. The chaparral of the lower slopes is practically the same as the other save that it has appeared more recently, and is the direct result of lumbering followed by successive fires which killed the reproduction and the thin stand of culled timber. Fire, either with or without the aid of lumbering, is directly responsible for all chaparral, the usual sequence being a forest denuded by fire, and replaced by chaparral. The process is a gradual one, usually continuing for many years."	Attrition theory of chaparral formation by repeated fires

Table A1. Continued.

Source	Location	Quote	Interpretation
Forest structure: old-growth forest			
Hodge (1906:12)	Whole Sierra	Q112: "The forest consists of trees of all ages but the large trees have a disproportionately large representation. Most of the stands which have not been culled are long over-mature."	Old-growth forests were all aged
Hall (1909:13)	Plumas National Forest	Q113: "Type B.- Yellow pine, sugar pine, douglas fir type...this type is a mixed forest of all age classes and advance reproduction occurs fairly evenly distributed...	Old-growth forests were all-aged
Flintham (1904:109)	Southern Sierra	Q114: "...the density of the virgin fir forests, and under the dense stand the presence of all stages of reproduction development from seedling to polewood stage indicates the great tolerance of the species."	White fir forests were all-aged
Leiberg (1902:59)	North Fork of the Feather River	Q115: "The merchantable timber in the basin is mostly an old growth, varying in age from 175 to 350 years. The large yellow and sugar pine, 3 feet or over in diameter, is rarely less than 200 years of age."	Old-growth forests were 175–350 years old
Leiberg (1902:74)	Middle Fork of the Feather River	Q116: "The yellow pine on these tracts is mostly old growth; that is, the greater percentage of suitable size for mill timber is over 150 years of age."	Old-growth forests were >150 years old
Leiberg (1902:58)	North Fork of the Feather River	Q117: "From Bear Ranch Hill to Big Bar Hill ... lies a heavy block of forest, the heaviest in the basin... Both the yellow and sugar pine in this heavy block of timber are exceptionally large size and of old growth. Much of the sugar pine runs above 5 feet basal diameter, with clear trunks 40 to 60 feet in height. The trees stand well apart and are set in the midst of a rather close and low old growth of different species of oak.	An old-growth forest had exceptionally large trees
Forest structure: open forests			
Sudworth (1900:520)	Southern Sierra	Q118: "Younger forests [ponderosa pine], 40 to 60 years old, are often very dense, but later these become open by natural thinning, excessive shade, and frequent fires."	Forests were open later in succession
Sudworth (1900:520)	Southern Sierra	Q119: "Forests of large, mature timber [ponderosa pine] are rarely if ever dense; the single big trees, or groups of three to six trees, stand far apart, forming a characteristically open forest..."	Old-growth forests were open
Sudworth (1900:521)	Southern Sierra	Q120: "Like the yellow pine, the older growth of incense cedar appears in an equally open stand, having to suffer in common with the pine, and with equal resistance, the thinning effects of fire."	Old-growth forests were open
Hodge (1906:11–12)	Whole Sierra	Q121: "The forest, as a rule, is rather open but the splendid development of the trees composing it permits a heavy stand of timber."	Old-growth forests were open
Leiberg (1902:57)	North Fork of the Feather River	Q122: "From Kimshew Creek south... The trees are from medium size to large, stand well apart, and the stands have comparatively little undergrowth."	Old-growth forests were open
Leiberg (1902:58)	North Fork of the Feather River	Q123: "...in general all of the Spring Garden Creek drainage bear good stands of excellent timber, consisting of yellow and sugar pine, red and white fir, incense cedar, and oak. The stands are open and the timber is of large size..."	Old-growth forests were open
Flintham (1904:19)	Southern Sierra	Q124: "The Yellow Pine Belt... In this belt the forest presents a rather open stand in which the yellow pine occurs pure or predominant. The timber is often of large dimensions and very merchantable, but it stands rather scattered..."	Old-growth forests were open
Leiberg (1902:32)	Northern Sierra	Q125: "In the eastern and trans-Sierran districts of the region the old-growth forests of the type are generally open on all slopes except the northern and on tracts with much seepage... On the rocky slopes of canyons and in the great gorges of the rivers the forest is always very open and scattered."	Old-growth forests were open, except on north-facing and near seeps
Leiberg (1902:105)	North Fork of the Yuba River	Q126: "From Woodville Creek to Canyon Creek ... in the eastern area good stands of red [Douglas-fir] and white fir, some yellow and sugar pine of large size, incense cedar and oak; all mixed with dense undergrowth and in rather open stands..."	Old-growth forests were open, but had dense shrubs

Table A1. Continued.

Source	Location	Quote	Interpretation
Leiberg (1902:112)	Middle Fork of the Yuba River	Q127: "From Snow Tent to Graniteville most of the timber is old growth. A large amount, fully 55 per cent, is white fir, the rest is red fir [Douglas-fir], yellow pine, incense cedar, and sugar pine, named in order of abundance. On the summits of the ridges these stands present an open appearance, except where fires have invaded them, and then they are choked with dense masses of brush and littered with much fallen timber, owing to the large percentage of white fir."	Old-growth forests were open, but had dense shrubs
Leiberg (1902:58)	North Fork of the Feather River	Q128: "From Bear Ranch Hill to Big Bar Hill … lies a heavy block of forest, the heaviest in the basin… Both the yellow and sugar pine in this heavy block of timber are exceptionally large size and of old growth. Much of the sugar pine runs above 5 feet basal diameter, with clear trunks 40 to 60 feet in height. The trees stand well apart and are set in the midst of a rather close and low old growth of different species of oak."	Old-growth forests were open, except for dense oaks beneath
Leiberg (1902:165)	Middle Fork of the American River	Q129: "From the lower end of French Meadows… On the slopes west of the canyon the stands are open and consist of yellow pine, 60 to 70 per cent, small quantities of white fir and of Shasta fir."	Forests were open
Leiberg (1902:93)	South Fork of the Feather River	Q130: "Region between American House and Clipper Mill, including Mooreville Ridge: … stands comparatively open."	Forests were relatively open
Leiberg (1902:93)	South Fork of the Feather River	Q131: "Region directly south of Lumpkin: Chiefly red [Douglas-fir] and white fir … often in close stands, but more generally of open growth…"	Douglas-fir and white fir forests were generally open
Leiberg (1902:77)	Middle Fork of the Feather River	Q132: "From Dogwood Peak to Franklin Hill the forest is open on the drier slopes…"	Forests were open on drier slopes
Hall (1909:3–4)	Plumas National Forest	Q133: "Type B.- Yellow pine, sugar pine, douglas fir type… 1. Southern and western slopes… Conditions are such, however, that the timber grows at wide intervals, except in the moister, cooler draws. There are apt to be patches of bare ground or brush between trees."	Forests were open, except in moist draws
Cooper (1906:9)	Whole Sierra	Q134: "Toward its lower extension [of the yellow pine-sugar pine type] sugar pine is either very scarce or lacking, while yellow pine forms the bulk of the stand and is associated with incense cedar. The forest of this part of the type is more open, as a rule, than that higher up… The stand, at its best, is rather dense, but in most localities fire and other causes have made frequent openings in it."	Forests were open at lower elevations
Forest structure: dense forests			
Leiberg (1902:63)	North Fork of the Feather River	Q135: "Break Neck, Fish, and Last Chance creeks: Sugar pine of small size, but thick set, scattered yellow pine of large dimensions, small red and white fir…"	Forests were dense
Leiberg (1902:90)	South Fork of the Feather River	Q136: "The central portion of the basin carries the heaviest stands of timber. The trees are moderately close set."	Forests were dense
Leiberg (1902:93)	South Fork of the Feather River	Q137: "Region directly south of Lumpkin: Chiefly red and white fir…often in close stands, but more generally of open growth…"	Forests were often dense
Cooper (1906:9)	Whole Sierra	Q138: "Toward its lower extension [of the yellow pine-sugar pine type] sugar pine is either very scarce or lacking, while yellow pine forms the bulk of the stand and is associated with incense cedar. The forest of this part of the type is more open, as a rule, than that higher up… The stand, at its best, is rather dense, but in most localities fire and other causes have made frequent openings in it."	Forests were dense, but with many openings
Leiberg (1902:100)	North Fork of the Yuba River	Q139: "The young growth is in thickset stands with little underbrush,"	Younger forests were dense
Sudworth (1900:520)	Southern Sierra	Q140: "Younger forests [ponderosa pine], 40 to 60 years old, are often very dense, but later these become open by natural thinning, excessive shade, and frequent fires."	Younger forests were very dense

Table A1. Continued.

Source	Location	Quote	Interpretation
California State Board of Forestry (1888)	Plumas County	Q141: "…there remain in the county at least one million two hundred and fifty thousand acres of heavily timbered land. The dense and heavy tracts of timber numerous and it is rather difficult to intelligently locate them. There are two prominently heavy belts of timber in opposite extremes of the county… No more valuable and unbroken bodies of sugar pine, yellow pine, spruce [Douglas-fir], fir, cedar abietine [Jeffrey pine] etc. can be found in the State … these magnificent forests are practically intact."	Old-growth forests were dense
Leiberg (1902:169)	Middle Fork of the American River	Q142: "…at the head of Duncan Canyon … timber of good quality and dimensions in stands of moderate density."	Older forests were dense
Leiberg (1902:32)	Northern Sierra	Q143: "In the eastern and trans-Sierran districts of the region the old-growth forests of the type are generally open on all slopes except the northern and on tracts with much seepage. In such localities the white fir is present in large quantities and gives density to the stands. In the central district, outside the canyon areas, the forest is of moderate density and is rarely what might be called open, except in stands of very old growth. Elsewhere large quantities of white and red fir [Douglas-fir] with oak combine to form thickset stands."	Old-growth forests were dense on north-facing slopes and near seepage; Very dense stands with oak, Douglas-fir, and white fir
Leiberg (1902:77)	Middle Fork of the Feather River	Q144: "…in the region around Lava Top, Wagner, and Lumpkin… The forest here is rather thickset, especially on the wetter slopes and flats."	Forests were dense, especially on moist slopes and flats
Flintham (1904:19)	Southern Sierra	Q145: "The Yellow Pine Belt… Up the slope the pine still predominating becomes mixed with cedar, sugar pine and occasional fir forming a denser stand."	Forests were denser at higher elevations of ponderosa pine
Flintham (1904:19)	Southern Sierra	Q146: "The Sugar Pine Belt… This belt, marked by greater density, and by the presence of a heavier stand of merchantable pine timber..."	Forests were denser in sugar pine belt
Flintham (1904:109)	Southern Sierra	Q147: "…the density of the virgin fir forests, and under the dense stand the presence of all stages of reproduction development from seedling to polewood stage indicates the great tolerance of the species."	Forests were dense in white fir
Forest structure: scattered trees on rocky ground			
Leiberg (1902:57)	North Fork of the Feather River	Q148: "Above Island Bar, the west side of the canyon, where not too rocky, supports a sparse growth of oak and yellow pine…"	Forests were sparse on canyon slopes
Leiberg (1902:61)	North Fork of the Feather River	Q149: "Canyon of North Fork of Feather River: Thin, open, scattered growth of yellow pine, oak … all of poor quality."	Forests were scattered on canyon slopes
Leiberg (1902:115)	Middle Fork of the Yuba River	Q150: "Eastern portions of main canyon: Scattered yellow pine on lowest slopes, growing on rocky ground, and of inferior quality owing to stunted growth and damage by fire."	Forests were scattered on canyon slopes
Leiberg (1902:150)	North Fork of the American River	Q151: "In the main canyon the yellow-pine type is thin… The stand is thin throughout, the timber of poor quality as a rule…"	Forests were thin on canyon slopes
Leiberg (1902:100)	North Fork of the Yuba River	Q152: "On the canyon slopes with southern exposures the forest is very thin, and consists chiefly of yellow pine and oak of small size throughout."	Forests were thin on canyon slopes
Leiberg (1902:59)	North Fork of the Feather River	Q153: "…east of Grizzly Mountain carries in most places a thin forest composed largely of yellow pine and white fir. The stands are open and irregular, owing to the extremely rocky nature of the ground on most of the slopes."	Forests were open and irregular on rocky slopes
Leiberg (1902:61)	North Fork of the Feather River	Q154: "French and Berry Creek drainage: Mixed stands of yellow-pine type: thin, open growth owing to rocky soil"	Forests were thin on rocky slopes
Leiberg (1902:62)	North Fork of the Feather River	Q155: "Region around Dixie Valley: Thin stands of yellow pine, much white fir…stands set on rocky ground … timber generally of poor quality."	Forests were thin on rocky slopes
Leiberg (1902:93)	South Fork of the Feather River	Q156: "Yellow pine, sugar pine, red and white fir of medium size and quality; thin stands owing to rocky soil."	Forests were thin on rocky slopes

Table A1. Continued.

Source	Location	Quote	Interpretation
Leiberg (1902:93)	South Fork of the Feather River	Q157: "Main Canyon of South Fork of Feather River: Yellow pine, sugar pine, red and white fir of medium size and quality; thin stands owing to rocky soil..."	Forests were thin on rocky slopes
Leiberg (1902:104)	North Fork of the Yuba River	Q158: "Slate and Canyon creeks drainage: In the lower portions yellow pine, sugar pine, white fir of medium quality but thin of stand owing to fires and rocky ground..."	Forests were thin on rocky slopes
Leiberg (1902:164)	Middle Fork of the American River	Q159: "The forest is mostly yellow-pine, not having been logged; the stands are thin and scattered, everywhere broken by tracts of chaparral or rocky exposures with little soil and hardly any tree growth."	Forests were thin on rocky slopes
Forest structure: understory trees			
Leiberg (1902:43)	Northern Sierra	Q160: "The destruction of young growth by fire during the last half century must have been enormous. Let anyone who doubts this examine the sapling stands now springing up in old-growth forests where fire has been kept out during the last twelve or fifteen years...these sapling stands, composed of yellow pine, red [Douglas-fir] and white fir, and incense cedar, singly or combined, are so dense that a man can with difficulty force his way through."	Reproduction of all species was dense, unless fires
Leiberg (1902:76)	Middle Fork of Feather River	Q161: "The forest contains only a moderate amount of undergrowth if we except the sapling stands, which in some portions of Mowhawk Valley are exceedingly thick."	Reproduction was dense
Plummer (1906:6)	T005NR015E and T005NR016E	Q162: "Generally the conifers reproduce rapidly, and in many places the thickets of young trees are almost impenetrable... In the valleys and on the lower slopes the principal undergrowth is composed of the young conifers..."	Reproduction was very dense in places
Gallaher (1913:535)	Nevada County	Q163: "Burned areas offer the best seed bed and extremely dense reproduction may often be found in open burns where fire had the pathological effect of making the unkilled but badly damaged trees produce seed in large quantities."	Reproduction was very dense after high-severity fire
Hall (1909:4)	Plumas National Forest	Q164: "Type B.- Yellow pine, sugar pine, douglas fir type... 1. Southern and western slopes... Reproduction is apt to be scant in marked contrast to northern slopes. Sugar pine reproduction is scanty and only where very favorable conditions obtain. Yellow pine forms the bulk of reproduction."	Reproduction was rare on south and west slopes; sugar pine reproduction rare
Hall (1909:4)	Plumas National Forest	Q165: "Type B.- Yellow pine, sugar pine, douglas fir type... 2. Northern and eastern slopes... Reproduction on these slopes is especially good. Whenever breaks occur in the Forest cover, the young seedlings come up so thickly that for some years all are apt to be retarded in growth."	Reproduction was good on north and east slopes, dense in openings
Flintham (1904:46–49)	Southern Sierra	Q166: "Reproduction Conditions in the Pine Type... Reproduction is generally more abundant and better distributed than in higher portions of the forest, and the finest reproduction stands in the Sierras occur in parts of this type ... the best reproduction has generally occurred under the stand ... where the timber has been thinned more or less by former fire damage. The reproduction...has also generally more thrift and vigorous appearance than higher in the forest ... principally due to the better conditions for growth ... since the forest is more open, lacking generally ... the density of the fir type, and the unfavorable conditions of suppression which there retards reproduction... The best stocking of reproduction ... occurs in the lower portion of the pine type under the opener stand—nearly pure of yellow pine, while in the sugar pine belt the greater density prevents such fine reproduction..."	Reproduction was best in the Sierra in lower elevation ponderosa pine, because the forest was open
Leiberg (1902:95)	South Fork of the Feather River	Q167: "Throughout the central region reproduction is moderate, the heavy underbrush, which has come as a sequel to the numerous surface fires, preventing much seedling growth. What young growth there is consists largely of white fir..."	Reproduction, except white fir, was limited by dense chaparral

Table A1. Continued.

Source	Location	Quote	Interpretation
Sudworth (1900:555)	Southern Sierra	Q168: "The inference, however, that sheep grazing is largely, if not entirely, accountable for the lack of forage plants in these forests can not at present be made to include entirely the destruction of young seedling trees... Unquestionably many millions of tree seedlings have been trampled to death by sheep, but frequent forest fires have also gone over the same ground. With the evidence now at hand all that can be safely said is that together fires and excessive grazing have reduced the ground cover to almost nothing."	Sheep grazing and fires kept reproduction rare
Sudworth (1900:521)	Southern Sierra	Q169: "So continuous and widespread are these forest fires that, except where some natural barrier or chance has prevented, they keep a very large percentage of the seedling growth down."	Fires kept most reproduction rare
Sudworth (1900:555)	Southern Sierra	Q170: "In general, these materials limit the fires to surface burning. The destruction wrought is, however, serious. Millions of tree seedlings are destroyed annually in one or another part of the region... This young growth is killed outright save such trees as have grown high enough to escape a complete singeing. Dense stands of yellow pine 25 to 50 years old suffer a thinning every time surface fires run through them, and not infrequently the younger stands succumb entirely."	Fires kept young reproduction rare
Show and Kotok (1924:26)	Whole Sierra	Q171: "It is shown that instead of uniformly thinning the stands of seedlings and saplings, a surface fire wipes out a certain portion of the stand wherever it runs. Outside the area actually burned, and yet within the boundary of the burn as a whole, there will be a certain amount of reproduction, even though small, that is able to survive."	Fires kept reproduction rare, except in unburned areas
Show and Kotok (1924:60–61)	Whole Sierra	Q172: "Surface fires during any season of the year, under any method of control, destroy practically all seedling reproduction up to 6 feet high on areas actually burned. Since these fires are normally patchy, however, a single or even a series of light fires does not necessarily result in wiping out completely all small reproduction within the exterior boundaries of the burned area. Sapling and pole reproduction suffer less seriously."	Fires kept reproduction rare, except in unburned areas or if sapling or pole size
Flintham (1904:66)	Southern Sierra	Q173: "Severe fires of course sweep off all reproduction growth... Smaller saplings under 6 feet high appear to be uniformly killed, but larger saplings from 10 to 20 feet high are more resistant."	Fires kept reproduction rare, unless sapling size
Sudworth (1900:532)	Southern Sierra	Q174: "The reproduction of this species [California black oak] is very persistent and abundant throughout its range. Frequent surface fires damage or kill the seedlings down to the ground, but rarely injure the strong deep roots, which sprout vigorously from year to year, until one shoot grows large enough to survive burning. The hard thick bark of even young trees endures considerable scorching without damage to the tree."	California black oak reproduction was abundant, unless fire, but the oak resprouts
Sudworth (1900:526)	Southern Sierra	Q175: "Red fir [Douglas-fir] shows but little reproduction in the region of its best growth, only occasional seedlings or young trees being seen among the greater abundance of pines and cedar. Young growth is much more frequent on the sides of rocky canyons where the old trees are scattered."	Douglas-fir reproduction was rare, except on canyon slopes
Sudworth (1900:521)	Southern Sierra	Q176: "The reproduction of incense cedar appears to be equal in abundance to that of the yellow pine, especially in the drier situations..."	Incense cedar reproduction was abundant
Flintham (1904:99–100)	Southern Sierra	Q177: "Small reproduction [of incense cedar] started under cover is capable of enduring heavy shade for years, and though the growth is slow and retarded, reproduction will push up slowly into large sapling size under the stand or through overtopping brush,–in this endurance and ability having the advantage over the young growth of any species but the fir in the forest.... Often where it is far outnumbered as a seed tree by other species in the stand, it has established the most abundant reproduction ... The species...is perhaps the most successful Sierra species in the establishment and growth of its reproduction."	Incense cedar reproduction was persistent and the most successful in the forest

Table A1. Continued.

Source	Location	Quote	Interpretation
Sudworth (1900:525)	Southern Sierra	Q178: "The reproduction of Jeffrey pine is observable everywhere in the vicinity of old trees in its lower range, but is nowhere abundant. At higher altitudes, however, seedlings and young trees are frequent."	Jeffrey pine reproduction occurred near old trees, and at higher elevation
Sudworth (1900:520)	Southern Sierra	Q179: "The reproduction of this pine [ponderosa pine] is remarkably persistent and abundant wherever it is not checked by fires and the excessive trampling of grazing herds…"	Ponderosa pine reproduction was abundant, unless fires
Sudworth (1900:520–521)	Southern Sierra	Q180: "The frequent open spaces in yellow-pine forests are sooner or later covered with dense patches of young trees, but these thickets may in turn be swept off by fire. Hence, with the added damage done by other agencies, the general impression is that there is little reproduction of this pine. The forest floor looks clean swept. But the remarkable reproductive power of this pine is seen only in localities where fences and the exclusion of fire have protected the incoming seedlings. Here the stand is so dense as to be quite impenetrable."	Ponderosa pine reproduction was very dense, unless fires
Hall (1909:4)	Plumas National Forest	Q181: "Type B.- Yellow pine, sugar pine, douglas fir type… 3. Yellow pine sub-type… Reproduction of the pine is good but apt to occur in thich [sic] patches then [sic] scattered…"	Ponderosa pine reproduction was more often dense
Moore (1913:10)	Plumas National Forest	Q182: "Yellow Pine… Reproduction is, on the whole, good. On benches or flats it comes in thickly in all open spaces, even in large ones. On the drier slopes it starts in the openings in the protection of the brush or California black oak and, to a certain extent, in the bare places."	Ponderosa pine reproduction was good, dense in openings
Flintham (1904:64)	Southern Sierra	Q183: "Under the open stand [ponderosa pine] in some localities where a light ground fire has run over the litter and bared the soil or left some layer of charcoal upon it, germination has been very fine, and a heavy stocking of seedlings often established."	Ponderosa pine reproduction was favored by fire
Moore (1913:12)	Plumas National Forest	Q184: "Yellow Pine-Fir… Reproduction is good, all species being well represented. That of yellow pine predominates in the larger openings or drier situations, that of Douglas fir and white fir under the pine, in smaller openings, and on moist situations. Incense cedar reproduces scatteringly and in small patches throughout the type."	Ponderosa pine reproduction was in large openings and on dry sites; White fir and Douglas-fir on moist sites and in small openings; Incense cedar was scattered
Moore (1913:11)	Plumas National Forest	Q185: "Mixed Conifers… The reproduction is good. It is scarce or lacking only in stands repeatedly burned, and on very thin, dry, burned over rocky soil. Even on the most unfavorable sites if fire is kept out the reproduction will be ample to replace the present stand … white fir predominates in the smaller openings, yellow pine in the larger … the moister patches of soil favoring the firs against the pine."	Ponderosa pine reproduction was in large openings and on dry sites; White fir and Douglas-fir on moist sites and in small openings;
Flintham (1904:50)	Southern Sierra	Q186: "The reproduction [in the yellow pine belt of the pine type] is often occurring in tall undergrowth (chaparral) of considerable density, which is pushed in under the open cover of the lower forest … the black oak … has played an important part as a nurse for the reproduction of all the different species of this type. The yellow pine … is generally the most abundantly reproduced and distributed, though areas of the cedar, but slightly mixed with the pine, often occur very densely stocked."	Ponderosa pine reproduction, at times with incense cedar, could be dense under chaparral and oak
Leiberg (1902:33)	Northern Sierra	Q187: "The type [yellow-pine] as a whole is maintaining its territorial extensions, but the relative proportions of its species is undergoing a decided change. The principal variations consist of a greatly lessened percentage of sugar pine, a decided increase in yellow pine in the northern portion of the central district of the region, and a uniform increase throughout all the areas in the proportion of incense cedar and white fir, with a corresponding decrease of yellow pine. The changes are due to logging operations and fire."	Ponderosa pine and sugar pine reproduction was declining, white fir and incense cedar increasing due to logging and fire

Table A1. Continued.

Source	Location	Quote	Interpretation
Sudworth (1900:522)	Southern Sierra	Q188: "The reproduction of sugar pine is evident throughout the range of the species. Moderate numbers of seedlings and saplings are always to be found in the vicinity of old trees and are usually mingled with the young growth of other timber trees. There is a marked difference between the persistent, prolific reproduction of yellow pine and the slower, less aggressive advance of the sugar pine."	Sugar pine reproduction was moderate, especially near old trees
Cooper (1906:17)	Whole Sierra	Q189: "In small openings in the virgin stand and along the edges of roads or broad trails cut through the virgin forest the conditions for sugar pine seem most favorable. Such conditions are usually very quickly filled with young growth of all species. . ."	Sugar pine reproduction and others were favored along roads and trails
Greeley (1907:106)	Southern Sierra	Q190: "Where sugar pine seedlings and saplings occur at all they are usually in groups under broken cover or in narrow openings in the stand. On the same sites fir and cedar crowd the sugar pine closely and bunches or large patches of these species occur in among the groups of sugar pine. Yellow pine, in this mixed forest, seeks the drier and warmer sites on the tops of ridges and southern exposures. Here it also is commonly found in large even-aged groups, from open bunches of mature trees to thickets of saplings and seedlings."	Sugar pine reproduction was rare except under openings; white fir and Douglas-fir in patches; ponderosa pine on drier sites, at times in thickets
Flintham (1904:81)	Southern Sierra	Q191: "It [sugar pine] is rarely a heavy component in the seed-tree stand, and often, due to unfavorable conditions in some localities, reproduction is very scanty under the stand, and the species seems to be hardly reproducing."	Sugar pine reproduction was scanty
Leiberg (1902:158)	North Fork of the American River	Q192: "Throughout the yellow-pine forest there is a noticeable deficiency of sugar pine and an abnormal increase of incense cedar. . . The yellow pine is holding its own . . . white and red fire [Douglas-fir] show no great change."	Sugar pine reproduction was deficient, incense cedar increasing
Greeley (1907:108)	Southern Sierra	Q193: "Except at lower elevations and on very warm exposures, where yellow pine grows in pure stand, dense thickets of fir and cedar crowd the young pine down to one fifth or less of the reproduction."	White fir, Douglas-fir and incense cedar reproduction was in dense thickets, ponderosa pine rarer, except on driest sites
Sudworth (1900:524)	Southern Sierra	Q194: "The reproduction of white fir is very general over the range of the species, and in some sections the young growth is exceedingly abundant. Thickets of seedlings and saplings are often found covering many acres, and to the exclusion of all other species. In locations where other young growth is present the white fir may comprise 40 to 60 per cent of the whole growth. The wonder is that mature trees of this species are not more abundant. But when fires occur, the richly resinous foliage and branches of the young growth suffer more severely than the pines or cedars. Owing to thinness of foliage and less resin, a few of the latter may escape fatal burning; but it is rare than any of a low thicket of firs ever survives even a surface fire."	White fir reproduction was common and very dense over some large areas, unless fires
Flintham (1904:54–55)	Southern Sierra	Q195: "The fir [white fir] forest abundantly reproduces itself, but the amount of reproduction varies with the degree of density, bearing a very close relation to the light conditions under the stand. . . Areas densely stocked with small seedling reproduction may be found very generally on the forest floor . . . though frequently stunted and suppressed by reason of the heavy shade, but small proportion of the seedlings surviving to reach sapling size. Many seedling areas, however, grow up into the densely crowded sapling groups frequently found. . . Partly suppressed bunches of close-crowding reproduction is a characteristic appearance under the fire forests. . ."	White fir reproduction was abundant and generally dense

Table A1. Continued.

Source	Location	Quote	Interpretation
Flintham (1904:113)	Southern Sierra	Q196: "Reproduction under the stand [white fir] is rarely well distributed, starting in bunches located by favorable condition for seedling growth and germination... Areas of dense small sapling growth—1 to 2 or 3 feet high and ten to twenty years old are often noted, grown up from densely stocked seedling areas..."	White fir reproduction was patchy but dense
Flintham (1904:51)	Southern Sierra	Q197: "The denser forest [in the sugar pine belt of the pine type] has generally prevented heavy stocking of young growth, and fine reproduction bodies are hardly to be noted... The yellow pine ... is here but scantily established... Sugar pine is at best but scantily reproduced, mixed sparingly with the more abundant sapling reproduction of white fir and cedar, which make up the bulk of the reproduction occurring in this type."	White fir and incense cedar reproduction was most abundant in denser forests of sugar pine belt; ponderosa pine and sugar pine reproduction scanty
Forest structure: understory shrubs			
Dudley (1896:260)	Sierra Forest Reserve, Tulare County	Q198: "The general testimony of the mountain and foot-hill people in regard to the changes which had occurred during the past ten or twenty years in the vegetation of the mountains was not uninteresting. They assert that the undergrowth in the mountain forests has greatly decreased since sheep-herding came into the mountains. At present one can ride his horse anywhere through these high mountain forests, excepting in the inaccessible rocky places; while twenty years since it would have been almost impossible to have wandered far from the trails, on account of the underbrush, undoubtedly more dense than in the Northern Sierras."	Understory by late 1890s had been reduced by sheep grazing, was dense historically
Sudworth (1900:554–555)	Southern Sierra	Q199: "...the principal forage for sheep and cattle on the open forest range consists of a few very hardy shrubs and low broad-leaf trees. There are practically no grasses or other herbaceous plants. The forest floor is clean... Barrenness is, however, not an original sin. From a study of long-protected forest land in the same region, and from the statements of old settlers, it is evident that formerly there was an abundance of perennial forage grasses throughout the forests of this territory. A dense growth of these grasses and many other herbaceous plants are plentiful now in all long-protected forests, whether grazed or not by cattle and horses... It would seem that this bare condition of the surface in the open range has been produced only through years of excessive grazing by millions of sheep—a constant overstocking of the range."	Understory by 1900 had been reduced by livestock grazing, was dense grasses and herbaceous plants historically
Leiberg (1902:57)	North Fork of the Feather River	Q200: "From Kimshew Creek south... The trees are from medium size to large, stand well apart, and the stands have comparatively little undergrowth."	Understory was sparse in open forests
Leiberg (1902:74)	Middle Fork of the Feather River	Q201: "Below 5,500 feet the forest is open; there is little undergrowth and only small quantities of litter ... while humus is almost absent."	Understory was sparse in open forests
Dudley (1896:260)	Sierra Forest Reserve, Tulare County	Q202: "In the pine and fir belt, the underbrush is largely wanting, except in rocky or damp places, so that beautiful stretches of open ground under the trees often appear; or perhaps long, gentle slopes, only carpeted by the squaw-mat (*Chamaebatia foliolosa*)... In the more rocky places are large patches of the blue brush (a species of *Ceanothus*), of the chincapin, and the shrubby wild cherry. Between these patches the ground is sometimes bare, sometimes covered with small annual plants."	Understory was lacking, except on rocky and moist sites which had chaparral
Fitch (1900*b*:571)	Yosemite area	Q203: "The forest is remarkably free from undergrowth, however, and only along streams, in the bottom of gulches, and on rocky southern slopes is the brush so thick as to impede progress."	Understory was lacking, except where dense along streams, in gulches and on south slopes

Table A1. Continued.

Source	Location	Quote	Interpretation
Hodge (1906:14)	Whole Sierra	Q204: "In the open forest, chaparral still forms an interrupted ground cover but in the sense [sic] forest it may be entirely lacking."	Understory was chaparral in open forest, lacking in dense forest
Leiberg (1902:32)	Northern Sierra	Q205: "With the exception of the tracts north and east of Sierra Valley, the eastern area of Truckee Basin north of Mount Pluto ridge, and the thickset restockings of young growth in the central districts of the region, there is a great amount of undergrowth in the forest which has attained its present proportions chiefly through the agency of fires. Most of it consists of species of ceanothus, collectively named 'buckbrush' by the inhabitants of the region.	Understory was chaparral in open forest due to fire, lacking in dense young forest
Flintham (1904:19)	Southern Sierra	Q206: "The Yellow Pine Belt... There is frequently a heavy mixture of black oak occurring as an understory to the pine, and chaparral, frequently quite heavy within the forest margin, often undergrows the stand."	Understory was chaparral, dense on forest margin
Plummer (1906:6)	T005NR015E and T005NR016E	Q207: "... on the summits and ridges, where yellow pine is found in its typical open stand, there is considerable *ceanothus* and *arctostaphylos*.	Understory was dense chaparral in open forests
Cooper (1906:9)	Whole Sierra	Q208: "Underbrush is seldom thick, except in openings. Where it exists it is made up of various species of manzanita and ceanothus, together with coffeeberry (*Rhamnus crocea*) and several other species."	Understory was chaparral, not dense, except in openings

Appendix B

Table B1. Latin names for trees and tall shrubs used as bearing trees by surveyors and names used by surveyors.

Latin names	Names used by surveyors
Firs	
Abies concolor (Gord. & Glend.) Lindl. ex Hildebr. var. *lowiana* (Gord. & Glend.) Lemmon, occasionally *A. magnifica*	White fir, fir
Abies magnifica A. Murray bis	Red fir, Shasta fir
Pseudotsuga menziesii (Mirb.) Franco	Spruce, Douglas-fir
Pines	
Pinus contorta Douglas var. *murrayana* (Balf.) Engelm.	Tamarack, hackmetack
Pinus jeffreyi Balf.	Jeffrey pine, Norway pine, Abertine
Pinus lambertiana Douglas	Sugar pine, S. pine, Sug. pine
Pinus monticola Douglas ex. D. Don	White pine
Pinus spp.	Pine, black pine, rock pine
Pinus–piñons	Nut pine
Pinus ponderosa Lawson and C. Lawson (pitch pine sometimes *P. jeffreyi*)	Yellow pine, Yel. pine, Pitch pine
Other conifers	
Calocedrus decurrens (Torr.) Florin	Cedar, incense cedar
Juniperus occidentalis Hook.	Juniper
Sequoia sempervirens (Lamb. ex D. Don) Endl.	Redwood, Sequoia, living giant
Tsuga mertensiana (Bong.) Carrière	Hemlock
Hardwoods	
Acer spp.	Maple, soft maple
Aesculus californica (Spach) Nutt.	Buckeye
Alnus incana (L.) Moench ssp. *tenuifolia* (Nutt.) Breitung, *A. rhombifolia* Nutt.	Alder, black alder
Arctostaphylos, likely often *A. viscida* Parry	Manzanita
Arbutus menziesii Pursh	Madrone
Cercocarpus (likely *C. ledifolius* Nutt.)	Mahogany
Cornus nuttallii Audubon ex Torr. & A. Gray	Dogwood
Fraxinus spp.	Ash
Notholithocarpus densiflorus (Hook. & Arn.) P.S. Manos, C. H. Cannon, and S. H. Oh	Tan oak
Platanus racemosa Nutt.	Sycamore
Populus fremontii S. Watson, *P. balsamifera* L. ssp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw	Balsam, cottonwood, poplar, balm

Table B1. Continued.

Latin names	Names used by surveyors
Populus tremuloides Michx.	Aspen, quaking aspen
Prunus emarginata (Douglas ex Hook.) D. Dietr.	Cherry
Prunus subcordata Benth.	Red oak (surveyor was mistaken)
Quercus chrysolepis Liebm.	Live oak, scrub oak
Quercus spp.	Oak, Am oak, pigeon oak, post oak, water oak, white oak, yellow oak
Quercus kelloggii Newberry	Black oak, Bk oak, Blk oak, pin oak
Salix spp.	Willow
Umbellularia californica (Hook. & Arn.) Nutt.	Pepperwood

Notes: Nomenclature generally follows USDA Plants: http://plants.usda.gov. Uncertain common names were identified by revisiting section corners and relocating the actual tree or by revisiting section lines where the tree was reported to have been common. Common names that could not be identified using these approaches (e.g., many oaks) were assigned only to a genus (e.g., *Quercus*).

Table B2. Shrub names used by surveyors in line data and Latin names.

Shrub names used by surveyors	Latin names
Bearberry/bear bush	*Chamaebatia foliolosa* Benth.
Birch/birch brush/sweet birch/lilac	*Ceanothus integerrimus* Hook. & Arn. and *C. parvifolius* (S. Watson) Trel. in southern Sierra
Black laurel	*Leucothoe davisiae* Torr. ex A. Gray
Blue brush	*Ceanothus integerrimus* Hook. & Arn. and *C. parvifolius* (S. Watson) Trel. in southern Sierra
Buck brush	*Ceanothus cordulatus* Kellogg, occasionally *C. cuneatus* (Hook.) Nutt. at lower elevations
Buckeye	*Aesculus californica* (Spach) Nutt.
Buckthorn	*Ceanothus cordulatus* Kellogg
Chamisal/Chamoise	*Adenostoma fasciculatum* Hook. & Arn.
Chaparral	*Ceanothus integerrimus* Hook. & Arn. primarily, but also occasionally *C. cordulatus* Kellogg
Cherry/wild cherry	*Prunus emarginata* (Douglas ex Hook.) D. Dietr.
Chincapin	*Chrysolepis sempervirens* (Kellogg) Hjelmqvist
Coffeeberry	*Rhamnus* L. spp.
Currant bush/gooseberry	*Ribes* spp., mostly *R. roezlii* Regel
Deer brush	*Ceanothus integerrimus* Hook & Arn.
Dogwood	*Cornus nuttallii* Audubon ex Torr. & A. Gray
Elm	*Celtis laevigata* Willd. var. *reticulata* (Torr.) L.D. Benson?
Greasewood	*Adenostoma fasciculatum* Hook. & Arn.
Ground oak	*Quercus vacciniifolia* Kellogg
Hawthorn	*Crataegus* spp.
Hazel	*Corylus cornuta* Marshall var. *californica* (A. DC.) Sharp
Huckleberry oak	*Quercus vacciniifolia* Kellogg
Laurel	*Ceanothus velutinus* Douglas ex Hook.
Mahogany	*Cercocarpus* spp.
Manzanita	*Arctostaphylos patula* Greene generally, *A. viscida* Parry at lower elevations
Maple brush	*Acer* spp.
Mountain ash	*Sorbus scopulina* Greene
Mountain whitethorn	*Ceanothus cordulatus* Kellogg
Pepperwood	*Umbellularia californica* (Hook. & Arn.) Nutt.
Plum/wild plum	*Prunus subcordata* Benth.
Poison oak	*Toxicodendron diversilobum* (Torr. & A. Gray) Greene
Sagebrush	*Artemisia* spp.
Scrub oak	*Quercus chrysolepis* Liebm., *Q. berberidifolia* Liebm., *Q. wislizeni* A. DC.
Snowbrush, white thorn, thorn	*Ceanothus cordulatus* Kellogg
Sweet birch	*Ceanothus integerrimus* Hook & Arn.
White thorn, thorn	*Ceanothus cordulatus* Kellogg
Whortleberry bush	*Vaccinium* spp.
Wild cherry	*Prunus emarginata* (Douglas ex Hook.) D. Dietr.
Wild lilac	*Ceanothus integerrimus* Hook. & Arn. and *C. parvifolius* (S. Watson) Trel. in southern Sierra
Wild plum	*Prunus subcordata* Benth.
Willow	*Salix* spp.

Note: Nomenclature follows USDA Plants: http://plants.usda.gov

APPENDIX C

Table C1. Quality of information recorded by surveyors of the western Sierra Nevada Mountains. Analysis of specific columns used only entries that are “Yes” or “Good,” “Very good,” or “Excellent.”

Surveyor	Recorded vegetation density	Recorded understory trees	Recorded understory shrubs	Recorded understory density	Recorded chaparral entry/exit	Line length surveyed (km)
North Sierra						
Major (>75 km)						
J. A. Benson	Yes	No	Good	Yes	Yes	130.3
L. D. Bond	Yes	Yes	Very good	Yes	No	596.9
Henry S. Bradley	Yes	Yes	Fair	Yes	Yes	338.1
William Burton	Yes	Yes	Excellent	Yes	Yes	93.4
James E. Freeman	Yes	No	Poor	Yes	Yes	367.4
James R. Glover	Yes	No	Very good	Yes	Yes	329.6
D. C. Hall	Yes	Yes	Good	Yes	Yes	264.5
John M. Ingalls	Yes	Yes	Fair	Yes	Yes	183.5
Arthur W. Keddie	Yes	Yes	Very good	Yes	Yes	119.4
Albert A. Smith	Yes	No	Poor	Yes	Yes	112.0
T. H. Ward	Yes	Yes	Poor	Yes	Yes	127.1
Minor (<75 km)						
J. M. Anderson	No	No	No	No	No	29.7
A. W. Brown	No	Yes	Poor	No	No	18.9
E. Dyer	No	No	Good	No	No	5.0
W. F. Ingalls	Yes	Yes	Good	Yes	No	9.6
C. P. Putnam	Yes	Yes	Good	Yes	Yes	28.3
James L. Trask	Yes	No	Poor	Yes	Yes	44.5
South Sierra						
Major (>75 km)						
James M. Anderson	Yes	Yes	Good	Yes	Yes	499.0
A. B. Beauvais	Yes	Yes	Very good	No	Yes	78.2
George S. Collins	Yes	Yes	Very good	Yes	No	202.0
James R. Glover	Yes	Yes	Good	Yes	Yes	285.3
John D. Hall	Yes	Yes	Good	Yes	Yes	121.8
S. A. Hanson	No	Yes	Good	No	No	612.9
Jarvis Kiel	Yes	Yes	Good	Yes	No	89.4
P. M. Norboe	Yes	Yes	Very good	Yes	Yes	273.9
W. H. Norway	Yes	Yes	Very good	Yes	No	321.9
C. F. Putnam	Yes	Yes	Fair	Yes	No	133.5
Minor (<75 km)						
P. Y. Baker	Yes	Yes	Good	Yes	No	11.7
Charles S. Collins	Yes	Yes	Very good	Yes	No	3.5
J. C. Fairchild	No	No	Poor	No	Yes	9.6
A. T. Herrmann	Yes	No	Very good	No	No	44.5
Mark Howell	Yes	Yes	Very good	Yes	No	51.6
Archibald McNeil	Yes	Yes	Fair	No	No	36.2
William Minto	Yes	No	Poor	Yes	Yes	8.0
Seth Smith	No	Yes	Poor	No	No	18.9

Appendix D

Table D1. Crown radius and Voronoi equations used in the reconstructions.

Species or group	Ln crown radius†	n	R^2_{adj}	Ln Voronoi area‡	n	R^2_{adj}
Abies concolor	−0.695 + 0.499 ln (dbh)	36	0.77	−0.161 + 0.768 ln (CR/(1/Meandist^2))	35	0.75
Calocedrus decurrens	−0.903 + 0.549 ln (dbh)	34	0.72	0.303 + 0.659 ln (CR/(1/Meandist^2))	34	0.61
Pinus jeffreyi	−0.375 + 0.443 ln (dbh)	10	0.66	−1.930 + 1.070 ln (CR/(1/Meandist^2))	10	0.95
Pinus lambertiana	−1.160 + 0.646 ln (dbh)	28	0.79	−0.275 + 0.754 ln (CR/(1/Meandist^2))	28	0.52
Pinus ponderosa	−1.140 + 0.615 ln (dbh)	31	0.74	0.342 + 0.650 ln (CR/(1/Meandist^2))	29	0.82
Pseudotsuga menziesii	−0.175 + 0.420 ln (dbh)	30	0.64	−0.231 + 0.702 ln (CR/(1/Meandist^2))	29	0.64
Quercus kelloggii§	0.693 + 0.271 ln (dbh)	31	0.21	−0.299 + 0.677 ln (CR/(1/Meandist^2))	30	0.63
"Fir"	−0.390 + 0.450 ln (dbh)	81	0.74	−0.522 + 0.785 ln (CR/(1/Meandist^2))	132	0.67
"Pine"	−1.070 + 0.605 ln (dbh)	93	0.67	0.409 + 0.635 ln (CR/(1/Meandist^2))	68	0.74
All species (pooled)	−0.711 + 0.523 ln (dbh)	206	0.70	−0.299 + 0.752 ln (CR/(1/Meandist^2))	204	0.69

† dbh = diameter at breast height (1.37 m).
‡ Meandist is a measure of local tree density, based on the mean distance among the four trees at the section corner.
§ Equations are shown for *Q. kelloggii*, but the crown-radius fit was poor, thus the "all species" equation was used instead.

Appendix E

Analysis of human-effect zones at the time of the surveys

I estimated buffer widths that represent the effect zone around each land use, so that I could use this to find the area less affected by Euro-American land uses. I used historical descriptions of land uses (e.g., Sudworth 1900, Leiberg 1902, Laudenslayer and Darr 1990, McKelvey and Johnston 1992, Gruell 2001, Beesley 2004), combined with more general analyses of effect zones for specific land uses (e.g., Forman et al. 2003), and a buffer analysis of an indicator of disturbance. The indicator is the area of patches of montane chaparral, which were observed to be created directly by logging as well as indirectly by high-severity fires spreading from ignitions by people or lightning fires in logging slash (Leiberg 1902, Show and Greeley 1926). I reasoned that, if more chaparral area occurred in the vicinity of a land use than in the larger study area, that is an added indicator of an effect-zone for the land use.

The effect zone is not known for many land-uses and only roughly known in general, and I am buffering line data which do not intersect all land-uses. Thus, I erred toward including too much area to increase the probability of approximating the complementary less-affected area.

I began with hypotheses about the width of effect zones for each land use. I expected a 100-m buffer around water-system features (ditches and reservoirs), as trees were likely not extensively removed near these features. I expected 200-m buffers around roads and trails, in part based on Forman et al. (2003), but also early photographs that show varying, but limited impact on forests near roads (Gruell 2001). I expected a 3220-m buffer (2 miles) around railroads, because Leiberg (1902:39) said: "...a strip about 4 miles wide, from Truckee to Colfax, paralleling the Southern Pacific Railroad, is said to have yielded up its forest chiefly to supply the locomotives...," also mentioned in McKelvey and Johnston (1992). However, this may be an overestimate of the effect zone, as Gruell (2001) showed that in six of seven early photographs of the Central Pacific Railroad line, logging occurred in the railroad right-of-way, but not on nearby slopes.

I expected a 1000-m buffer around farms, ranches, and buildings, assuming that individuals may have most sought and transported fuel wood and building materials within this distance, but would be unlikely to burn near their infrastructure. Around sawmills, I expected a 2414-m buffer (1.5 miles), based on Beesley (2004), who suggested that early Sierran sawmills typically would cut timber within a 2.5- to 3-mile circle before moving to a new location, also suggested by Berry (1917). However, Sudworth (1900:513) said: "A common practice of mill operators is to consume all saw timber in a radius from the plant of 2 1/2 to 3 miles, and then move to another site." Around mining operations, I hypothesized only a 1000-m buffer. Mine timbers and wood for other uses were often supplied by sawmills, not by the mining opera-

Table E1. Estimated human-affected section-line lengths and areas.

		Northern Sierra				Southern Sierra			
Land use category	Buffer (m)	*n*	Length (km)	Percent of total	Area in buffer (ha)†	*n*	Length (km)	Percent of total	Area in buffer (ha)†
Railroad	3218	17	0.34	0.33	15,782	1	0.02	0.22	…‡
Transportation	200	…	…	…	10,801	…	…	…	3,469
Road	…	657	13.72	13.30	…	102	2.04	22.57	…
Trail	…	302	6.04	5.86	…	178	3.56	39.38	…
Bridge	…	1	0.02	0.02	…	0	0.00	0.00	…
Total	…	960	19.78	19.18	…	280	5.60	61.95	…
Water system	100	…	…	…	2,439	…	…	…	37
Ditch	…	801	15.99	15.50	…	11	0.20	2.21	…
Reservoir	…	10	0.32	0.03	…	0	0.00	0.00	…
Total	…	811	16.31	15.53	…	11	0.20	2.21	…
Ranch/farm	1000	…	…	…	26,680	…	…	…	9,198
Farm/field	…	50	10.33	10.01	…	2	1.09	12.06	…
Fence	…	149	2.89	2.89	…	44	0.89	9.85	…
Ranch/pasture	…	2	0.07	0.07	…	1	0.17	1.89	…
Total	…	201	13.38	12.97	…	47	2.15	23.78	…
Building	1000	145	2.89	2.80	30,337	39	0.85	9.40	9,971
Logging/sawmill	4000	37	33.74	32.71	64,563	8	0.16	1.77	20,760
Mining	1000	153	16.67	16.16	30,765	3	0.06	0.67	826
Miscellaneous	…	2	0.04	0.04	…	0	0.00	0.00	…
Grand total	…	2326	103.15	100.00	…	389	9.04	100.00	…
Human-affected lines	…	…	103.2	3.7	…	…	9.0	0.3	…
Remainder of lines	…	…	2694.4	96.3	…	…	2836.1	99.7	…
Total lines	…	…	2797.5	100.0	…	…	2845.2	100.0	…

† Areas inside buffers may overlap among land uses, so cannot be summed at the bottom of the column.
‡ An ellipsis (…) indicates that data were not available or an entry would not be appropriate.

tions themselves (Beesley 2004). Early photos show that local removal of timber near some larger mining operations could extend beyond 1000 m, but in many other cases the forest appears to have remained unaltered even within 100 m of mining operations (Gruell 2001), thus 1000 m may be a high estimate of the average width of the effect zone.

To refine these hypotheses, I buffered each occurrence of every land use (Table E1) using buffers of 100 m, 200 m, 500 m, and 1000 m and larger buffers mentioned above for specific land uses, then tested whether the percentage of chaparral area inside the buffered area exceeded the percentage of chaparral area in the study area, suggesting a concentration in the buffer area. To ensure a sufficient sample, I only completed the analysis if there were at least 10 occurrences of the land use and the area inside the buffered land use exceeded 1000 ha. If an effect was observed at a particular buffer width, I expanded the buffer width to further investigate the extent of an effect zone. After reviewing the results of this buffer analysis of chaparral patches, I finalized buffer widths, buffered each land use and measured its area, then merged all the buffers into a single map of buffered human effects.

Some potentially indirect effects on forest structure cannot be spatially modeled. Fires were reportedly started by sheep herders moving across these landscapes in the late-1800s (Leiberg 1902, McKelvey and Johnston 1992), although this effect may have been overestimated by early observers (Vankat and Major 1978). Excessive grazing by livestock, widely evident by A.D. 1900 (Leiberg 1902, Vankat and Major 1978) may have reduced fine fuels enough by the time of the surveys to have also reduced fire spread. I could not model effect zones from these mobile or undefined sources, as they extend for unknown distances or from unknown locations.

Combined human effects, in terms of their length along section lines, are more than ten times greater in the northern Sierra than the southern Sierra (Table E1). The buffer analysis of chaparral percentage shows sawmills had a substantial effect near the mill and a detectable effect extended beyond the hypothesized 2414 m, so I extended the buffer to 4000 m, where the level of chaparral is similar to the study area (Fig. E1a). This 4000 m distance (about 2.5 miles) is

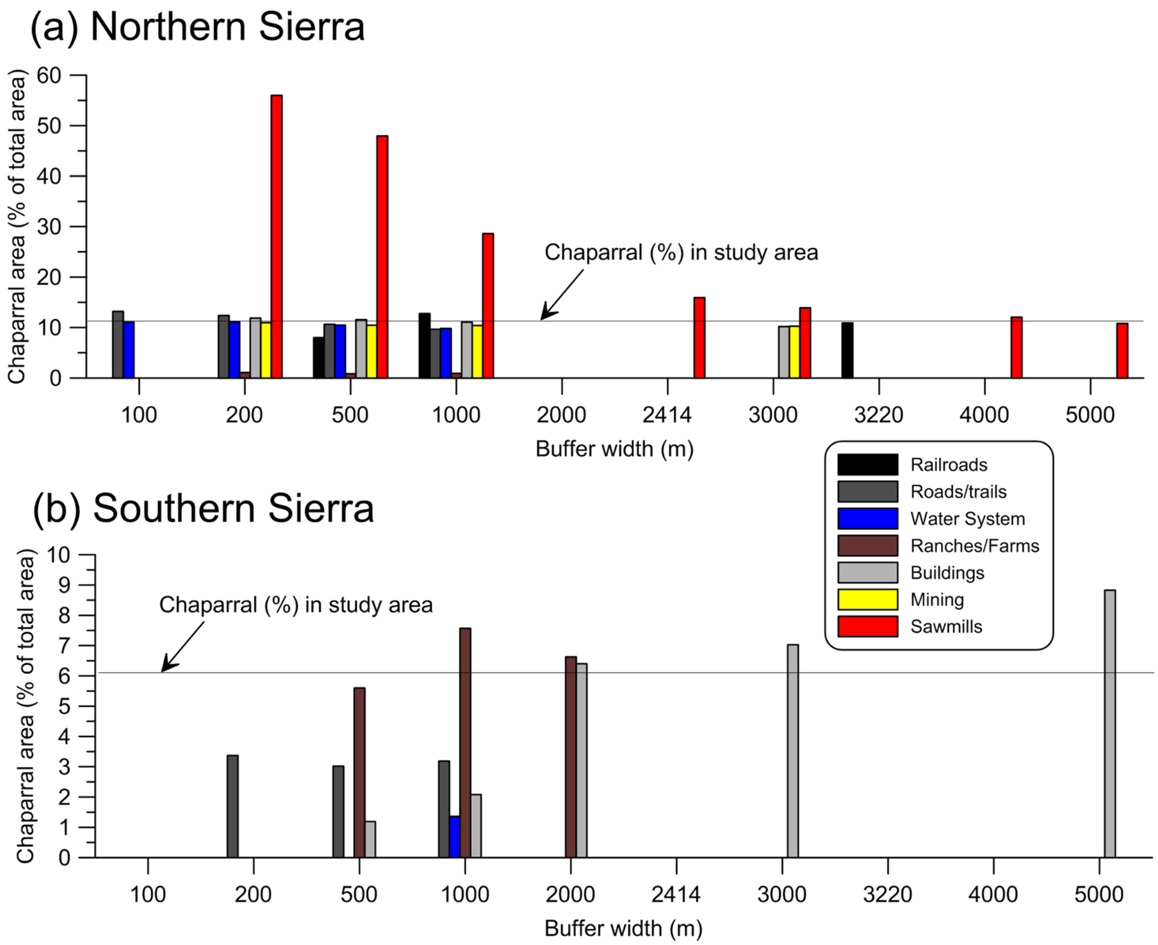

Fig. E1. Expected and observed chaparral area in potential effect zones for seven land-uses in the (a) northern and (b) southern Sierra Nevada study areas. The expected percentage is the percentage of chaparral in the study area as a whole.

remarkably similar to the 2.5 to 3 mile radius that Sudworth (1900:513) suggested, which validates his observation and also this buffer analysis approach. Slightly more chaparral occurs in the railroad buffer of 1000 m but not in the hypothesized 3220 m buffer (Fig. E1a), but because of Leiberg's quote, I decided to leave the buffer at 3220 m. Although ranches and farms showed slightly elevated chaparral within 1000 m in the southern Sierra, they showed much less chaparral than expected in the northern Sierra, so I left the buffer at 1000 m. People may generally, but not always have been successful in avoiding fires and other disturbances near their ranches and farms. Similarly, there was no elevated chaparral within 1000–3000 m buffers in the northern Sierra, but there is slightly elevated chaparral in 2000–5000 m buffers in the southern Sierra. Looking at the map, it appears possible that one fire could have been ignited and escaped from near buildings in the southern Sierra, but more likely the buildings happened to be near a wildfire. Since there were four times as many ranches and farms in the analysis of the northern Sierra, I left the buffer at 1000 m for buildings. Road-and-trail buffers of 100 m and 200 m have very slightly elevated chaparral in the northern Sierra, but not in the southern Sierra, thus I left the buffer at 200 m. As hypothesized, there is no detectable effect from water systems or mining, but I left buffers at 100 m and 1000 m, respectively, to err on the side of

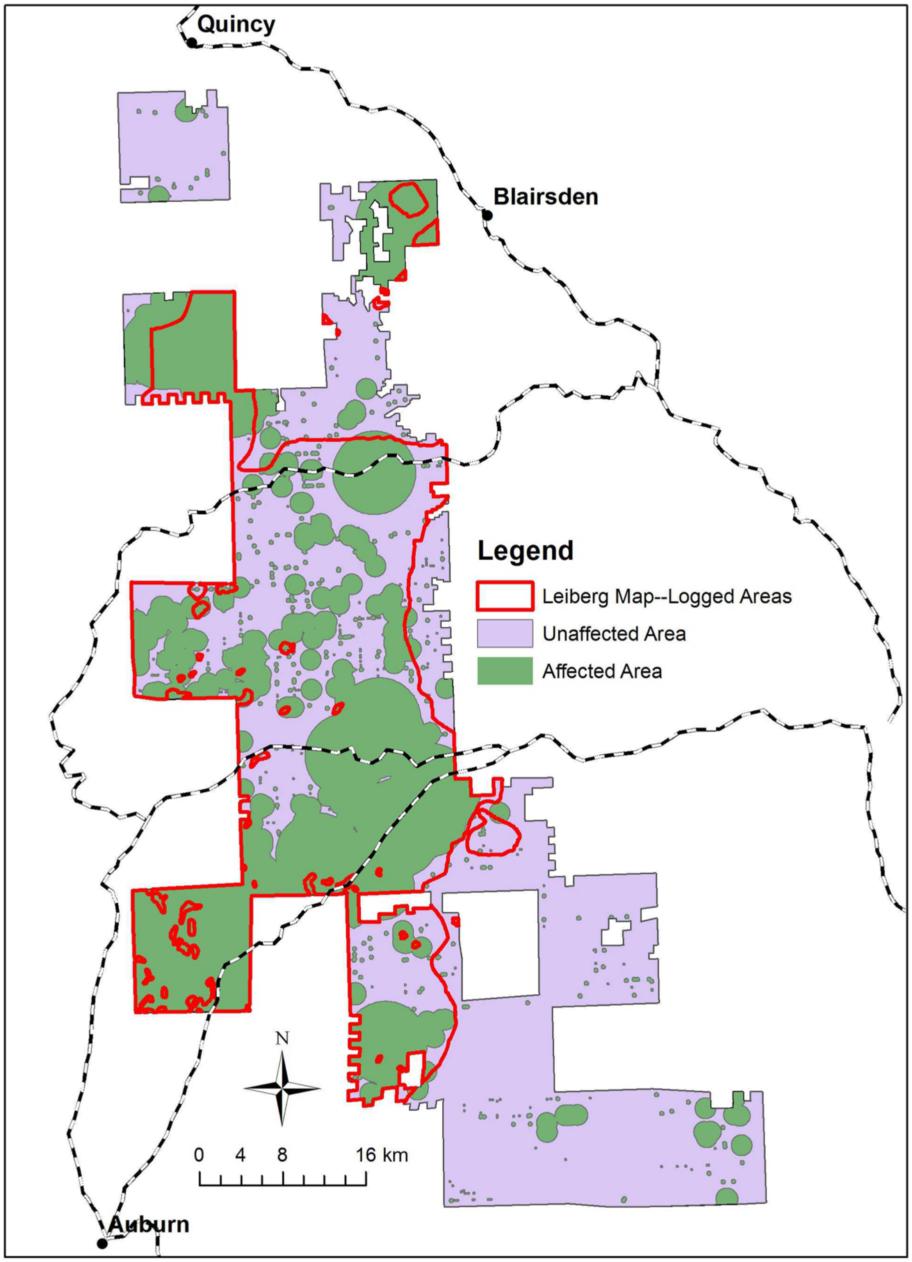

Fig. E2. Comparison of the merged human-effects map and the Leiberg (1902) map of logged/culled timber areas in the northern Sierra Nevada study area.

excluding any effects.

The map is a model and of course has limitations, but it does have some validation in early scientific reports and maps of human-affected areas. The human-effect area from the survey data matches well with the area that Leiberg (1902) mapped as having been logged/culled (Fig. E2), likely with many other associated land uses, including roads and trails, a water system etc. There are areas inside Leiberg's mapped area that had likely not been logged or otherwise altered by the time of the surveys, but were altered later, by the time of Leiberg's mapping. I do not have a digital version of Fitch's (1900*a*, *b*) maps of 30′ quadrangles, which overlap a few townships of my southern Sierra study area in and just west of Yosemite. However, these maps show that there was no area in the overlap mapped as logged/culled, and the survey data also document no logging in this overlap area.

Appendix F

Succession of chaparral patches to forest

Are chaparral patches successional to forests or more permanent because of their environmental setting? I tested this in the two study areas by examining recent aerial photographs of locations that were dominated by chaparral at the time of the surveys.

I selected two townships in the north and two in the south that had the most chaparral at the time of the surveys. These four townships cover about 37,000 ha and include some steep canyon slopes, some ridgetops, as well as more gentle topography, and include both low and high elevations. I downloaded, for each township, the 8–10 digital orthophoto quads (DOQs) from the U.S. Geological Survey (http://earthexplorer.usgs.gov) needed to cover the area of chaparral. These black-and-white photos have about 1-m pixel resolution, sufficient to see moderate-sized individual trees, and are dated from 1993. I overlaid these DOQs on the line-segments that surveyors identified as dominated by chaparral shrubs (e.g., *Ceanothus integerrimus*, *C. cordulatus*, *Arctostaphylos patula*, *A. viscida* etc.). Surveyors were required to map the location where they left forest and entered chaparral and vice versa.

Human effects were visually evident in the aerial photographs, in some areas, in the form of roads, contouring, logging in nearby forests, and other disturbances. I could not ground-truth to ensure that apparent chaparral was truly still chaparral. I also could not determine whether chaparral patches that persisted were the result of a fire since the time of the surveys. It is also possible that some areas that are now forested had trees that were planted.

The comparisons, over periods of 109–118 years, show that 21.8% of the chaparral present at the time of the surveys was still chaparral by 1993, and 78.2% of the chaparral became forest (Table F1). Greater persistence of chaparral, mostly in T004SR020E, was strongly associated with southerly-facing slopes, as virtually all patches on northerly-facing slopes were forested by 1993. Previous studies have shown that montane chaparral may remain dominant for up to about 60 years after fire in the northern Sierra (Conard and Radosevich 1982), and more than 100 years if fires recur (Wilken 1967). I did not determine whether fires recurred in the chaparral areas I sampled in this study. In the Lake Tahoe area, chaparral area declined by 62.4% on average on mostly xeric southerly-facing slopes during a >120-year period after fire that included no subsequent fires (Nagel and Taylor 2005). Early authors also noted that 2/3 to 3/4 of chaparral areas was recovering to forest (Appendix A: Q95, Q98). This is a little less than the 78.2% decline observed here in 109–118 years, although the more southerly, xeric slopes here showed less than the 78.2% decline. Vankat and Major (1978) also documented, using repeat photography, that chaparral stands in Sequoia National Park that were evident in photographs taken before 1920

Table F1. Percentage of chaparral present at the time of the surveys that was still chaparral or was forested by A.D. 1993 in four townships in the northern and southern Sierra.

Township	Elevations (m)	Survey/DOQ years and period	No. chaparral line segments		Length of chaparral line segments (km)		Percentage of survey line length (%)	
			Survey	Recent	Survey	Recent	Still chaparral	Now forested
North Sierra								
T003NR009E	1050–1800	1884/1993 = 109	38	16	28.6	7.0	24.5	75.5
T013NR013E	1370–1525	1875/1993 = 118	28	2	22.3	0.9	4.0	96.0
South Sierra								
T004SR020E	1370–1525	1883/1993 = 110	23	44	31.2	10.9	34.9	65.1
T011SR027E	1825–2400	1883/1993 = 110	12	6	8.3	0.9	10.8	89.2
Overall	1050–2400	109–118 years	90	68	90.4	19.7	21.8	78.2

showed invasion and/or increase in trees by the 1970s. Vankat and Major (1978:382) said "These findings support the hypothesis of Show and Kotok (1924) that stands of such shrubland vegetation are the result of single intense fires, or are the cumulative effect of repeated fires in areas of potential forest vegetation."

Based on these findings, I suggest that about 80% of the chaparral in my western Sierra Nevada study areas could succeed to forest on a 60–120 year time-scale, rather than persist because of its environmental setting. However, all montane chaparral likely could be maintained as chaparral over long periods if fires recur (Wilken 1967). This is tempered by the finding that fire may actually be less likely in chaparral than in surrounding forests (Nagel and Taylor 2005), although this was not the suggestion of Show and Kotok (1924), who envisioned that fires in chaparral were more frequent, larger, and more severe than in forests (Appendix A: Q100–Q103). However, all fires that could maintain chaparral by killing trees would be high-severity fires, as commonly noted by early observers (Appendix A: Q100, Q102, Q103).

Appendix G

Table G1. Forest-density estimates for historical forests of the western Sierra Nevada Mountains and nearby areas in California cross-validated with survey-based estimates. Estimates are divided into ponderosa pine-Douglas-fir, Sierran mixed conifer, and white fir phases. General estimates are those too vague in location to allow specific comparison with survey estimates.

Phase, general estimate/ specific comparison, and summary statistic	Author	Source	Author estimate (trees/ha)			Survey estimate (trees/ha)		RMAE (%)†
			Conifers	All trees, incl. oaks	Year	All trees, incl. oaks	Year	
Ponderosa pine–Douglas-fir								
General	Parsons and DeBenedetti (1979)	Tree-rings	...	210‡	1875			
	Hall (1909:10)	Inventory	...	75	1906			
Mean density			...	143				
Mixed-conifer								
Specific	Bonnicksen (1975)	Tree-rings	175§	...	1890	183¶	1879	4.6
	Collins et al. (2011)	Inventory	215#	...	1911	212‖	1879	1.4
	North et al. (2007)	Tree-rings	67	...	1865	129‖	1883	...††
	Parsons and DeBenedetti (1979)	Tree-rings	...	235‡	1875	241‡‡	1879	2.6
	Scholl and Taylor (2010)	Tree-rings	...	160	1899	160‖	1879	0.0
	Sudworth (1900) Fish Camp 2	Inventory	...	217	1900	232	1873	6.9
	Sudworth (1900) Sugar Pine Mill	Inventory	...	257	1900	278	1873	8.2
	Sudworth (1900) 1 mile west	Inventory	...	247	1900	278	1873	12.6
Mean RMAE								5.2
General	Cooper (1906)							
	Butte Co. 762 m	Inventory	247	294	1906			
	Butte Co. 1067 m	Inventory	237	247	1906			
	Butte Co. 1219 m	Inventory	328	370	1906			
	Butte Co. 1372 m	Inventory	205	217	1906			
	Madera Co. 1219 m	Inventory	325	342	1906			
	Madera Co. 1524 m	Inventory	254	260	1906			

Table G1. Continued.

Phase, general estimate/ specific comparison, and summary statistic	Author	Source	Author estimate (trees/ha) Conifers	All trees, incl. oaks	Year	Survey estimate (trees/ha) All trees, incl. oaks	Year	RMAE (%)†
	Hall (1909)							
	Plumas National Forest	Inventory	...	88	1906			
	Plumas National Forest	Inventory	...	154	1906			
	Hodge (1906)							
	Calavaras Co. 1524 m	Inventory	...	88	1906			
	Fresno R. headwaters	Inventory	...	684	1906			
	Stephens (2000) -C & N							
	Five average stands	Inventory	...	229	1899			
	Four large stands	Inventory	...	235	1899			
	Sudworth (1900) San Joaquin R.	Inventory	...	336	1900			
Mean density and RMAE			266	273		293¶¶		7.0
SD density			50	152		477		
White fir								
Specific	Parsons and DeBenedetti (1979)	Tree-rings	...	270‡	1875	260‡‡	1879	3.7
	Sudworth (1900) Fish Camp 1	Inventory	158	...§§	1900	119	1873	24.7
Mean RMAE								14.2
General	Cooper (1906) Butte Co. 1524 m	Inventory	180	186	1906			
	Hodge (1906:16) California	Inventory	...	364	1906			
	Sudworth (1900)							
	Bubbs Creek	Inventory	...	395	1900			
	Chiquito Creek	Inventory	...	287	1900			
	N. Fork Kings River	Inventory	...	247	1900			
Mean density and RMAE			...	292		293¶¶		0.3
SD density			...	77		477		

† RMAE = relative mean absolute error, which is 100 × (|Survey estimate − Author estimate|)/Author estimate.
‡ Interpolated from Parsons and DeBenedetti (1979:26–27, Fig. 1). Too little land area occurred in the ponderosa pine-Douglas-fir phase to allow specific comparison.
§ Estimate is from Bonnicksen (1975:106, Fig. 14). A count of trees in this figure is 112 trees in the 80 m × 80 m plot = 175 trees/ha.
¶ From the survey polygon enclosing the author's study area.
# Interpolated from Fig. 2A in Collins et al. (2011).
|| From a mean of all reconstruction polygons in the author's study area.
†† RMAE is not calculated, because the North et al. (2007) reconstruction of 67 trees/ha likely underestimates 1865 tree density. North et al. (2007:335) say: "Our survey is much more likely to detect larger diameter trees and tree species that have slow decay rates. This bias means that our 1865 reconstruction underestimates small-tree density...".
‡‡ From survey polygons clipped by the specific forest type, using CALVEG, within a 500 m buffer on each side of the Generals Highway in Sequoia and Kings Canyon National Park, as described by Parsons and DeBenedetti (1979).
§§ An ellipsis (...) indicates that an estimate is not available.
¶¶ The pooled estimate of mean density for Sierran mixed-conifer forests (Table 4).

Table G2. Historical basal-area (BA) and quadratic mean diameter (QMD) for dry forests of the western Sierra Nevada Mountains and nearby areas in California in comparison with survey-based estimates. Estimates are divided into Sierran mixed conifer and white fir phases. General estimates are those too vague in location to allow specific comparison with survey estimates.

Phase, general estimate/ specific comparison, and summary statistic	Author	Author estimate				Survey estimate			RMAE† (%)	
		Source	QMD (cm)	BA (m^2/ha)	Year	QMD (cm)	BA (m^2/ha)	Year	QMD	BA
Mixed conifer										
Specific	North et al. (2007)	Tree-rings	50	52	1865	58	262	1883	16.0	50.0
	Scholl and Taylor (2010)	Tree-rings	53	30	1899	77	48‡	1879	45.3	60.0
	Sudworth (1900) Fish Camp 2	Inventory	114§	221	1900	79	48¶	1873	30.7	78.3
	Sudworth (1900) Sugar Pine Mill	Inventory	113§	256	1900	47	59¶	1873	58.4	77.0
	Sudworth (1900) 1 mile west	Inventory	141§	387	1900	55	34¶	1873	70.0	91.2
Mean RMAE									36.1	71.3
Mean RMAE#									30.7	55.0
General	Cooper (1906:13) Madera Co. 1524 m	Inventory	41§	35	1906					
	Hodge (1906:20) Calavaras Co. 1524 m	Inventory	47§	15	1906					
	Stephens (2000)-C & N									
	Five average stands	Inventory	86	130	1899					
	Four large stands	Inventory	110	215	1899					
Mean			84	149		55.7	36			
SD			37	129		16.3	24			
Mean#			48	33		55.7	36		16.0	9.7
SD#			5	15		16.3	24			
White fir										
Specific	Sudworth (1900) Fish Camp 1	Inventory	47§	150	1900	64	48	1873	36.2	68.0
General	Cooper (1906) Butte Co. 1524 m	Inventory	50§	37	1906					
	Hodge (1906:16) California	Inventory	24§	16	1906					
Mean			40	68						
SD			14	72						
Mean#			37	27						
SD#			18	15						

† RMAE = relative mean absolute error, which is 100 × (|Survey estimate − Author estimate|)/Author estimate.
‡ From a mean of all polygons in the author's study area.
§ Calculated as the diameter of a tree with mean basal area.
¶ From the survey polygon enclosing the author's study area.
# Calculated without the data from Sudworth (or Stephens 2000, which summarizes Sudworth).

Appendix H

Oaks maintained by mixed- and high-severity fire

California black oak is of concern because it is ecologically and culturally significant in the Sierra Nevada, Cascades, and Klamath and is thought to be declining because conifers have overtopped it due to fire exclusion (Cocking et al. 2012, 2014). As shown in the text, oaks were abundant at the time of the surveys, particularly in the northern Sierra Nevada (Table 4). They were not always identified to species by surveyors, but most were likely California black oak, with fewer canyon live oak. Oaks were listed as the first tree on 16.2% of section-line length in the unaffected area in the northern, but only 2.3% in the southern Sierra. Using the 9-corner composition reconstruction, I selected polygons in which

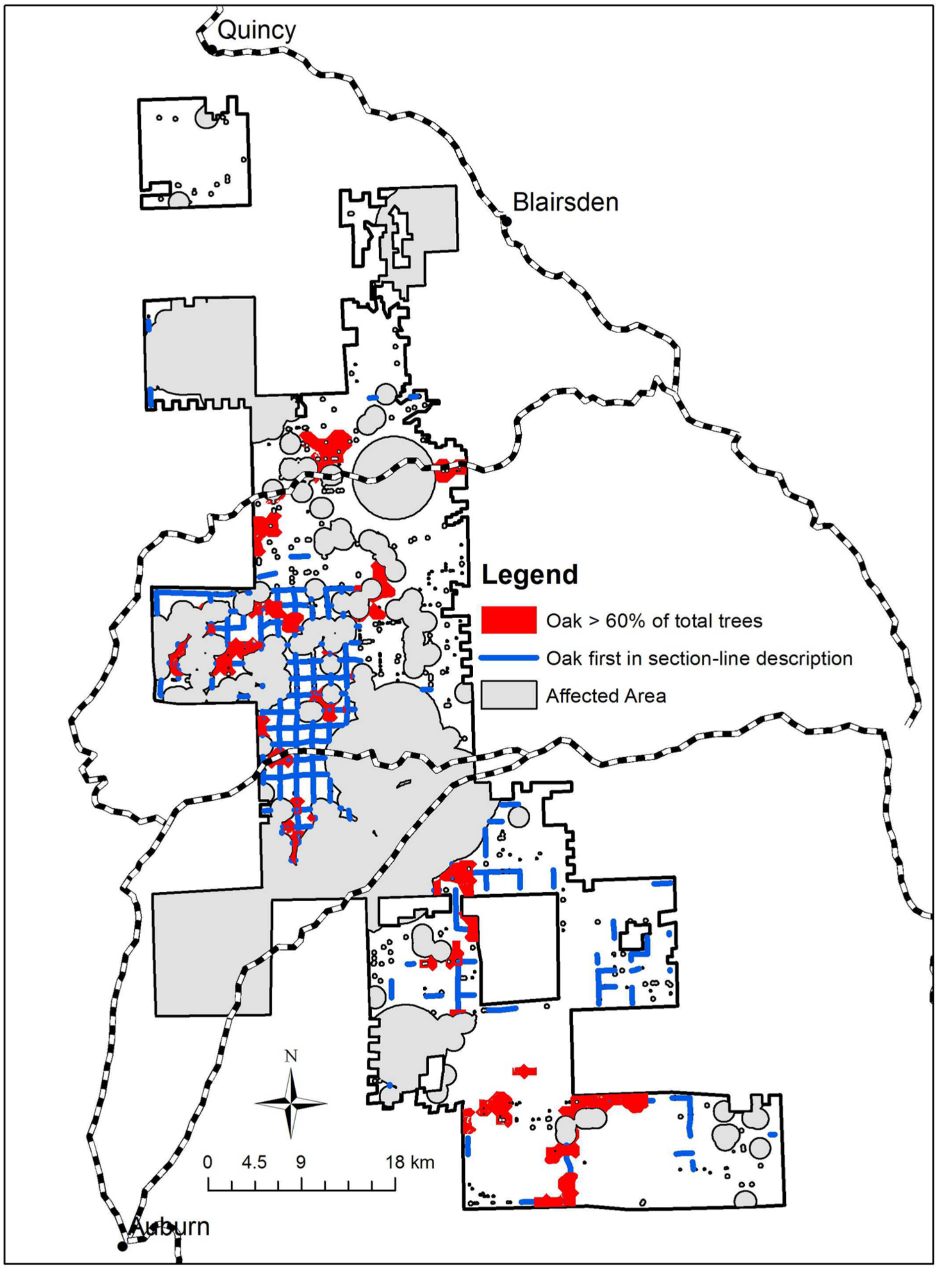

Fig. H1. Oak concentrations and section-lines with oaks first.

$\geq$60% of the trees were oaks, thus concentrations of oaks, to see how they were distributed and whether oak concentrations were favored by, or damaged by mixed- and high-severity fires. I reasoned that if oaks were damaged by mixed- and high-severity fires, then concentrations of oaks would be found most often in areas that had exclusively low-severity fire over the reconstruction period, the 110-years prior to the surveys. However, Cocking et al. (2014) showed that high-severity fire actually promotes persistence and restoration of oaks in competition with conifers, at least on small scales. There is no statistical test because it is ambiguous what the sample units

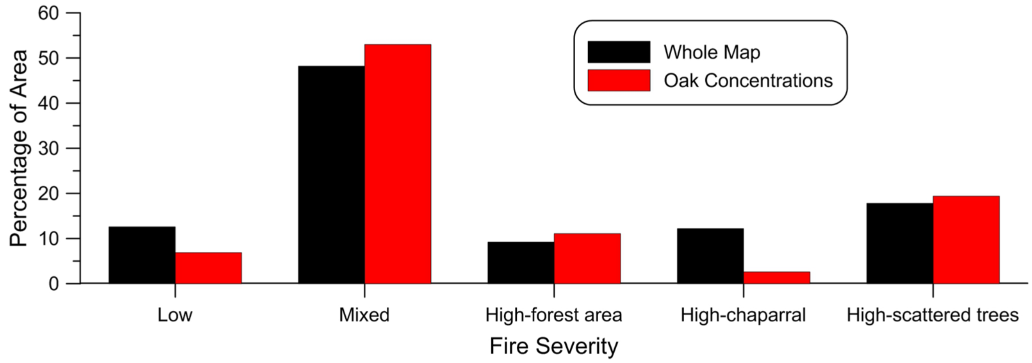

Fig. H2. Distribution of fire severities across the unaffected area in the whole map and in the areas of the oak concentrations in the northern Sierra Nevada.

are, some spatial autocorrelation exists, and what I really have is not a sample, but an estimate of the full population of all concentrations for the study area, which itself is representative, but not a statistical sample of the full SMC forest range.

In the northern Sierra, the oak concentrations covered 11,286 ha (8.5%) of the 133,482 ha unaffected area, but in the southern Sierra they covered only 1,368 ha (0.7%) of the 196,461 ha unaffected area. Only the northern Sierra is shown (Fig. H1) and analyzed further because it had sufficient sample size. As shown in Table 4, oaks were most abundant in the ponderosa pine-Douglas-fir phase, thus at lower elevations of the overall Sierran mixed-conifer forest.

Generally, concentrations were each the size of one polygon, thus about 750–800 ha, but occasionally twice that size and occasionally smaller due to clipping by the boundary of the unaffected area (Fig. H1).

Oak concentrations were not most abundant in areas with exclusively low-severity fire (Fig. H2) over the reconstruction period. That should have occurred if oaks had been widely damaged by higher-severity fire. Instead, oak concentrations were found across all fire severities (Fig. H2), but were a little favored by mixed-severity fire, disfavored by low-severity fire and also disfavored overall by high-severity fire (Fig. H2). Lower overall occurrence in high-severity fire was because of much lower occurrence in recently burned areas, represented by chaparral (High-chaparral). Concentrations were slightly favored in the later successional stages after high-severity fire, represented by scattered trees (High-scattered trees) and by early-successional forest (High-forest area).

The relatively low level of oak concentrations in low-severity fires is consistent with lower vigor and lack of release of oaks in low-severity fires found by Cocking et al. (2014). The slightly positive association with mixed-severity fires is consistent with the observation that oak populations are multi-aged (Garrison et al. 2002, Cocking et al. 2012) but are favored by higher-severity fires (Cocking et al. 2014). Mixed-severity fires are more intense than low-severity fires, but leave more survivors than high-severity fires. The same may be true for high-severity fire areas with scattered trees and in early-successional forests. It is unclear whether much fewer oak concentrations in chaparral represents actual mortality of oaks or if they just had not yet resprouted sufficiently to be visually apparent to surveyors above the chaparral shrubs. The fact that they are favored in later successional stages suggests they were present, but not seen.

Concentrations of oaks occurred commonly after both mixed- and high-severity fires and were slightly favored after mixed-severity fires. Low-severity fires, in contrast, led to fewer concentrations of oaks, but did lead to some, likely because the mechanism of small high-severity fires identified by Cocking et al. (2014) was historically part of the low-severity fire regime. However, overall, low-severity fires were less effective per unit area at creating concentrations than were the historically dominant higher-severity fires, particularly the mixed-severity fires.

The post-fire successional sequence after mixed- and high-severity fires is likely to naturally favor oaks early on, followed later by conifers that outgrow and overtop the oaks. Given the 281-year historical fire rotation in the northern Sierra Nevada (Table 7), there would typically be ample time for conifers to naturally recover after fire and overtop the oaks. This is simply the natural recovery of coniferous forest after mixed- and high-severity fire, not "encroachment" as labeled by Cocking et al. (2012). Fire exclusion could perhaps increase the hectares over which this process proceeds. Higher-severity fire is essential to maintain the SMC forest and its oaks.