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Implications of spatially extensive historical data from surveys for restoring dry forests of Oregon's eastern Cascades

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Abstract. Dry western forests (e.g., ponderosa pine and mixed conifer) were thought to have been historically old and park-like, maintained by low-severity fires, and to have become denser and more prone to high-severity fire. In the Pacific Northwest, early aerial photos (primarily in Washington), showed that dry forests instead had variable-severity fires and forest structure, but more detail is needed. Here I used pre-1900 General Land Office Surveys, with new methods that allow accurate reconstruction of detailed forest structure, to test eight hypotheses about historical structure and fire across about 400,000 ha of dry forests in Oregon's eastern Cascades. The reconstructions show that only about 13.5% of these forests had low tree density. Forests instead were generally dense (mean = 249 trees/ha), but density varied by a factor of 2–4 across about 25,000-ha areas. Shade-tolerant firs historically were 17% of trees, dominated about 12% of forest area, and were common in forest understories. Understory trees and shrubs dominated on 83.5%, and were dense across 44.8% of forest area. Small trees (10–40 cm dbh) were >50% of trees across 72.3% of forest area. Low-severity fire dominated on only 23.5%, mixed-severity fire on 50.2%, and high-severity fire on 26.2% of forest area. Historical fire included modest-rotation (29–78 years) low-severity and long-rotation (435 years) high-severity fire. Given historical variability in fire and forest structure, an ecological approach to restoration would restore fuels and manage for variable-severity fires, rather than reduce fuels to lower fire risk. Modest reduction in white fir/grand fir and an increase in large snags, down wood, and large trees would enhance recovery from past extensive logging and increase resiliency to future global change. These forests can be maintained by wildland fire use, coupled, near infrastructure, with prescribed fires that mimic historical low-severity fires.

Key words: Cascade Mountains; dry forests; fire history; historical forest structure; land surveys; mixed-conifer forests; Oregon; *Pinus ponderosa*; restoration; variable-severity fire.

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Introduction

Until recently, dry western forests were thought to have been historically open, maintained by low-severity fire, to have become denser from EuroAmerican livestock grazing, logging, and fire exclusion, and to require restoration (e.g., Covington and Moore 1994). In the Pacific Northwest, restoring dry forests is important in part because they provide habitat for species, such as the Northern Spotted Owl (*Strix occidentalis caurina*), that are declining and the subject of recovery actions (USFWS 2011). Uncharacteristic high-severity fires were thought to be threatening these forests and the owl (e.g., Spies et al. 2006). However, recent research

Table 1. Tree-ring reconstructions, counts of extant trees, and early scientific observations of tree density in dry forests in and near the Oregon eastern Cascades province.

Author(s)	Location	Reconstructed value
Tree-ring reconstructions		
Youngblood et al. (2004)	Metolius Research Natural Area, 60 km northwest of Bend	34–94 trees/ha in ponderosa pine†
Morrow (1986)	Pringle Falls Experimental Forest, 40 km southwest of Bend	167 trees/ha in ponderosa pine‡
Youngblood et al. (2004)	Pringle Falls Experimental Forest, 40 km southwest of Bend	35–79 trees/ha in ponderosa pine†
Perry et al. (2004)	Mount Bachelor volcanic chain, 30 km southwest of Bend	40–80 trees/ha in ponderosa pine in eight stands, <30 trees/ha in 5 stands§
Agee (2003*b*)		
Ponderosa pine variant	Crater Lake	348 trees/ha in dry mixed conifer¶
Sugar pine variant	Crater Lake	170 trees/ha in dry mixed conifer¶
Extant trees and stumps		
Merschel (2010)	North Deschutes National Forest	58 trees/ha in dry mixed conifer#
	South Deschutes National Forest	55 trees/ha in dry mixed conifer#
Early scientific observations		
Munger (1917)	Embody, 50 km SE of Lapine	136 trees/ha in ponderosa pine||
	Near Lapine	33 trees/ha in ponderosa pine||
	Klamath Lake Region	152 trees/ha in dry mixed conifer||

† These estimates are for only present "upper-canopy" trees in these forests, which likely underestimate the total number of trees >10 cm present in A.D. 1900.
‡ This is the mean of the pre-1886 trees, to be compatible with the survey dates, present in two stands sampled by Morrow, based on his figures (Morrow 1986: Figs. 8–11).
§ This estimate is for "trees >150 yrs plus large stumps" and likely underestimates the A.D. 1900 historical tree density; data are from Perry et al. (2004: Fig. 2).
¶ These forests are described by Agee as dry mixed conifer, but the abundance of pre-EuroAmerican white fir could suggest they are moist mixed conifer. Stands with white fir numerically dominant, as they are in these stands, were generally excluded.
# These estimates, from Merschel's Table 11, are only for extant trees and extant stumps, so they likely underestimate the number of trees present before EuroAmerican settlement.
|| These estimates are only for trees, in Munger's tables, that were >10 cm in diameter.

suggested dry forests and fire in the Northwest were variable historically (Hessburg et al. 2007), and the fraction of fire that burned at high severity lacks a recent upward trend (Hanson et al. 2009). However, detailed reconstructions of the variable historical structure and fire are not yet available to provide a reference framework for interpreting recent fire or for guiding restoration and management.

In dry forests of Oregon's eastern Cascades, the subject of this study, Weaver (1943) first suggested that fire exclusion since about A.D. 1900 was leading to: (1) dense stands of ponderosa pine regeneration and shade-tolerant trees, formerly killed by surface fires, beneath mature pines, (2) increased mortality of mature trees by beetles, because of competitive stress from dense regeneration and (3) increased fuels and unnaturally severe fires, leading to brush fields. He characterized historical forests as "... like a park, with clean-boled trees and a grassy forest floor" and with sparse understories: "a few small bushes of bitterbrush still persist in the larger openings" (Weaver 1961:571). Weaver's hypotheses have been supported, elaborated, and modified by much subsequent research, reviewed in the mid-1990s to mid-2000s (Agee 1993, 1994, 2003*a*, Youngblood 2001, Hessburg and Agee 2003, Hessburg et al. 2005).

Although historical structure and fire in Oregon's eastern Cascades forests have been studied, most evidence is from scattered anecdotal early accounts and observations (Appendix A) and only six scientific studies (Table 1). Weaver's ideas about fire exclusion were even criticized for limited evidence, in appended comments by A. A. Brown, who said "overstocked and stagnating stands seem so far from typical of the region for which he speaks that one wonders if Mr. Weaver is not generalizing too much from a single area" (Weaver 1943:14). In contrast to Arizona, where many tree-ring reconstructions of historical forest structure exist (e.g., Abella and Denton 2009), tree-ring reconstructions in Oregon's eastern Cascades are limited (Table 1).

However, the Interior Columbia Basin Ecosystem Management Project (ICBMP) included a spatially expansive analysis in the 1990s, which documented historical conditions and changes since EuroAmerican settlement (Hann et al. 1997, Hessburg et al. 1999). Historical evidence was from interpretation of early aerial photography (1930s–1960s). Hessburg et al. (2007) used these data for about 300,000 ha of dry mixed-conifer forests, mostly in eastern Washington, and found that old, park-like forests and low-severity fire did not dominate. Instead, these forests were dominated by ponderosa pine and Douglas-fir, but with a preponderance of intermediate-aged patches and a diversity of structures, reflecting fires varying in severity from low to high. Because this study used early aerial photography, the details of historical forest structure (e.g., tree density, diameter distributions) could not be reconstructed, and remain unknown except for the half dozen studies (Table 1). Moreover, Hessburg et al. had to account for the several decades of EuroAmerican land uses before the earliest aerial photos. Similarly, a spatially extensive 1930s survey of old growth (Cowlin et al. 1942) took place after extensive logging had begun.

Here I use General Land Office (GLO) survey data, that are also spatially extensive but from several decades earlier, before widespread logging and fire exclusion, to reconstruct detailed forest structure and fire, using new methods that allow accurate reconstructions (Williams and Baker 2010, 2011). I used the reconstructions to test eight hypotheses (Table 2) representing prevailing evidence prior to the Hessburg et al. (2007) study. This prevailing evidence has not been explicitly tested in the eastern Cascades of Oregon with spatially extensive data, and is still considered an appropriate restoration framework for the Northwest (Johnson and Franklin 2009). Also, the Hessburg et al. study could not address some hypotheses (H_2–H_5 below). Note that it is I, not authors, who provided specific quantitative criteria (e.g., 10%) for qualitative phrases (e.g., rare, minor, relatively free, dominated by), so that hypotheses could be quantitatively tested. I tried to choose reasonable criteria, but err a little on the side of generosity toward the hypotheses.

H_1 is supported by evidence in Weaver (1943, 1959, 1961), Agee (2003*a*), Hessburg and Agee (2003), Wright and Agee (2004), Youngblood et al. (2004), Hessburg et al. (2005), and by some early observations (Appendix A: Q4, Q45, Q47, Q49, Q50, Q52, Q53). Many tree-ring reconstructions support this hypothesis (Table 1), and it is also supported by the logical inference that low-severity fires would have kept tree density low (e.g., Youngblood 2001, Hessburg et al. 2005). H_2 is supported by evidence in Hessburg and Agee (2003), Perry et al. (2004, 2011), Hessburg et al. (2005), and Spies et al. (2006), and two early observations (Appendix A: Q65, Q67). Support was not primarily evidence of the actual historical abundance of shade-tolerant trees, but instead the logical inference that low-severity fires would have kept these trees rare, and observation that they increased after EuroAmerican settlement (e.g., Youngblood 2001, Hessburg et al. 2005, Johnson et al. 2008). However, early descriptions from Forest-Reserve reports or survey data do show shade-tolerant trees were rare in some dry forests in eastern Washington (Camp et al. 1997, Wright and Agee 2004), but were ≥20% of trees in others (MacCracken et al. 1996). The related H_3 is from Morrow (1986) and

Table 2. Hypotheses about historical dry forests in the eastern Cascades, to be tested in this study. See text for sources.

Hypothesis	Description
H_1	Historical forests generally (>90% of area) had low tree density (i.e., <100 trees/ha)
H_2	Douglas-fir and other shade-tolerant trees (grand fir/white fir, incense cedar) were historically a minor component (i.e., <10% of trees) in these forests, and the areas where they were most abundant were confined to moist sites (e.g., north-facing slopes)
H_3	Lodgepole pine was historically a minor component (i.e., <10% of total trees) in pumice-zone dry forests
H_4	Historical forests were relatively free (i.e., <10% of area) of small understory trees
H_5	Historical forests were relatively free (i.e., <30% of area) of understory shrubs
H_6	Historical forests generally were dominated by large trees (i.e., >50% of trees were larger than 60 cm)
H_7	Historical forests were dominated by low-severity fire (i.e., <10% of area with other fire severities)
H_8	Historical forests had high-severity fires that burned only at long fire rotations (i.e., >400 years)

Perry et al. (2004), who suggested that Sierran lodgepole pine increased with fire exclusion in Oregon's eastern Cascades.

H_4 is based on several studies (Weaver 1943, 1961, Hessburg and Agee 2003, Perry et al. 2004, Youngblood et al. 2004, Hessburg et al. 2005), but also is mostly based on the idea that low-severity fires would have kept understory trees rare (e.g., Hessburg et al. 2005). This is supported by early observations that suggest tree regeneration was poor or sparse (Appendix A: Q2, Q3, Q5, Q57). Some other observations characterized tree regeneration as scattered or patchy, with the patches sometimes dense (Appendix A: Q54, Q58, Q61). Regarding H_5, many authors suggested, based on early accounts (Appendix A: Q68–Q72, Q74–Q76), and the idea of historically frequent fires, that dry forests of the study area had few shrubs and small trees (e.g., Johnson et al. 2008, Busse and Riegel 2009). Agee (1994:17) said that, in ponderosa pine forests in the eastern Cascades, "open, parklike stands had substantial grass and forb cover ..." and "... herbaceous vegetation dominated the understory."

H_6 was reviewed by several authors (e.g., Spies et al. 2006). Youngblood (2001) and Hessburg and Agee (2003) suggested large trees dominated historically and Youngblood et al. (2004) estimated current old growth may be only 3–15% of historical old growth. Kennedy and Wimberly (2009) estimated via simulation that dry forests on the Deschutes National Forest could have supported about 35% older forest. However, surveys of Oregon's eastern Cascades in 1930–1936 showed (1) ponderosa pine forests were in the "large" or old-growth stage (dominant trees averaged >56 cm diameter) on 78.0% of the Deschutes area and 82.0% of the Klamath Plateau, and (2) dry mixed-conifer forests were in the large stage across 80.0% of the Deschutes area and 99.0% of the Klamath Plateau (Cowlin et al. 1942: Table 4).

H_7 is supported by reviews (Agee 1993, 1994, 2003*a*, Youngblood 2001), fire-history studies (e.g., McNeil and Zobel 1980, Bork 1984, Morrow 1986, Wright and Agee 2004), and some early observations (Appendix A: Q1–Q6). Dry mixed-conifer forests in eastern Washington had some patchy high-severity fire in a low-severity fire regime (Agee 2003*a*, Hessburg and Agee 2003, Wright and Agee 2004). Hessburg et al. (2005) later suggested dry forests in the Northwest may have had mixed-severity fire as well, but toward the low end of 20–70% overstory mortality.

H_8 is supported by several studies. Hessburg et al. (2005:120) said "... severe fire behavior and fire effects were uncharacteristic of dry forest-dominated landscapes ... Rarely, dry forest landscapes were relatively more synchronized in their vegetation and fuels conditions and affected by climate-driven, high-severity fire events ...." Wright and Agee (2004:455) said high-severity fire "historically occurred at the stand scale (10–100 ha), not the landscape scale (> 1000 ha)." Spies et al. (2006) mentioned patch-scale (e.g., 1 ha) high-severity fire in historical dry forests. Johnson et al. (2008) thought moister, north-facing slopes had some high-severity fire. One early observation suggests high-severity fire was rare in these forests (Appendix A: Q9).

Methods

Study area

The study area includes dry forests in and near Oregon's eastern Cascades province for the Northwest Forest Plan (http://www.reo.gov/gis/data/gisdata). Dry forests include ponderosa pine and dry mixed-conifer forests, which typically have ponderosa pine (*Pinus ponderosa*) dominant, with some Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*) or white fir (*Abies concolor*), western larch (*Larix occidentalis*), Sierran lodgepole pine (*Pinus contorta* var. *murrayana*), sugar pine (*Pinus lambertiana*), incense cedar (*Calocedrus decurrens*), or western juniper (*Juniperus occidentalis*) (Appendix B). Because surveyors did not distinguish grand and white fir, calling both "white fir" or just "fir," I refer to both here as white fir. I used the GLO survey data themselves, supplemented by the NW ReGAP Ecological Systems map of Oregon (http://www.pdx.edu/pnwlamp/existing-vegetation), to limit the study to dry forests from the top of the dry mixed conifer to the lower limit of ponderosa pine. ReGAP is a national ecosystem mapping program, based on 30-m Landsat satellite data (http://gapanalysis.usgs.gov). I used two map categories for ponderosa pine: 4240 Ponderosa Pine and 4301 Oregon White Oak-Ponderosa Pine. Where pine was co-dominant in surveys, I included some 4204 Western Juniper, 4217 Mixed

California Black Oak-Conifer, and 5304 California Montane Woodland and Chaparral. I used four map categories for dry mixed-conifer: 4205 East Cascades Mixed Conifer, 4214 Southwest Oregon Incense Cedar-Douglas-fir Mixed Conifer, 4215 White Fir Mixed Conifer, and 4232 Eastside Douglas-fir-Ponderosa Pine Mixed Conifer. Inclusion of 4237 Lodgepole Pine on Normal Soil and 4267 Lodgepole Pine on Pumice, Ash or Barren Soil was unavoidable in the central region where lodgepole forms a mosaic with ponderosa pine forests. I included small areas in other categories if large pines, likely ponderosa or sugar pine, dominated the GLO data.

These broad ReGAP categories include some moist mixed-conifer forests, which had to be omitted or removed. Thus, to further identify dry mixed-conifer forests, I either did not enter data or I removed: (1) section lines where the most- or second-most abundant tree in the surveys was spruce, hemlock, Shasta red fir, or western white pine, which characterize moist mixed conifer or subalpine forests, (2) section corners in the surveys with $\geq$2 of these four species, and (3) quarter corners with two white fir or section corners with $\geq$3 white fir, which likely are moist mixed-conifer forests. The resulting sample generally spans the ponderosa pine series and dry plant-association groups in the Douglas-fir, white fir-grand fir, and lodgepole pine series (Simpson 2007). However, the sample tends toward the dry side of ecotones between dry and moist mixed conifer, which may mean the sample underestimates the abundance of firs. Because they represent early succession, or possibly natural non-forested or sparse-forest conditions, I omitted 1,002 ha of burned forest, 9,219 ha of openings, and 11,707 ha of "scattered" trees from calculations, but they are shown on maps (e.g., Fig. 1). The final sample is 78% pines, 17% firs, and 5% other trees (Appendix B).

I divided the study area into three regions (Fig. 1), each with 100,000–150,000 ha of sample area (Table 3, Fig. 1) to facilitate geographical analysis. The central region is defined by the pumice zone, based on the Oregon geology map (Walker et al. 2003), which has a different ecology, often with lodgepole pine on flats and ponderosa pine or dry mixed-conifer forests on rises (Kerr 1913). The two other regions extend north and south to state borders.

The General Land Office surveys and early historical observations

The study uses historical data from GLO surveys done in the late-1800s. Surveyors recorded species, diameter, and distance to four (one per 90° of azimuth) "bearing trees" at section corners and two (one per 180° of azimuth) at quarter corners (0.8 km along a section line). By revisiting section corners to relocate extant bearing trees, we found that surveyors nearly always selected the closest tree in each quadrant; thus, bearing-tree data represent a valid statistical sample of trees that allows reconstruction of forest structure (Williams and Baker 2010). Along each 1.6 km section line, surveyors also recorded the dominant trees and shrubs (and some grasses) in order of abundance, and qualitative descriptions of density. Data from the earliest valid and complete surveys were input into a geographical information system, and used to reconstruct understory composition, as well as tree density, composition, and diameter distributions using our new methods (Williams and Baker 2011).

I selected townships included in the sample based on the quality and dates of surveys. Many townships could not be used, because surveyors did not record required trees (e.g., only two rather than four trees at corners) or understory trees and shrubs, or inconsistently recorded data. The sample includes the best GLO data for dry forests of Oregon's eastern Cascades. Of the 33 surveyors, 6 recorded excellent data covering 70% of the sample townships (Appendix C).

The sample townships were surveyed before dry forests of the region were transformed by industrial logging or fire exclusion. Mining expanded in the 1860s, and livestock grazing in the 1870s, but population and agriculture did not expand widely until the 1880s (Robbins 1997). Even in 1900, only a few small sawmills were in operation near Bend and Klamath Falls (Leiberg 1900, Robbins 1997, Bowden 2003). The railroad and expanded logging reached Klamath Falls in 1909 and Bend in 1911 (Robbins 1997, Bowden 2003). Depopulation of Indians was thought by Perry et al. (2004) to have significantly reduced fire by the middle-1800s. However, the idea that historical burning by Indians was widespread, rather than local and limited, is not supported by sound evidence (Whitlock and Knox 2002). Fire

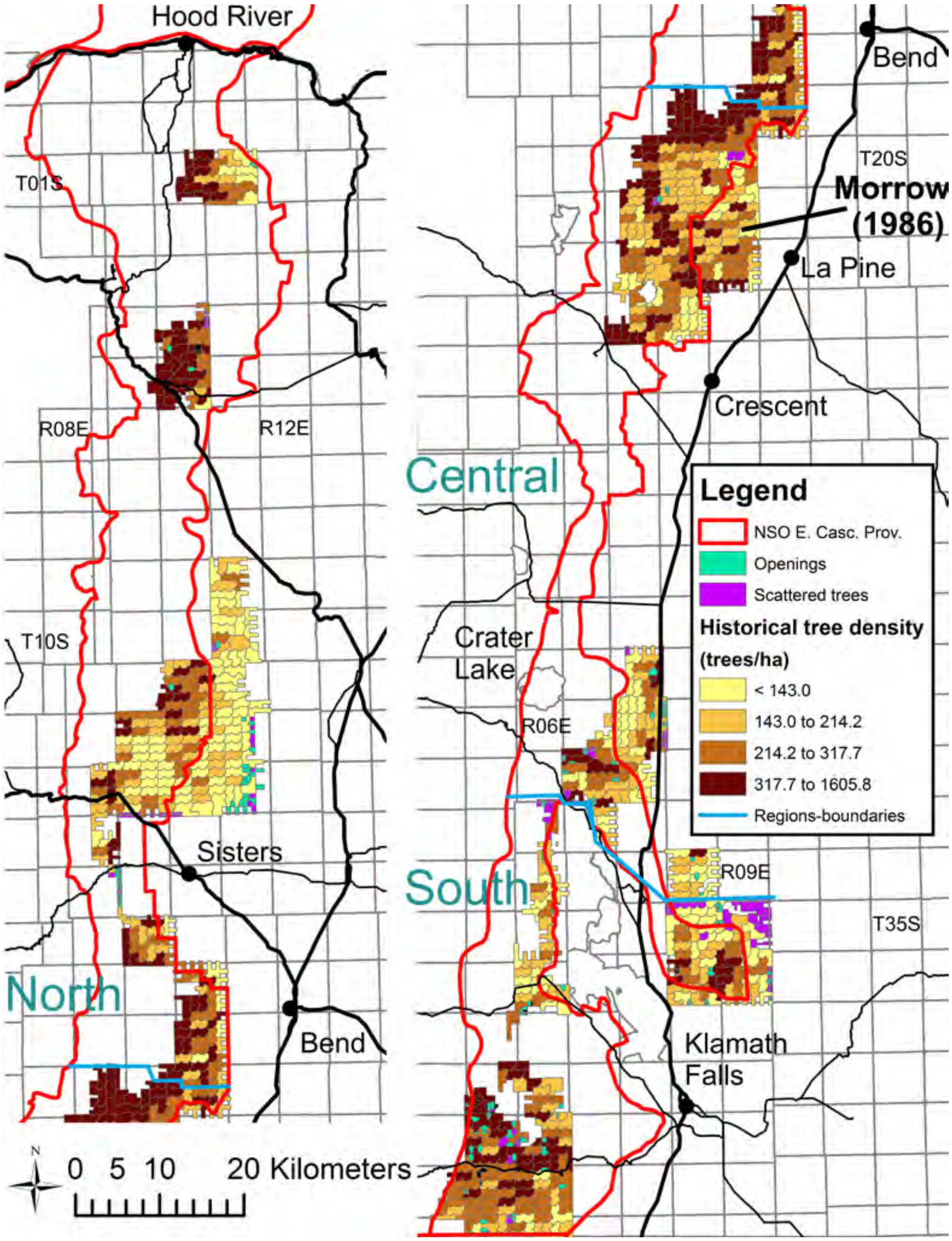

Fig. 1. Historical tree density, reconstructed from GLO survey tree data at the 6-corner pooling level. Township boundaries are shown in gray as a backdrop. The tree-density classes represent the quartiles of the distribution of tree density across the whole study area (Table 3). Openings were defined as areas with no trees, and scattered trees were defined as areas with $\geq$50% of expected trees missing. Small black areas indicate surveyor direct observations of burned areas. The location of the only available tree-ring reconstruction of full tree density is shown (Morrow 1986).

Table 3. Historical tree density and composition, based on reconstructions from GLO tree data.

Variable	Study area	Region: North	Region: Central	Region: South	Ponderosa pine	Mixed conifer
Tree density, 6 corner						
Total area in sample (ha)	398,346	146,615	147,625	104,106	122,905	139,768
n (number of polygons)	730	268	272	190	568	551
Mean (trees/ha)	249	246	262	233	219	275
First quartile	143	111	152	156	126	170
Median	214	211	215	224	195	239
Third quartile	318	328	344	306	283	352
Maximum	1606	1055	1606	732	1055	1606
Composition, 9 corner						
Total area in sample (ha)	398,313	146,786	147,269	104,258	123,330	140,141
n (number of polygons)	492	181	183	128	411	396
Firs						
Mean (%)	17.1	16.9	6.6	33.0	13.4	21.1
First quartile	0.0	0.0	0.0	15.2	0.0	0.0
Median	8.3	8.3	0.0	33.3	4.5	13.0
Third quartile	27.3	21.9	9.1	47.6	20.8	34.7
Maximum	90.9	90.5	65.4	90.9	80.8	90.9
Pines						
Mean (%)	77.3	75.0	92.7	58.5	81.1	73.5
First quartile	60.0	56.7	88.9	43.7	66.7	54.2
Median	87.5	86.4	100.0	56.4	90.9	80.8
Third quartile	100.0	96.0	100.0	73.0	100.0	95.8
Maximum	100.0	100.0	100.0	100.0	100.0	100.0

Notes: Units for tree density are numbers of trees per hectare. Units for composition are percentages of total trees.

exclusion is considered insignificant until 1900 (Weaver 1943, Busse et al. 2000, Youngblood et al. 2004) or even 1915 (Morrow 1986). Of 3,351 lines in the sample townships, 99% were surveyed from A.D. 1856–1900 (median = 1882).

I compiled early observations from publications (e.g., Weaver 1943, 1959, 1961), scientific studies (Foster 1912, Munger 1917), and Forest-Reserve reports by government scientists done in A.D. 1900–1903, which cover 53 of 60 sample townships (Leiberg 1900, 1903, Dodwell and Rixon 1903, Langille 1903, Plummer 1903). These are sorted by topic (Appendix A).

Field research

I field-checked and translated common names used by surveyors for trees (Appendix B) and understory species (Appendix D) into Latin names. I navigated to section corners and relocated and identified surviving original bearing trees that were unknown (e.g., sassafras pine). I also navigated to section lines where unknown understory species (e.g., chaparral, laurel) were dominant or co-dominant with a known species. Unknown species were checked and identified at about 20 section corners and 50 section lines, and almost no uncertainties remain (Appendix D).

To acquire data for fitting reconstruction equations (Williams and Baker 2011), I completed modern surveys at 73 corners across the study area, including ponderosa pine and dry mixed-conifer forests with a wide spectrum of stand ages and densities. For each corner, I measured attributes of some or all of the four nearest trees, but usually no more than two per species per corner, aiming for 20–25 for each main tree in the surveys (Appendix B). For rare species, trees were added near corners to increase sample size. For each tree, I measured diameter at breast height (dbh) using a caliper, and crown radius using a laser distance meter (Laser Technology, Inc.) and canopy densitometer (Geographic Resource Solutions, Arcata, California). I measured crown radius once for uniform crowns and the longest and shortest radii for irregular ones.

I also collected data to estimate the Voronoi area for each tree, which represents the area of ground controlled by the tree (Delincé 1986). Tree density equals the land area divided by mean Voronoi tree area, which Munger recognized (1917: Table 6). I estimated Voronoi area for each tree by measuring the distance with a laser distance meter, and bearing with a sighting compass, to the center of ≥6 nearest trees (Delincé 1986), until ≥1 occurred per 90° of azimuth. I used these data in ArcGIS (ESRI, Inc.) to measure the tree's Voronoi area. Equations were fit with regression (Minitab, Inc.) after logarithmic transformation (Appendix E). For crown radius, separate equations were fit for each species and for "fir" and "pine." Insufficient data and poor fit prevented Voronoi equations by species, which were pooled into three groups (Appendix E), based on similarity of the slope and intercept of initial Voronoi equations.

Reconstructions and statistical tests using the survey data

GLO survey notes are online (http://www.blm.gov/or/landrecords/survey/ySrvy1.php). The necessary data were downloaded, extracted, and entered into ArcGIS point (tree data) and route (section-line data) databases, then exported as spreadsheets. These were used with Minitab macros to complete calculations for hypothesis testing. Output tables were joined to the ArcGIS data for display and analysis. The dataset includes 11,856 trees and 3,351 section-line segments for 5,073 km of section lines across 398,346 ha. This is equal to about 43 townships of data, but includes parts of 60 individual townships. The sample includes about 42% ponderosa pine and 58% dry mixed-conifer forest. The part of the study area inside the Oregon Eastern Cascades province (Fig. 1) contains 45% of the 524,000 ha of dry forests that occur inside this province.

I used a chi-square goodness-of-fit test for each hypothesis that the area of the study area with each attribute (observed) is no different from the hypothesized fraction of the study area with the attribute (Ott 1988). Tests for H_1, H_2, H_6, and H_7 use GLO tree data, and tests for H_2-H_5 use section-line data (Table 2). Public-land survey lines approximate systematic line-intercept transects that provide unbiased estimates of percent cover (Butler and McDonald 1983):

$$C_a = \sum_{i=1}^{n} a_i / A \qquad (1)$$

where C_a = percent cover of property a across the study area, a_i is the fraction of line-intercept transect i with property a of n total transects, and A is the area of study. I used one-way analysis of variance to test for differences in means between groups (e.g., among regions) and the Tukey multiple comparison test to determine which means differ (Ott 1988). Sample sizes are large (e.g., 730 reconstruction polygons), so even small differences may be statistically significant. The area containing the GLO sample data is also large (45%) relative to the population, which is dry-forest area inside the Oregon Eastern Cascades province. I thus focus on ecological significance.

Potential missing section-line data must be addressed. Nearly all surveyors, including the best, at times did not record information about understory trees or shrubs. If a surveyor never recorded understory information about any lines (Appendix C), that surveyor's data are excluded from understory calculations, but otherwise their lines are included. Some surveyors specifically said "no undergrowth" or "no shrubs" when the understory lacked shrubs; in those cases, when they did not record information about another line, it could be that this was a lapse in recording and not an indication that understory shrubs were lacking, or it could be that these lines also lacked shrubs. These "not recorded" cases are thus ambiguous. Since many previous authors thought understory trees and shrubs were uncommon, I conservatively interpreted "not recorded" cases as a lack of trees or shrubs, and the tables reflect this, but I provide a multiplier in the table that allows the numbers to be calculated assuming "not recorded" represents missing data.

Tree data must be pooled to increase sample size and accuracy. As in Williams and Baker (2011), I estimated: (1) tree density for 6-corner pools (520 ha) to test H_1, (2) tree composition for 9-corner pools (780 ha) to test H_2 and H_3, and (3) diameter distributions for 12-corner pools (1040 ha) to test H_4, H_6, H_7, and H_8. Pools were generally formed from a 2:1 ratio of contiguous quarter corners and section corners, to offset the inequality of two trees at quarter corners and four trees at corners. In the accuracy trial (Williams and Baker 2011), relative mean absolute error (RMAE) was about 22% in a modern calibration and 17% in a cross-validation with tree-ring reconstructions for six-corner density; 9-corner composition was about 90% similar to plot data and 12-corner diameter distributions were about 87–88% similar to plot data. I used 10-cm bins for diameter distributions (Williams and Baker 2011). Reconstructions include up to 730 tree-density polygons, 492 composition polygons, and 369 diameter-distribution polygons. These GLO-based reconstructions approach the accuracy of tree-ring reconstructions, but are hundreds of times more spatially extensive (Williams and Baker 2011).

I reconstructed fire severity, evident in forest structure, as in nearby studies (e.g., Taylor and Skinner 1998, Hessburg et al. 2007) to test H_7 and H_8. Williams and Baker (in press) calibrated forest structure with fire severity, based on 64 tree-ring reconstructions in dry forests where authors reconstructed historical fire severities. We calibrated the structure associated with low-severity fire in dry forests to be: (1) mean tree density $<$ 178 trees/ha, (2) small conifers ($<$30 cm diameter) $<$ 46.9% of total trees, and (3) large conifers ($\geq$40 cm diameter) $>$ 29.2% of total trees. High-severity was identified by small conifers $>$ 50% of total trees and large conifers $<$ 20% of total trees, and mixed severity was between low and high. For reconstruction of fire severity, I intersected 6-corner tree density with 12-corner diameter distributions for conifers, then classified resulting 6-corner polygons into the three levels of fire severity. This improves on earlier studies, as forest structure is directly reconstructed from surveys done before widespread logging and fire exclusion, and severities are calibrated with tree-ring studies.

To help address H_7, I estimated low-severity fire rotation for the study area in two ways. First, although several fire-history studies were done in the study area, only Bork (1984) estimated area burned, needed to estimate fire rotation. I interpolated area-burned estimates for each fire (Bork 1984: Fig. I-22) from A.D. 1700 (to have a common starting year for all sites) to 1900, when fire exclusion is thought to have begun. I then calculated fire rotation as the period (200 years) divided by the sum of the fractions of the sample area burned by each fire, a standard formula (Baker 2009). Second, I used the section-line data to approximate the fire rotation. I used snowbrush ceanothus (*Ceanothus velutinus*) as an indicator of recent fire within only the low-severity fire area. Snowbrush ceanothus reappears profusely after fire by resprouting and reseeding, and within 5–10 years, it often becomes dense and dominant (Foster 1912, Zavitkovski and Newton 1968, Conard et al. 1985, Ruha et al. 1996), as also documented by early observations (Appendix A: Q21, Q22, Q24, Q25). However, because snowbrush is relatively shade-intolerant, as regenerating trees overtop it and it is damaged by snow, it often declines to low levels by about 15 years after fire (Zavitkovski and Newton 1968, McNeil and Zobel 1980). In some cases, snowbrush can have an effective period of dominance lasting 20–40 years (Conard et al. 1985). To approximate the fire rotation for low-severity fire, I calculated the fraction of total section-line length, within only the low-severity area, on which snowbrush ceanothus was listed either first or second by surveyors. I then estimated fire rotation, based on the maximum period during which snowbrush remains dominant or co-dominant after fire, using 15 and 30 years as the possible estimates, divided by the fraction of the landscape burned during that period (fraction of total line length that listed snowbrush first or second).

To analyze H_8, I approximated historical high-severity fire rotation as in Williams and Baker (in press). The approximation is from the number of years high-severity fire was detectable using forest structure evident in the GLO data, divided by the fraction of the forested landscape in which those fires occurred. The number of years fire was detectable is defined by the age of an average 40-cm tree, the key tree size that separates the definitions of fire severity (see above). Munger (1917: Table 10) dated 1,618 ponderosa pines at ten sites nearly spanning my study area. The average 40-cm tree was about 120 years old in the north, 115 years old in the central region, and 105 years old in the south, which I use in each region as the years fire was detectable using forest structure. Since these are single approximations for the whole population, I simply qualitatively interpret the result. Since no previous study has even approximated historical high-severity fire rotation, as the necessary data are difficult to obtain, the approximation has value.

Validation

The ability of crown-radius and Voronoi reconstruction equations to estimate forest-structure parameters has been validated in an extensive accuracy trial (Williams and Baker 2011). Here, I supplemented this with a small, local trial. At 15 corners, I used modern survey data I collected, and the derived equations (Appendix E) to estimate tree density and compare it to an estimate from a square plot, centered on the corner and enlarged to contain 30–50 trees. This trial showed RMAE in mean tree density across five three-corner pools was 25.1%, which is better than the 30.4% RMAE for three-corner pools in the nearby Blue Mountains (Williams and Baker 2011). Also, species-specific crown-radius equations reduced RMAE from 28.0%, for pooled species equations, to 25.1%, so species-specific equations can increase accuracy. This trial also showed that Mean Harmonic Voronoi Density (MHVD) was the best density estimator for the study area, as in the nearby Blue Mountains (Williams and Baker 2011), and it is thus used in this study.

For cross-validation (Williams and Baker 2011), only one of the tree-ring reconstructions (Table 1), at Pringle Falls (Morrow 1986: Fig. 1), is of tree density, includes all trees >10 cm dbh, and is inside the study area. Youngblood et al. (2004) is only for upper-canopy trees, not all trees. Perry et al. (2004) included only counts of trees pooled across sites, not density and not at individual sites. Agee (2003*b*) was outside the study area. The estimate of density of pre-1886 trees (compatible with survey dates) was 167 trees/ha (mean for stands 28 and 29; Morrow 1986: Figs. 8–11). In comparison, reconstructed tree density, from the mean of four 3-corner pools near these stands, was 175 trees/ha, which supports that the reconstructions are valid and accurate.

The methods of fire-severity reconstruction have been validated (Williams and Baker, in press), but I added to this by comparing fire-severity reconstructions to information in Forest-Reserve reports done by government scientists in A.D. 1900–1903 (Leiberg 1900, 1903, Dodwell and Rixon 1903, Langille 1903, Plummer 1903). These describe forest structure, often explain which part of a township and how much area burned at high severity, and describe the extent of fires of all severities (e.g., fire evident throughout the township). Information is only at the coarser township scale, but covers 53 of my 60 townships within a few decades of surveys. I considered the fire-severity reconstruction for a township to be validated if: (1) the area and location of high severity in the reconstruction generally matched the area and location of high-severity fire, or contiguous areas described as having small trees, in the township description, (2) if the township description recorded little (i.e., <5% of township) high-severity fire, or described mature or large timber, and the reconstruction identified the area as having predominantly low- or mixed-severity fire, (3) if the township description mentioned attributes expected in a mixed-severity fire regime (e.g., patches of burned area or brushfields) and the reconstruction identified the area as predominantly mixed severity, and (4) where the reconstruction showed multiple fire severities in the township, they also were evident in the township description.

The fire-severity reconstructions match township descriptions in the Forest-Reserve reports well. Three of the 53 townships had unusable descriptions. Of the remaining 50, in 42 townships (84%) the GLO reconstructions generally matched the township descriptions, although the township descriptions did not distinguish low and mixed severity well. In eight townships (16%), my reconstructions and the township descriptions did not match. Mis-matches were usually not large; for example, in T014SR008E, the reconstruction showed only low and mixed-severity fire, but the township description has 372 ha (4% of the township) of "burned area," which is high severity. The precision of this test is not high, as I had to judge what is a match, but the results do support the validity of reconstructions. The fire-severity reconstructions are further validated by comparing them to previous findings (Hessburg et al. 2007) in the study area (see Discussion).

Results

H_1 was rejected (X^2 (1, $N = 730$) = 4824.5, p = 0.000). Only 13.5% of forest area had open, low-density forests, with <100 trees/ha, and only 25% of forest area had somewhat low density (i.e., <143 trees/ha, the first quartile in Table 3). Historical tree density across the study area (Fig. 1) was instead high for dry forests, with a mean of 249 trees/ha (Table 3). Dry mixed-conifer forests were quite dense on average, with a mean of 275 trees/ha, and were significantly denser than ponderosa pine forests, with a mean of 219 trees/ha (F (1, 1117) = 42.55, p = 0.000). Lodgepole pine forests were similar to mixed-conifer forests, and are pooled with them. There was no significant difference in mean tree density among regions (F (2, 727) = 1.92, p = 0.147), likely due to high within-region variability. Overall, 25% of forest area had very dense forests, between 318 and 1606 trees/ha (Table 3, Fig. 1) and even 25% of ponderosa pine forests had ≥283 trees/ha (Table 3). This evidence against H_1 is also supported by a few early observations (Appendix A: Q45, Q46, Q48, Q51).

Instead of widespread low-density forests, generally dense forests with a mixture of densities characterized historical forest landscapes at the scale of a few townships. Low-density forests were well distributed across regions, with somewhat more relative area in the north (Table 3, Fig. 1). Dense forests were also well distributed, with slightly more in the south. Some contiguous areas of three to five townships (e.g., north of Sisters) had more low density and others (e.g., south of Hood River, southwest of Bend, southwest of Klamath Falls) had more high density, but neither low- nor high-density forests formed large blocks (Fig. 1). At the scale of a few townships (e.g., 25,000 ha), tree density usually varied by a factor of two to four or more (Fig. 1). This large variability was noted by Munger (1917; Appendix A: Q46).

H_2 also was rejected (X^2 (1, N = 11,856) = 966.3, p = 0.000), based on the number of shade-tolerant trees versus total trees (Appendix B). Section-line data also show that firs were the most abundant trees across 12.0% of forest area, were either first or second in abundance across 56.8% of forest area, and were present on 64.8% of forest area (Table 4). Firs were the most abundant tree across 14.6% of dry mixed-conifer forests, but only 3.1% of ponderosa pine forests (Table 4). Firs were present in 80.5% of mixed-conifer forests and 40.9% of ponderosa pine forests, a significant difference (F (1, 805) = 29.95, p = 0.000). Incense cedar, in contrast, was almost never the most abundant tree, and was second on only about 5% of the forest area, but was present across about 25% of forest area (Table 4). Firs made up 17.1% of total trees across the study area, and 21.1% of trees in dry mixed-conifer forests, but their abundance varied significantly among regions (F (2, 489) = 75.12, p = 0.000). All three regions differed, based on Tukey's MCP), from only 6.6% of total trees in the central region to 33.0% in the south (Table 3). Understory shade-tolerant trees were also historically common, as explained below (H_4).

Firs, which made up almost all shade-tolerant trees (Appendix B), were not confined to moist sites (second part of H_2). Firs were somewhat concentrated, as median composition was only 8.3% firs, yet 25% of forest area had ≥27.3% firs (Table 3). Fir concentrations (≥27.3% firs) were widely distributed across available environments, indicating a lack of confinement to moist sites. However, selection was significant for higher elevations and slopes >5 degrees, but not for aspect and slope position (Fig. 2).

Lodgepole pine was not historically a minor component of pumice forests (H_3 was rejected), based on two tests. First, in an 11,000-ha area enclosing sample sites of Perry et al. (2004), using surveys from 1880–1883, lodgepole pine was listed as the first tree on 27.1 km (23%) of 117.0 total km of section-lines in the area, and H_3 was rejected here (X^2 (1, N = 117) = 22.5, p = 0.000). Also, lodgepole was 59% and ponderosa pine 41% of 54 pines identified to species, and the lodgepole were all <40 cm dbh. The 11,000 ha area was reconstructed to have had widespread evidence of mixed-severity fire in 1880–1883, with some area of both high severity and low severity. Second, the surveyor who did the area of the Morrow (1986) study did not distinguish pines, but they were in the next township south, done in 1882 by Henry C. Perkins. In a 3000-ha area of similar topography, lodgepole is the first tree (ponderosa second) on 24.1 km (62.6%) of 38.5 km of section lines, with the remaining 14.0 km "pine-fir," thus H_3 is also rejected here (X^2 (1, N = 38) = 120.1, p = 0.000). Early observations also document that lodgepole pine was historically abundant and regenerated, and even dominated to the exclusion of other trees, after high-severity fires in dry forests in the central zone (Appendix A: Q28–Q31, Q33–Q36, Q59).

Understory trees were present on 2223 km (57.4%) of the 3873 km of section lines in the sample, so H_4 was rejected (X^2 (1, N = 3,873) = 9,667.5, p = 0.000). Also, understory trees were present and dense on 30.3% of forest area (Table 4). Understory trees were present on 79.4% and dense on 56.9% of forest area in the north region,

Table 4. Historical section-line length covered by overstory trees and understory trees and shrubs.

Length covered	Study area	Region: North	Region: Central	Region: South	Ponderosa pine	Mixed conifer
Overstory shade-tolerant trees						
Percentage with fir first†	12.0	8.9	3.0	14.7	3.1	14.6
Percentage with fir first or second	56.8	55.4	32.1	60.2	36.8	68.2
Percentage with fir present	64.8	57.6	37.5	77.8	40.9	80.5
Percentage with incense cedar first	0.2	0.1	0.0	0.3	0.0	0.1
Percentage with incense cedar first or second	4.7	7.9	0.0	1.7	6.9	1.3
Percentage with incense cedar present	24.8	29.8	0.0	34.7	23.2	24.4
Total line length in sample (km)‡	4312.7	1601.3	1570.4	1140.9	1363.1	1381.0
Understory shade-tolerant trees						
Percentage with fir first†	10.2	22.1	2.5	8.2	4.1	16.8
Percentage with fir first and dense	6.6	13.8	1.1	6.3	3.1	11.0
Percentage with fir present	27.8	42.5	25.3	15.9	16.5	36.4
Percentage with incense cedar first	0.1	0.1	0.0	0.0	0.0	0.0
Percentage with incense cedar first and dense	0.0	0.0	0.0	0.0	0.0	0.0
Percentage with incense cedar present	2.6	0.8	0.0	4.4	0.7	4.6
Total line length in sample (km)‡	3894.4	1154.3	1554.3	1209.5	945.3	1424.4
Multiplier for correcting for missing data§	1.182	1.028	1.284	1.238	1.195	1.126
Understory shade-intolerant trees						
Percentage with pine first†	44.1	49.0	63.9	13.8	48.0	37.6
Percentage with pine first and dense	21.9	38.1	19.7	8.6	28.0	17.8
Percentage with pine present	51.0	67.7	65.8	15.3	52.7	46.5
Total line length in sample (km)‡	3894.4	1154.3	1554.3	1209.5	945.3	1424.4
Multiplier for correcting for missing data§	1.182	1.028	1.284	1.238	1.195	1.126
Understory trees of any species						
Percentage with understory trees	57.4	79.4	66.6	24.9	58.3	55.7
Percentage with dense understory trees	30.3	56.9	20.9	16.6	35.2	29.3
Total line length in sample (km)‡	3872.6	1154.3	1554.3	1209.5	945.3	1424.4
Multiplier for correcting for missing data§	1.182	1.028	1.284	1.238	1.195	1.126
Understory shrubs of any species						
Percentage with understory shrubs	71.0	83.2	58.1	77.5	67.4	82.2
Percentage with dense understory shrubs	43.6	54.0	22.9	40,0	40.6	41.8
Total line length in sample (km)‡	3992.4	1234.6	1499.2	1258.6	1027.9	1447.7
Multiplier for correcting for missing data§	1.178	1.054	1.274	1.209	1.222	1.112
Understory trees or shrubs of any species						
Percentage with understory trees or shrubs	83.5	96.5	78.0	77.9	81.4	89.0
Percentage with dense understory trees or shrubs	44.8	67.4	30.4	40.1	51.4	44.9
Total line length in sample (km)‡	3863.0	1154.3	1499.2	1209.5	941.7	1422.5
Multiplier for correcting for missing data§	1.165	1.028	1.274	1.238	1.191	1.101

† Surveyors were instructed to record overstory trees and understory shrubs and trees by listing them in order of abundance.
‡ Line lengths differ between overstory and understory, because some surveyors recorded overstory information but not understory information. Line lengths also differ between understory trees and understory shrubs for the same reason.
§ Where the surveyor did not record information for a particular section line for understory trees or shrubs, this lack of information is ambiguous and can be interpreted two ways: (1) the lack of an entry means there were no understory trees or shrubs, which is how the percentages in this table were calculated, or (2) the surveyor neglected to make an entry and the data are missing. The former case provides a low estimate of the percentages. In the latter case, the correct percentages would be higher, and can be calculated by applying the multiplier to the percentages in the table.

but were present on only 24.9% and dense on only 16.6% of the south region (Table 4). Pines were the most abundant understory trees, were present on 51% of forest area, present and most abundant on 44.1% of forest area, and were dense and most abundant on 21.9% of forest area (Table 4). Even understory shade-tolerant trees were common. Understory firs were present on 27.8% of forest area, were the most abundant understory tree on 10.2% of forest area, and were most abundant and also dense on 6.6% of forest area (Table 4). Understory firs were most abundant in dry mixed-conifer, where 36.4% had understory firs; understory incense cedars were rare, but present on 2.6% of forest area (Table 4). Early observations show that thickets of tree regeneration were common in places, also scattered, often dense, and may have been favored by fire interludes (Appendix A: Q60, Q61–Q64).

Overall, 2834 km (71.0%) of 3992 km of forest area in the sample had understory shrubs, so H_5 was rejected (X^2 (1, N = 3,992) = 3,194.3, p = 0.000), varying from 83.2% in the north to 58.1% in the central region (Table 4). An observation

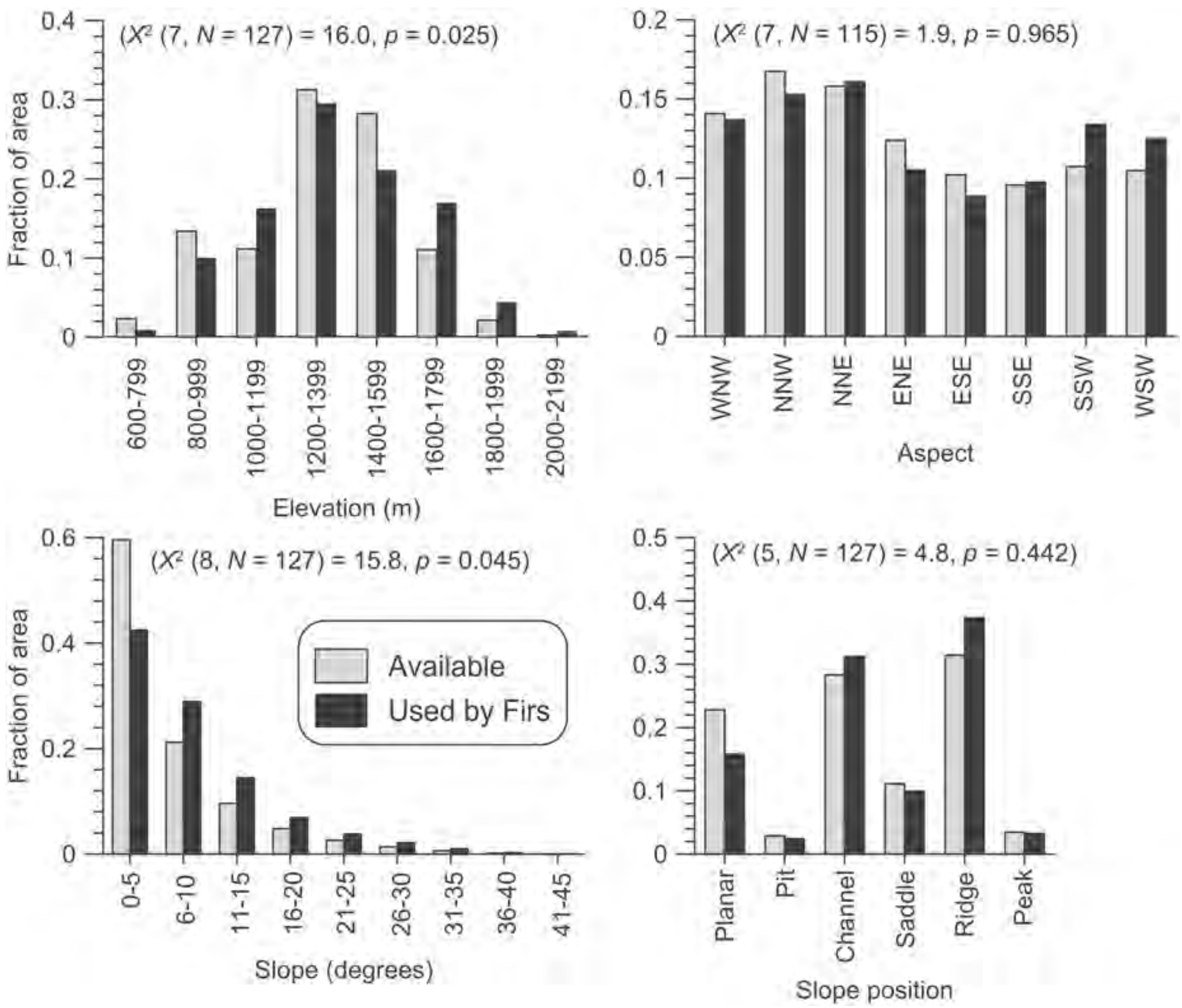

Fig. 2. Area supporting fir concentrations with respect to four topographic variables. A concentration of firs is a reconstruction polygon with firs ≥27.3% of total trees, which represents the fourth quartile of fir composition. Available is simply the fraction of the total forest area with each environmental attribute, and the area used by firs is the fraction of the total area of concentrations of firs that has each environmental attribute. If the used fraction exceeds the available fraction, that indicates selection. Chi-square values show that the null hypothesis, that the two distributions do not differ, can be rejected only for elevation and slope. Note that aspect has a smaller sample size, because it is only calculated where slopes are ≥5 degrees.

also suggested shrubs were abundant in the south region (Appendix A: Q73). Within the 71.0% of area with understory shrubs, about half had antelope bitterbrush first, one-sixth had snowbrush, one-eighth had greenleaf manzanita, and the rest was a mixture. Understory shrubs were dense across 43.6% of forest area, from 54.0% in the north to 22.9% in the central region (Table 4). Shrubs were more abundant in dry mixed-conifer forests than in ponderosa pine forests (Table 4). Many early observations suggested understory shrubs were sparse (Appendix A: Q68–Q72, Q74–Q76), perhaps because observations were for the 29% of forest area without understory shrubs at the time of the surveys (Table 4).

Hypotheses H_4 and H_5 together implied an open understory with few small trees or shrubs, but this is rejected. Surveyors explicitly recorded "no shrubs" or "no undergrowth" on only 16.5%

of forest area, thus 83.5% of forest area had understory trees or shrubs, with 96.5% in the north and about 78% in the other regions, and they were dense across 44.8% of forest area (Table 4). Dry mixed-conifer forests had understory trees and shrubs across 89% of the area (Table 4).

H_6 was rejected, as trees >60 cm were only 18.0% of total trees (X^2 (1, $N = 11856$) = 4,856.4, $p = 0.000$). Trees from 10–40 cm were numerically dominant (60% of total trees) when pooled across the 11,856 trees in the study area (Fig. 3). This pattern had consistency, as 10–40 cm trees were >50% of trees across 72.3% of forest area. Large trees would certainly have been prominent because of their size and canopy position, and in this sense likely were generally dominant. Pooled diameter distributions for individual species show four patterns (Fig. 3). First, all species had abundant small trees (<40 cm). Second, most species, including white fir, incense cedar, western juniper, western larch, and lodgepole pine seldom were >60–70 cm. Only sugar pine, ponderosa pine, and Douglas-fir commonly had larger trees. Third, three species (white fir, western larch, Douglas-fir) had a peaked distribution with fewer trees in the smallest size class(es). Finally, lodgepole pine's distribution stood out, with few trees >40 cm diameter.

H_7 was rejected (X^2 (1, $N = 1132$) = 5741.3, $p = 0.000$), as 76.5% of forest area had structural evidence of mixed- or high-severity fire, and only 23.5% of forest area had evidence solely of low-severity fire (Table 5), although low-severity fire likely also occurred in mixed- and high-severity areas. Fire-severity percentages (Table 5) differed among regions (X^2 (2, $N = 1076$) = 131.8, $p = 0.000$). Low-severity-fire was highest in the north (32.5%) and south (29.4%) and least (10.4%) in the central region (Table 5, Fig. 4). Overall, 26.2% of forest area had evidence of high-severity fire, which varied from 41.4% in the central region to 8.9% in the south (Table 5, Fig. 4). Overall, structural evidence of mixed-severity fire was dominant (50.2% of study area), but varied from 44.2% in the north to 61.7% in the south (Table 5, Fig. 4). Fire-severity percentages (Table 5) also differed among vegetation types (X^2 (2, $N = 2609$) = 50.2, $p = 0.000$). Dry mixed conifer had less low-severity and more high-severity fire than did ponderosa pine forests (Table 5). Lodgepole pine on pumice had hardly any low-severity, and was dominated by high-severity fire (Table 5). Early observations support the occurrence of high-severity fire in lodgepole pine (Appendix A: Q13, Q32, Q35) and lodgepole pine regeneration after high-severity fire (Appendix A: Q28–Q31, Q33, Q34, Q36).

Using Bork's area-burned data (Bork 1984: Fig. I-22), I estimated fire rotation for low-severity fire to be: (1) 78 years at Cabin Lake, southeast of Lapine in dry ponderosa pine, (2) 29 years at Pringle Butte, about 40 km southwest of Bend in ponderosa pine with lodgepole pine nearby, and (3) 71 years nearby at Lookout Mountain in a dry mixed-conifer forest. Using snowbrush ceanothus, I approximated low-severity fire rotation as 47–142 years (Table 6).

H_8 is supported for the study area and for north and south regions, as high-severity rotations were estimated at 435, 515, and 1180 years, respectively, and is supported for ponderosa pine and dry mixed-conifer forests, with rotations estimated at 705 years and 496 years, respectively (Table 5). It is not supported for the central region, where the rotation was 278 years (Table 5), or for lodgepole pine forests on pumice in that region, where the rotation was 171 years (Table 5).

Discussion

Historical dry forests in Oregon's eastern Cascades were denser than previously estimated, and denser than that calculated using GLO data in similar western forests. The historical mean tree density of 249 trees/ha substantially exceeds most estimates from tree-ring reconstructions, extant trees and stumps, and early scientific observations (Table 1). Causes of this disparity are discussed later. Historical mean tree density in the eastern Cascades (249 trees/ha), exceeded the 217 trees/ha in the Colorado Front Range, 167 trees/ha in Oregon's Blue Mountains, and 142–144 trees/ha in northern Arizona from GLO data (Williams and Baker, in press). Moreover, the 13.5% that was open, low-density forest (<100 trees/ha) in the eastern Cascades was much lower than the 23% in Oregon's Blue Mountains, 23–33% in northern Arizona, and 40% in the Colorado Front Range (Williams and Baker, in press). This may reflect more dry mixed-conifer

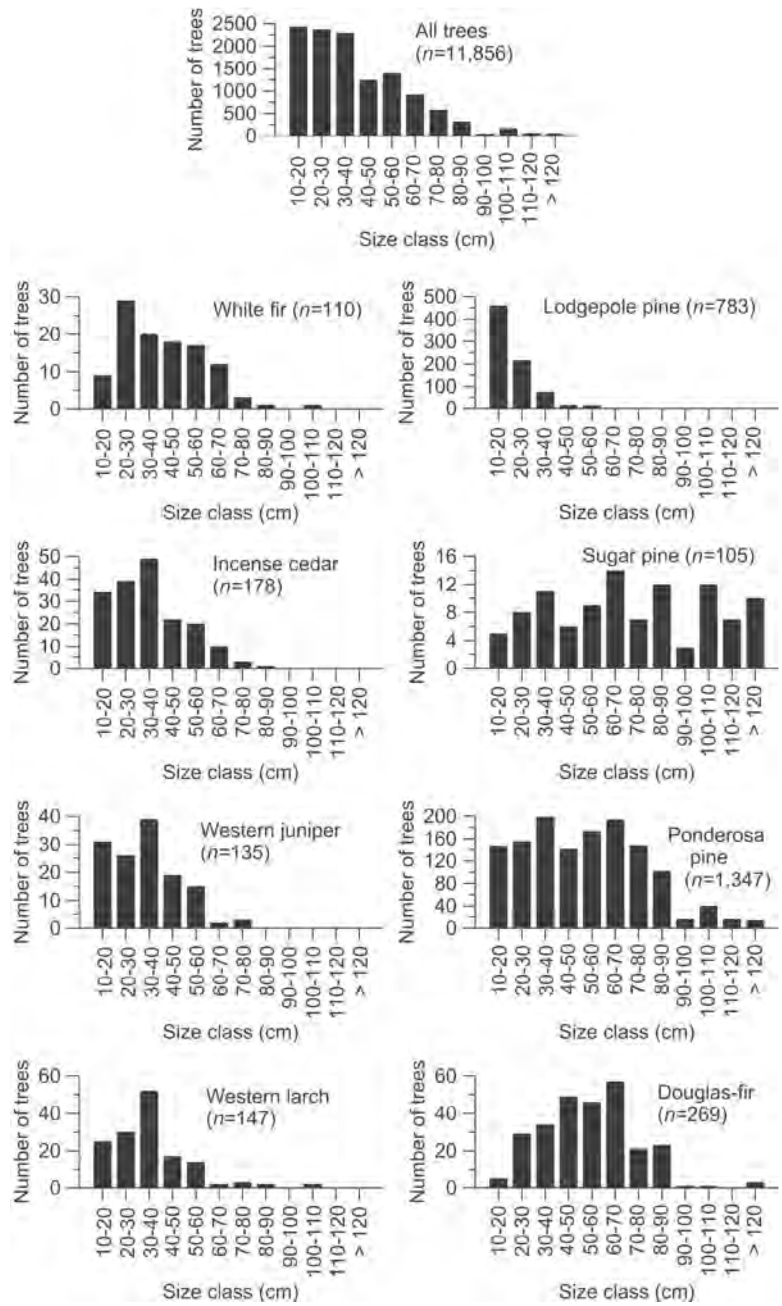

Fig. 3. Historical tree-diameter distributions for trees recorded by the surveyors, pooled across the study area. Shown are the distributions for all trees, regardless of species ($n = 11{,}856$), and individual species with sufficient data ($n > 100$).

forest and steeper, more complex topography in the study area than other areas. However, even ponderosa pine forests, with a mean of 219 trees/ha (Table 3), were denser than in other areas.

Very dense forests (>300 trees/ha) characterized ≥25% of historical landscapes in the study area. Even ponderosa pine forests had >283 trees/ha over 25% of the area (Table 3). There is some other evidence of historically high tree density in Northwestern dry mixed-conifer for-

Table 5. Percentage of historical forest area meeting the low-severity fire model, percentage of forest area by fire severity, and approximate high-severity fire rotation.

Metric	Study area	Region: North	Region: Central	Region: South	Ponderosa pine	Mixed conifer†	Lodgepole pine on pumice
Total forested area in sample (ha)	398,217	146,555	147,502	104,160	123,576	140,422	22,051
Low-severity fire model							
Parameter 1: % of forest with <177.6 trees/ha	36.7	40.9	34.8	33.5	57.4	24.7	28.8
Parameter 2: % of forest where <46.9% of conifers were <30 cm	49.0	62.3	22.2	68.3	60.2	52.3	11.1
Parameter 3: % of forest where >29.2% of conifers were ≥40 cm	57.8	69.0	31.8	78.7	69.6	62.5	18.1
Low severity: % of forest that meets all 3 parameters	23.5	32.5	10.4	29.4	39.8	18.1	4.6
Reconstructed fire severity							
Low (% of total forested area)	23.5	32.5	10.4	29.4	39.8	18.1	4.6
Mixed (% of total forested area)	50.2	44.2	48.2	61.7	44.0	58.9	28.1
High (% of total forested area)	26.3	23.3	41.4	8.9	16.2	23.0	67.3
High-severity fire rotation							
Period of observation (years)	114.1‡	120	115	105	114.1‡	114.1‡	115
High-severity fire rotation (years)§	435	515	278	1180	705	496	171

† Mixed conifer in this case (not in other tables) excludes lodgepole pine on pumice, which is treated in the next column.
‡ Calculated as mean of periods in the three regions, weighted by forested area in each region.
§ Calculated as period of observation/(% high fire severity/100.0).

ests (Agee 2003*b*: 348 trees/ha at Crater Lake; MacCracken et al. 1996: 371 trees/ha at Entiat, WA).

Open, low-density forests with <100 trees/ha, although only 13.5% of total forest area, were found in some contiguous areas (e.g., north of Sisters; Fig. 1). These appear to be in areas that are relatively flat, gently sloping, or undulating. Also, the open, low-density condition may be ephemeral, a temporary condition after episodes of low- to mixed-severity fire (Morrow 1986, Hessburg et al. 2007). Contiguous areas with open, low-density forests at the time of the surveys appear to often correspond with evidence of low- and mixed-severity fire (Figs. 1 and 3). Morrow's (1986) tree-ring reconstructions of age structure in ponderosa pine-lodgepole pine forests in the study area first suggested tree density and composition fluctuated in this area as episodes of fire were followed by recovery:

"Historical accounts of open, park-like ponderosa pine forests were made during periods of low stocking following the increased fire activity between 1840–1885. These forests were much more open during periods of increased fire activity that apparently killed smaller trees and shrubs than during periods of less fire activity and high survivorship. It is clear that the density and structure of the prehistoric stands were not constant. The historic accounts provide a short glimpse of the changing primeval forest" (Morrow 1986:69).

Morrow's hypothesis makes sense, as does Hessburg et al.'s (2007) similar explanation. Temporal evidence of the fluctuation would provide added validation. The hypothesis im-

Table 6. Estimated fire rotation (years) for low-severity fire, within the low-severity fire area, using snowbrush (*Ceanothus velutinus*) dominance in the section-line data as the indicator of recent low-severity fire. See text for explanation.

Ceanothus dominance in section-line data	Fire rotation (in years), assuming *Ceanothus* dominates: For 15 years after fire	For 30 years after fire
Either first or second	15.0/0.3199 = 47	30.0/0.3199 = 94
First	15.0/0.2112 = 71	30.0/0.2112 = 142

Note: The calculation is the period of *Ceanothus* dominance (in years) divided by the fraction of the total section-line length, within the low-severity fire area, that has *Ceanothus* dominant either first or second or just first.

plies that open, low-density forests may naturally change to denser forests with abundant small trees and shrubs as they recover from episodes of fire. The study area, as explained below, certainly contained abundant historical evidence of small trees and shrubs consistent with this hypothesis.

Shade-tolerant trees (grand fir/white fir, Douglas-fir, incense cedar) were usually not the most abundant trees, but were not historically rare (H_2) in study-area forests. Firs actually dominated on 12% of forest area overall and 14.6% of dry mixed-conifer forests, and occurred in 65% of forest area overall and 80.5% of dry mixed-conifer forests. With 25.0% of forest area having >27.3% firs (Table 3), firs were much more abundant than in northern Arizona, but similar to the Blue Mountains, where 19.3% of forest area had >30% fir, and Colorado Front Range, where 26.9% of forest area had >30% firs (Williams and Baker, in press). Both white fir and Douglas-fir had pooled size-class structures that suggest ongoing, if episodic regeneration that allowed these trees to become canopy dominants or co-dominants (Fig. 3). Fir concentrations were not confined to moist sites (Fig. 2), as suggested by previous studies and in a recent review (Perry et al. 2011), nor were they forced by fire into topographic refugia, as in Washington (Camp et al. 1997). Firs were less abundant in the central region than the other regions (Table 4), perhaps partly because of a shorter fire rotation in the central region. However, firs were found across all aspects and slope positions, although somewhat favored by higher elevations and steeper slopes (Fig. 2). It is also possible that fir concentrations are related to environment at finer resolutions than can be detected with GLO data.

Regarding H_3, the survey data show that Sierran lodgepole pine was abundant, and often small in stature historically, likely because it is favored by mixed- and high-severity fire. Dominance of high- and mixed-severity fire, relatively short high-severity fire-rotation (Table 5), and early observations all suggest the historical abundance of Sierran lodgepole pine in pumice-zone dry forests was promoted by mixed- and high-severity fire. Historical lodgepole mosaics are also documented in the central region, from early photographs and observations (Johnson et al. 2008). Although this tree is non-serotinous, it regenerates readily after patchy high-severity fire or moderate-severity fire with survivors (Agee 1993). It can out-compete ponderosa pine early in post-fire succession, through superior seeding, but appears short-lived, based on its size-structure (Fig. 3) and evidence of susceptibility to insects and disease (Agee 1993). It is also favored by soils and frost conditions on flat areas on pumice (Kerr 1913, Youngberg and Dyrness 1959). Some previous researchers thought abundant young lodgepole and other trees were from fire exclusion (Morrow 1986, Perry et al. 2004), but did not reconstruct fire history in their study areas, and thus mis-interpreted age structures. Abundant lodgepole pine today represent post-fire regeneration after mid-1800s fires, not fire exclusion, as documented by mixed- and high-severity fire evidence and abundant small lodgepole from 1880–1883 surveys.

Hypothesis H_4 was rejected because understory trees, particularly pines but also firs, were present on 57.4% of historical forest area and dense on 30.3% of forest area. Dry forests in the Blue Mountains had understory trees on much less area, only 33.2% of forest area, and northern Arizona and Colorado had even lower levels of understory trees, with presence over only 1.2–9.9% of forest area (Williams and Baker, in press). On the Warm Springs Indian Reservation northwest of Bend, West (1969*a*) reconstructed evidence of historical tree-regeneration thickets, with tree density from 5,000–10,000 trees/ha, that he linked to regeneration after insect-killed patches of trees were blown down and then burned. Early observations also document scattered dense thickets of tree regeneration. A likely explanation of common or dense understory trees is that, where fires burned with moderate severity or even patchy high severity, as in West's example, tree regeneration was stimulated by the opening of the canopy.

Historical forests generally were not numerically dominated by large trees (H_6). Instead, trees from 10–40 cm in diameter made up 60.0% of total trees, trees 10–40 cm in diameter were >50% of trees across 72.3% of forest area, and all tree species had small trees (Fig. 3). Numerical dominance by small trees is also supported by directly measured stand structures in the south region (Munger 1917). The abundance of old-growth forests documented by Cowlin et al.

(1942) suggests large old trees were common across substantial area, but reconstructions show that old forests were dense and also had abundant small trees. Fire-resistant ponderosa pine and Douglas-fir had more large trees, suggesting they more commonly survived mixed- or high-severity fires (Fig. 3), consistent with Hessburg et al. (2007:14) who found that "where large trees were present, they formed a remnant overstory representing less than 30% of total canopy cover." Size-distributions for white fir, western larch, and Douglas-fir hint at episodes of regeneration linked to fires (western larch) or fire-free periods (white fir, Douglas-fir). A fire-free period led to canopy white fir in mixed-conifer forests at Crater Lake (Agee 2003*b*).

Regarding H_5, shrubs also were present on 71.0% of historical forest area and dense over 43.6% of forest area, even more so in dry mixed-conifer forests. Dry forests in northern Arizona and Colorado had much lower historical levels of understory shrubs, with shrubs present on only 0.3–11.1% of forest area, except 18.3% in the Blue Mountains, still much lower than in the eastern Cascades (Williams and Baker, in press). The main shrubs in Oregon's eastern Cascade dry forests historically and today are: (1) greenleaf manzanita, which resprouts from underground lignotubers or from seed (Ruha et al. 1996), (2) snowbrush ceanothus, with fire-stimulated re-sprouting and seeds (Conard et al. 1985), and (3) antelope bitterbrush, which regenerates rapidly after fire from rodent seed caches (Sherman and Chilcote 1972) or other means (Busse and Riegel 2009). Abundant fire-adapted shrubs capable of rapid recovery after fire suggest these forests lacked extended periods or areas without shrubs, as shown by the reconstructions. Early observations of sparse or shrubless areas may indicate early postfire conditions or environmental settings unfavorable to shrubs, as found across 29% of the forest area (Table 4).

Estimated fire rotations for low-severity fire show they did not occur at intervals short enough to keep understory trees and shrubs at low levels. Reports of short intervals for low-severity fire (e.g., Agee 1993) used mean composite fire intervals, which underestimate fire rotation and mean fire interval (Baker and Ehle 2001, Baker 2009). Directly estimated fire rotations are 29–78 years at the three sites (Bork 1984), a range that includes the 53-year low-severity fire rotation for dry forests in eastern Washington (Wright 1996). Indirect estimates from snowbrush ceanothus (Table 6) are quite rough, but support the direct estimates. Mean intervals of 29–78 years between low-severity fires allow many trees to regenerate over large areas, reach sufficient size to resist mortality in low-severity fires (Baker and Ehle 2001) and allow shrubs to fully recover after fire. A 30-year fire-free interval allowed white fir to ascend into the canopy in mixed-conifer forests at Crater Lake (Agee 2003*b*). That low-severity fire occurred at modest rotations helps explain widespread understory trees and shrubs, large areas with dense understory trees and shrubs, and the common occurrence of dense forests with firs (Fig. 1, Tables 3–4).

Regarding H_7, the reconstructions show that historical forests were not dominated by low-severity fire, but instead had all severities, including substantial high-severity fire (Table 5, Fig. 4). Simulation shows that the historical mean tree density of 249 trees/ha across the study area is congruent with the variety of fire severities found in the reconstructions (Johnson et al. 2011). The mixtures (18.1% low severity, 58.9% mixed severity, and 23.0% high severity) in dry mixed conifer are also quite similar to those of Hessburg et al. (2007) for dry mixed conifer, who found 18.5% low, 51.7% mixed, and 29.8% high severity in their ESR5 vegetation type, which included some of the Deschutes. This similarity adds validation to both reconstructions. Hessburg et al. (2007) found no difference in fractions by severity, comparing ponderosa pine and Douglas-fir cover types, but in my study area, ponderosa pine forests had more low- and less mixed- and high-severity fire (Table 5). A recent review of mixed-severity fire in Northwestern forests suggested variable-severity fire did not occur historically in ponderosa pine forests or dry mixed-conifer forests, except in Washington (Perry et al. 2011). However, the reconstructions show that both ponderosa pine and dry mixed-conifer forests in the Oregon eastern Cascades historically experienced a variety of fire severities, including substantial high severity (Table 5).

The rate of historical high-severity fire was not high (H_8). The overall 435-year high-severity fire rotation (Table 5) is shorter than the 522-year rotation estimated for dry forests in northern Arizona and 849 years in the Blue Mountains, but not as short as the 271-year rotation estimated for the Colorado Front Range (Williams and Baker, in press). A charcoal-based paleoecological reconstruction (Long et al. 2011) from Tumalo Lake (T018SR010E, 18 km west of Bend), on the ecotone between moist and dry mixed-conifer forests, shows a recent "fire-episode" frequency of about 3 per 1000 years (333-year mean). This site is near the border between north and central regions, which have estimated rotations of 435 and 278 years (mean = 357 years), respectively, congruent with the paleo-estimate. This adds validation to the high-severity fire reconstruction, and also suggests the charcoal estimate is primarily detecting high-severity fires.

The GLO reconstructions show that most past hypotheses about dry-forest structure and fire severity were rejected, just as they were by Hessburg et al. (2007) for eastern Washington and part of Oregon's Deschutes National Forest. Past understanding of historical variability in these forests was limited by: (1) too much extrapolation from spatially limited or anecdotal data, (2) incomplete analysis of historical observations, (3) the inherently limited and often biased sample from tree-ring-based studies, and (4) misinterpretation of fire-history parameters. Weaver (1959, 1961) thought selected observations of park-like historical conditions represented the whole landscape, but the GLO reconstructions show they did not (Fig. 1, Tables 3–5), as in eastern Washington (Hessburg et al. 2007). Weaver missed that scattered historical observations actually do include evidence of low-, mixed- and high-severity fires, young postfire forests, brushfields, dense understory shrubs and small trees, and other features of historically variable fire severity and forest structure. Tree-ring studies are invaluable, but use extant evidence, which is inherently limited because few sites are relatively free of EuroAmerican land-use effects, selection among sites is often biased by a focus on old-growth forests, and because they are so labor intensive that it is difficult to study much land area. Variability in tree density and fire severity (Figs. 1 and 4) shows that studies of less than about 25,000 ha in dry forests are likely to provide only partial understanding. Most studies in the region covered much less area, did not estimate fire rotation, and incorrectly assumed that mean composite fire intervals estimate fire rotation and mean fire interval (Baker and Ehle 2001). These limitations led to incomplete understanding of historical dry forests and fire elsewhere in the West (Hessburg et al. 2007; Williams and Baker, in press).

Spatially extensive reconstructions from the GLO surveys and early aerial photography (Hessburg et al. 2007) overcome many of these limitations, but have some others. They, like historical observations and tree-ring reconstructions, "provide a short glimpse of the changing primeval forest" (Morrow 1986:69). Structure-based reconstruction of fire from the GLO surveys and early aerial photography cannot always discriminate effects of fire from insects, disease, and other disturbances. Spatial extent and contiguity suggest fire rather than insects or disease, which rarely are stand-replacing (Youngblood et al. 2004). Also, GLO surveys do not provide details of forest structure below the area of reconstruction polygons, about 520 ha for a 6-corner pool. Early aerial photography, in contrast, allows reconstruction down to about 4 ha (Hessburg et al. 2007). However, the GLO surveys do allow accurate reconstruction of spatial variability in parameters of forest structure across large landscapes, prior to many EuroAmerican land uses, not possible with other methods.

Fuel reduction is not ecological restoration in dry forests

Today's fuel-reduction focus in dry forests was based on the theory that frequent, low-severity fires maintained widespread low-density historical forests, which are thought today to have a large surplus of trees and wood that can be removed, providing both ecological benefits and wood products (e.g., Johnson and Franklin 2009). The reconstructions show that this theory of historical fire and forest structure is incorrect for dry forests in the eastern Oregon Cascades. This theory now has also been rejected for dry forests in eastern Washington (Hessburg et al. 2007), the Blue Mountains, Oregon (Williams and Baker, in press), the Rocky Mountains (Baker et al. 2007; Williams and Baker, in press), and northern

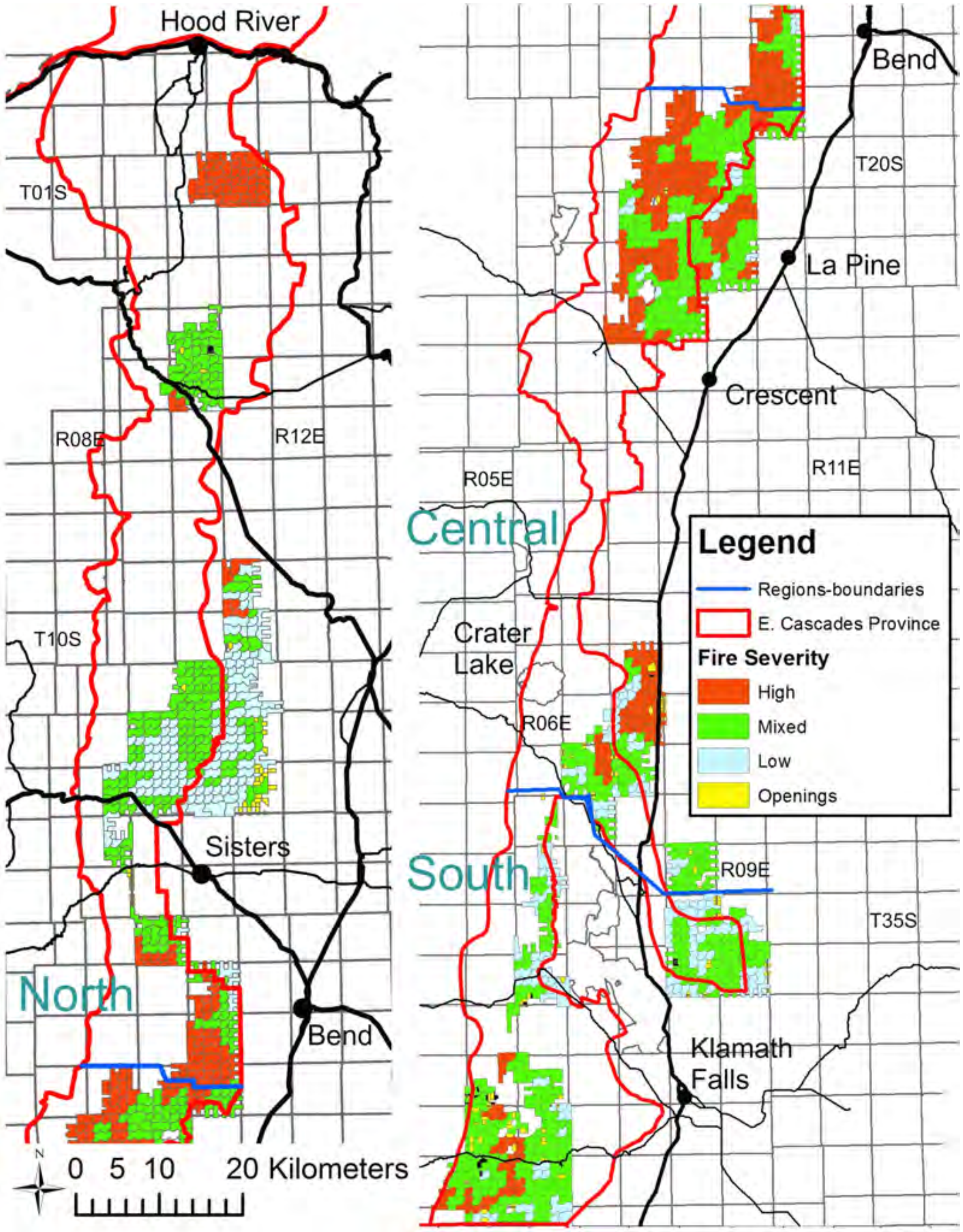

Fig. 4. Fire severity evident in forest structure at the time of the surveys. See text for definitions of the three fire-severity classes.

Arizona (Williams and Baker, in press).

Commonly proposed fuel-reduction actions would generally alter or degrade, rather than restore these Oregon forests. First, the idea that the risk of high-severity fire, or the fraction of fire burning at high severity, has increased and needs to be lowered (e.g., Spies et al. 2006, Perry et al. 2011), is not supported. This study shows that high-severity fire was a substantial component of historical fire regimes in both dry mixed conifer and ponderosa pine forests (Table 5, Fig. 4). Also, the risk of high-severity fire has not increased relative to historical landscapes, as the 435-year approximation of historical high-severity fire rotation is little different from the 469-year recent high-severity rotation in old forests in the eastern Oregon Cascades (Hanson et al. 2009). The fraction of total fire burning at high severity also has not increased. For example, a recent fire perceived as unnaturally severe in dry forests of the eastern Oregon Cascades (2003 B&B Spies et al. 2006), actually had only 5% high severity (http://www.mtbs.gov). Much of the high severity was at higher elevations outside dry forests, and the fraction of high severity in dry forests was quite low relative to the fraction of historical forest area with evidence of high-severity fire (Table 5, Fig. 4). The fraction of total fire burning at high severity in dry forests of the eastern Cascades also did not increase from 1984–2005 (Hanson et al. 2009). If the goal is maintaining or restoring historical fire regimes, treating large land areas (e.g., about 45% of dry forests in 20 years; Johnson and Franklin 2009) to reduce high-severity fire would, if effective, substantially add to fire exclusion and alter or degrade, not restore these forests.

Second, the common practice of burning or mechanically removing understory trees and shrubs to reduce fire risk and lower competition in dry forests will alter or degrade, rather than restore forest structure, since understory trees and shrubs were historically abundant (Table 4), small trees were numerically dominant, and these forests were generally dense (Table 3). The notion that trees in these forests today are unnaturally stressed by competition due to abnormally high tree density (e.g., Johnson and Franklin 2009, Perry et al. 2011) is not supported. Although tree density may be higher today, relatively dense and even very dense forests, with a wide diversity of tree sizes, were historically the norm in the dry forests of the eastern Cascades, even in ponderosa pine forests (Table 3).

Even if the focus is on perpetuating dry forests in the face of impending climatic change, fuel reduction, as currently practiced, is mis-directed, as understory trees and shrubs are key sources of ecosystem resilience in an era of droughts, beetle outbreaks, and more fire. The dominant conifers, ponderosa pine and Douglas-fir, have thick bark and elevated crowns and may resist fire (Baker 2009), but are vulnerable to severe droughts and beetle outbreaks (Littell et al. 2010). Thinning might increase the resistance of large, old trees to droughts and beetle outbreaks up to a point (Fettig et al. 2007). However, in general it is the smaller established trees, not the large, old trees, that often partly survive and may recover after severe droughts and beetle outbreaks (Cole and Amman 1969, McCambridge et al. 1982, McDowell et al. 2008). Native shrubs, in contrast, have fire and drought adaptations (see above), are not prone to outbreak insects, and provide key nurse roles in enhancing conifer survival and regeneration (Foster 1912, Zavitkovski and Newton 1968, Conard et al. 1985). It may be more difficult to maintain resistance than resilience, particularly as climatic change becomes more severe (Millar et al. 2007). Northwestern pines, in particular, are expected to decline as their suitable climate disappears (Littell et al. 2010). Fuel reduction, as currently practiced, compromises ecosystem resilience by placing too much emphasis on resistance by old conifers.

Reconfiguring ecological restoration in dry forests of the Oregon eastern Cascades

If fuel reduction is an inappropriate focus for restoration, given this study, what management actions would be compatible with the findings? I suggest a combination of no action, modest active restoration with a re-directed focus, and passive restoration, if the goals are to restore dry forests, using historical fire and forest structure as a guide, while considering climatic change. First, since expansive treatment is infeasible, due to cost, it is fortunate that a substantial fraction of dry mixed-conifer forests, that are currently dense, need no restoration treatment at all, since dense forests with substantial fir characterized sizable fractions of the study area (Table 3).

Second, evidence is compelling that a century of industrial logging of large trees, particularly pines (Robbins 1997, Bowden 2003), led to an increase in small firs (West 1969*b*, Hessburg and Agee 2003). However, the magnitude of increase is not yet quantified. This study shows that firs were more abundant and widespread historically than previously thought, but may underestimate the historical abundance of firs overall in dry forests, because I focused on the driest forests. Also, there is some emerging data (e.g., Merschel 2010), but no comparable published spatially extensive statistical sample of today's forests for comparison. Nonetheless, it is likely that some areas could be restored by reducing white fir/grand fir to its more modest historical levels, but not as in common fuel-reduction approaches today. The approach would instead be to retain the high diversity of tree sizes that occurred historically, including small firs in forest understories and mid-size, sub-canopy firs. Also beneficial would be restoration of elements of old forests lost to logging, including large live trees, as well as large snags and down wood (Youngblood et al. 2004), which would also help the Northern Spotted Owl (Hanson et al. 2010). Since Northern Spotted Owls may be favored by the firs, since the density reduction is likely modest and unlikely to provide economic gain, and since ecological threats from firs appear low, I suggest passive restoration through self-thinning is most sensible. If adaptive-management thinning trials proposed for spotted owl recovery (USFWS 2011) show that owls would benefit, perhaps a short period of active management makes sense, but there is no ecological reason ongoing silviculture (e.g., Johnson and Franklin 2009) should be needed.

Third, regional- and landscape-scale variation is worth maintaining or restoring, including geographical areas of denser forests with more firs (e.g., southwest of Klamath Falls) and low-density ponderosa pine forests (e.g., north of Sisters), as well as the high-severity fire and mosaic of lodgepole and ponderosa pines, that characterized pumice-zone forests (Fig. 4, Table 5). Although park-like old-growth dry forests may be ephemeral, ultimately succumbing to high-severity fire (Hessburg et al. 2007), long high-severity rotations suggest that restoring diversity to today's mosaic of logged, recovering forests will provide long-term benefits for wildlife and ecosystem functioning. At the landscape scale of a few townships (e.g., 25,000 ha), maintaining or restoring the mosaic of tree densities, which varied by a factor of 2–4 or more (Fig. 1), is important to enhancing resilience to climatic change (Millar et al. 2007, Halofsky et al. 2011). Here, too, retention of the historical diversity of tree sizes, even in ponderosa pine forests (Fig. 3) is important. Since pure ponderosa forests are not generally habitat for spotted owls, concern for adverse effects of active management is lower and can focus on effects on other species.

Finally, in all restoration treatments in dry forests, understory fuels (shrubs and small trees) would be maintained and restored, rather than reduced, and then maintained by modest (multi-decadal) low-severity fire rotations that allow high cover of shrubs and small trees. The diversity of tree sizes and potential for mixed- and high-severity fires that occurred historically can be restored and maintained. Rather than measuring success by reduction in torching index and creation of fire-safe forests (e.g., Perry et al. 2004, Johnson et al. 2011), success would be measured by perpetuation of the historical diversity of fire severities and forest structures. This can best be achieved with ongoing wildland fire use (Zimmerman et al. 2006) or multi-objective wildland fires, supplemented near infrastructure by prescribed fires, not aimed at fuel reduction, but instead at mimicking historical low-severity rotations, severities, and spatial patterns (Baker 2009). These forests are more likely to persist through the impending period of climatic change if the ecosystem resilience conferred by the historical density and diversity of shrubs and small trees is restored, along with the historical landscape diversity of forest structure that resulted from variable fire severity.

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Supplemental Material

Appendix A

Table A1. Early observations (up to about A.D. 1920) about fire and forest structure in dry forests of Oregon's eastern Cascades and nearby areas. Observations are arranged by topic, then from general locations to specific and from north to south. Phrases in square brackets are this author's insertions for clarification.

Source	Location	Quote	Interpretation
Low-severity fires			
Munger (1917:9–10)	Eastern Oregon ponderosa pine forests	Q1: "... by far the greatest amount of damage is done by surface fires which work in an inconspicuous way. Light, slowly spreading fires that form a blaze not more than 2 or 3 feet high and that burn chiefly the dry grass, needles, and underbrush start freely in yellow-pine forests, because for several months each summer the surface litter is dry enough to burn readily. Practically every acre of virgin yellow-pine timberland in central and eastern Oregon has been run over by fire during the lifetime of the present forest, and much of it has been repeatedly scourged."	Widespread surface fires burn at low intensity
Munger (1917:11)	Eastern Oregon ponderosa pine forests	Q2: "Each fire kills the seedlings and some of the saplings, so that, if the fires are of frequent occurrence, no young growth has a chance to replace the mature trees that die from natural causes."	Low-severity fires kill young trees
Von Wernsted (1906) cited in Weaver (1959:16)	Warm Springs Indian Reservation 90 km northwest of Bend; north region	Q3: "The yellow pine reproduction is uneven and on the whole poor on account of ground fires which have been frequent in the past... Fires have been frequent in the past and there is hardly any area that does not show signs of old fires. In the yellow pine the effect has been mainly to keep down the reproduction..."	Widespread low-severity fires kill most young trees
Leiberg (1900:248)	Southern part of Eastern Oregon Cascades; central and south regions	Q4: "But the open character of the yellow-pine type of forest anywhere in the region examined is due to frequently repeated forest fires more than to any other cause..."	Frequent low-severity fires maintain open forests
Leiberg (1900:288–289)	Southern part of Eastern Oregon Cascades; central and south regions	Q5: "On the eastern side of the Cascades, especially, fires have run through the yellow-pine timber many times. The absence or relative scarcity of young growth and underbrush is here very noticeable and striking..."	Frequent low-severity fires maintain open forests
Leiberg (1900:290)	Southern part of Eastern Oregon Cascades; central and south regions	Q6: "A fire in stands of this species [ponderosa pine] runs rapidly, burns low, and with no great intensity owing to the extremely light humus cover."	Low-severity fires are fast and low in intensity

Table A1. Continued.

Source	Location	Quote	Interpretation
Mixed-severity fires			
Leiberg (1900:424), Dodwell and Rixon (1903:286–287)	T037S R005E; 40 km northwest of Klamath Falls; south region	Q7: "In many localities the fires have made a clean sweep of the timber, and the areas have grown up to brush; in other places they have been of low intensity, burning 40 per cent of a stand here, 5 per cent there, or merely destroying individual trees, but consuming the humus and killing the undergrowth."	Fires are high-severity in places and low-severity in other places
Leiberg (1900:446)	T039S R005E; 40 km west of Klamath Falls; south region	Q8: "Fires have run everywhere in the forest stands, suppressing the young growth, burning great quantities of the firs, and filling the forest with a great many small brushed-over tracts in place of the consumed timber."	Fires are high-severity in places and low-severity in other places
Munger (1917:9)	Eastern Oregon ponderosa pine forests	Q9: "Occasionally a fire gets into the tops of the trees in a pure yellow-pine forest on a slope and sweeps over the whole hillside, perhaps a square mile in extent, killing all the trees in its path. This spectacular form of fire damage is uncommon, however; ..."	High severity in parts of fires
Weaver (1961:569).	southern part of Eastern Oregon Cascades; central and south regions	Q10: "The last great fire, or series of fires, covered over 200,000 acres [80,972 ha] during the summer of 1918... Little is known of the 1918 fire, except that it covered most of the central portion of the reservation [Klamath Indian Reservation] and that in general it did not cause excessive damage, except where it crowned through lodgepole pine stands and in the vicinity of Skelloch Draw and Military Crossing. There it crowned in patches of ponderosa pine. Extensive pole stands of this species there date back to the 1918 fire."	Fire was low severity over large areas but high severity in places
High-severity fires in ponderosa pine forests			
Weaver (1961:569)	Southern part of Eastern Oregon Cascades; central and south regions	Q11: "The last great fire, or series of fires, covered over 200,000 acres [80,972 ha] during the summer of 1918... Little is known of the 1918 fire, except that it covered most of the central portion of the reservation [Klamath Indian Reservation] and that in general it did not cause excessive damage, except where it crowned through lodgepole pine stands and in the vicinity of Skelloch Draw and Military Crossing. There it crowned in patches of ponderosa pine. Extensive pole stands of this species there date back to the 1918 fire."	High-severity fires in ponderosa pine forests
High-severity fires: large fires			
Langille (1903:36)	North region	Q12: "... along the eastern slope, toward the plains ... tamarack has done more than any other species to restock the immense burns that have taken place in this part of the reserve."	Very large high-severity fires

Table A1. Continued.

Source	Location	Quote	Interpretation
Leiberg (1900:278)	T030S R008E, T031S R008E, T030S R009E, T031S R009E; 30 km east of Crater Lake; central region	Q13: "The largest burns directly chargeable to the Indian occupancy are in Ts. 30 and 31 S., Rs. 8 and 9 E. In addition to being the largest they are likewise the most ancient. The burns cover upward of 60,000 acres, all but 1,000 or 1,100 acres being in a solid block. This tract appears to have been systematically burned by the Indians during the past three centuries. Remains of three forests are distinctly traceable in the charred fragments of timber which here and there litter the ground. Two of these were composed of lodgepole pine. The most ancient one appears to have consisted of yellow pine, which would be the ultimate forest growth on this area following a long period of freedom from fire."	High-severity fires exceeding 24,000 ha
Low-severity fires and brushfields			
Munger (1917:11)	Southern part of Eastern Oregon Cascades; central and south regions	Q14: "Each fire kills the seedlings and some of the saplings, so that, if the fires are of frequent occurrence, no young growth has a chance to replace the mature trees that die from natural causes. . . If this process is continued long enough, it will annihilate the yellow pine by gradually killing off the old trees and at the same time preventing the survival and maturity of any young ones. This very thing has happened in places in the Siskiyou Mountains and southern Cascades. Here areas once covered by fine stands of yellow-pine timber are now treeless wastes, covered only by brush or mock chaparral."	How low-severity fires could eventually lead to brushfields
High-severity fires and brushfields			
Langille (1903:68)	T001N R010E; 25 km northeast of Mt. Hood; north region	Q15: "Creeping fires have destroyed much of the timber, and dense brush has followed"	High-severity fires led to brushfields
Langille (1903:48)	T001S R010E; 15 km northeast of Mt. Hood; north region	Q16: "The greater part of this township has been burned over and has grown up to a dense tangle of willow, ceanothus, and other shrubs."	High-severity fires led to brushfields
Langille (1903:64)	T004S R011E; 35 km southeast of Mt. Hood; north region	Q17: "In the northwestern sections the brush is very dense where old burns have taken place"	High-severity fires led to brushfields
Foster (1912:213)	Southern part of Eastern Oregon Cascades; central and south regions	Q18: "Brush occurs very generally throughout the forest [the old Crater National Forest], occasionally forming an exclusive cover, but ... there is evidence that this condition is temporary..."	High-severity fires led to brushfields
Leiberg (1900:286)	Southern part of Eastern Oregon Cascades; south region	Q19: "Growths after fires on the eastern side of the Cascades in pure yellow-pine forest may be either brush or timber... Brush growths after fire are due to induced semiarid conditions... Where, in such places, fire has lessened the ratio of soil humidity, permanent brush growths usually take the place of the forest"	High-severity fires in ponderosa pine forests led to brushfields

Table A1. Continued.

Source	Location	Quote	Interpretation
Leiberg (1900:355)	T032S R012E; 70 km southeast of Crater Lake; 40 km east of south region	Q20: "The mill timber is exclusively yellow pine, fire marked throughout, easy of access from the Sycan, hence from the Sprague River Valley; of medium quality, much intersected by lodgepole-pine reforestations after fires; the lodgepole stands extensively invaded by recent fires which have utterly destroyed them in many places, giving rise to fire glades covered with brush."	High-severity fires in lodgepole pine forests led to brushfields
Dodwell and Rixon (1903:272), Leiberg (1900:382)	T034S R006E; 35 km south of Crater Lake; south region	Q21: "Where the yellow-pine stands have been destroyed heavy brush growths of the vellum-leaved ceanothus have followed."	High-severity fires in ponderosa pine forests led to brushfields dominated by *Ceanothus velutinus*
Dodwell and Rixon (1903:278)	T035S R006E; 45 km south of Crater Lake; south region	Q22: "Many of the burned-over tracts are covered with dense brush growth of various species of shrubs, the vellum-leaved ceanothus being the most common and prominent species."	High-severity fires led to brushfields dominated by *Ceanothus velutinus*
Dodwell and Rixon (1903:286–287)	T037S R005E; 40 km northwest of Klamath Falls; south region	Q23: "In many localities the fires have made a clean sweep of the timber, and the areas have grown up to brush; in other places they have been of low intensity, burning 40 per cent of a stand here, 5 per cent there, or merely destroying individual trees, but consuming the humus and killing the undergrowth."	High-severity fires led to brushfields in many places
Foster (1912:216)	T037S R005E; 40 km northwest of Klamath Falls; south region	Q24: "... a slope east of Lake of the Woods is typical... It consists of a large brush-covered area with scattering trees of yellow pine and white fir–trees of the lower-slope type ... the brush is the ubiquitous *Ceanothus*, with small clumps of *Salix*."	High-severity fires led to brushfields dominated by *Ceanothus velutinus* with scattered tree regeneration
Dodwell and Rixon (1903:288)	T037S R006E; 30 km northwest of Klamath Falls; south region	Q25: "Fires have run throughout the entire township, consuming 25 per cent of the timber and badly damaging the remainder. Brush growths composed chiefly of the vellum-leaved ceanothus (*Ceanothus velutinus*) have covered the burned areas in place of reforestations."	High-severity fires led to brushfields dominated by *Ceanothus velutinus*
Leiberg (1900:428)	T037S R010E; 15 km northeast of Klamath Falls; south region	Q26: "Fires have run throughout, and the forest is in consequence much broken by brushed-over fire glades."	High-severity fires led to brushfields
Leiberg (1900:446)	T039S R005E; 40 km west of Klamath Falls; south region	Q27: "Fires have run everywhere in the forest stands, suppressing the young growth, burning great quantities of the firs, and filling the forest with a great many small brushed-over tracts in place of the consumed timber."	High-severity fires led to many small brushfields
High-severity fires: the lodgepole pine and ponderosa pine mosaic			
Langille (1903:36)	Northern part of Eastern Oregon Cascades; north region	Q28: "Lodgepole pine reclaims large burned tracts and is valuable in promoting the growth of more desirable species."	High-severity fires favor lodgepole pine

Table A1. Continued.

Source	Location	Quote	Interpretation
Munger (1917:18)	Eastern Oregon Cascades; central region	Q29: "It [lodgepole pine] is a thrifty and militant species, and has the ability to occupy burns to the exclusion of all others. With the help of periodic surface fires, which have encouraged its reproduction and at the same time discouraged the reproduction of yellow pine, it has been able to encroach upon land where yellow pine might be growing"	High-severity fires favor lodgepole pine; low-severity fires have favored lodgepole pine over ponderosa pine
Leiberg (1900:250)	Southern part of Eastern Oregon Cascades; central region	Q30: "The aspect of the *murrayana* form, in its ultimate development, is that of close or moderately open stands of tall, straight, slender trees covering well-drained uplands. This form of the subtype is in every case a reforestation after fires, in this region after stands of yellow-pine."	High-severity fires in ponderosa pine forests favor lodgepole pine
Leiberg (1900:355)	T032S R012E; 70 km southeast of Crater Lake; 40 km east of central region	Q31: "The mill timber is exclusively yellow pine, fire marked throughout, easy of access from the Sycan, hence from the Sprague River Valley; of medium quality, much intersected by lodgepole-pine reforestations after fires; the lodgepole stands extensively invaded by recent fires which have utterly destroyed them in many places, giving rise to fire glades covered with brush."	High-severity fires in ponderosa pine forests favor lodgepole pine
Leiberg (1900:371)	T033S R012E; 75 km southeast of Crater Lake; 40 km east of central region	Q32: "The township contains a small bunch of yellow-pine stands of poor quality in the northwest corner. The balance of the township is covered with stands of lodgepole pine burned to the extent of 65 per cent by fires in recent times, and carrying here and there small scattered stands of yellow pine of little or no commercial value."	High-severity fires in lodgepole pine
Leiberg (1900:284)	Southern part of Eastern Oregon Cascades; central and south regions	Q33: "On the levels as well as on the mountain areas east of the Cascades, where the normal forest growth is chiefly yellow pine with small admixtures of sugar pine and white fir, reforestations after fires are nearly always pure growths of lodgepole pine."	High-severity fires in ponderosa pine forests favor lodgepole pine
Leiberg (1900:286)	Southern part of Eastern Oregon Cascades; central and south regions	Q34: "Growths after fires on the eastern side of the Cascades in pure yellow-pine forest may be either brush or timber... When timber, the reforestations are usually lodgepole pine."	High-severity fires in ponderosa pine forests favor lodgepole pine
Weaver (1961:569)	Southern part of Eastern Oregon Cascades; central and south regions	Q35: "The last great fire, or series of fires, covered over 200,000 acres [80,972 ha] during the summer of 1918... Little is known of the 1918 fire, except that it covered most of the central portion of the reservation [Klamath Indian Reservation] and that in general it did not cause excessive damage, except where it crowned through lodgepole pine stands..."	High-severity fires in lodgepole pine
Dodwell and Rixon (1903:152)	T18S to T029S; central and south regions	Q36: "The young growth east of the mountains is generally lodgepole pine and yellow pine where that timber is found, and in nearly every case where burns occur the lodgepole predominates."	High-severity fires favor lodgepole pine

Table A1. Continued.

Source	Location	Quote	Interpretation
High-severity fires and tree regeneration: larch			
Langille (1903:36)	Northern part of Eastern Oregon Cascades; north region	Q37: "Tamarack has done more than any other species to restock the immense burns that have taken place in this part of the reserve. This is largely due to the fact that the thick bark of this tree resists fire better than any other species, and more seed trees are left to cast their seed upon the clean, loose soil and ashes immediately after a fire. The seeds are small and light, and are carried to remote places by the winds and covered deeply by the fall rains. In the spring a dense mass of seedlings covers the ground and grows rapidly. The thickets become so dense that it is impossible to travel through them. In time, only the fittest survive, and there remains a thrifty, vigorous stand of this valuable timber."	Western larch survives and reseeds after high-severity fire
High-severity fires and tree regeneration: multiple species			
Leiberg (1900:284)	T039S R004E; T039S R005E; T039S R006E; T040S R004E; T040S R005E; T040S R006E; T041S R004E; T041S R005E; T041S R006E; 20–50 km southwest of Klamath Falls; south region	Q38: "But in the yellow-pine areas of Ts. 41, 40, and 39 S., Rs. 4 to 6E, inclusive, reforestations after fires are not composed of lodgepole pine. Reforestations here are yellow pine, red and white fir, sugar pine, and incense cedar; in short, the same species again come in which flourished before the fire."	A variety of species regenerate after high-severity fires south of the pumice zone in the central region
Forest structure: age/size structure			
Munger (1917:11)	Eastern Oregon ponderosa pine forests	Q39: "Each fire kills the seedlings and some of the saplings, so that, if the fires are of frequent occurrence, no young growth has a chance to replace the mature trees that die from natural causes."	Low-severity fires leave few small trees
Munger (1917:11)	Eastern Oregon ponderosa pine forests	Q40: "Yellow pine normally occurs in Oregon in uneven-aged stands in which trees of all ages are in intimate mixture; frequent fires prevent the stand from having the proper number of young trees."	Ponderosa pine forests are typically uneven-aged, with few young trees
Munger (1917:18)	Eastern Oregon ponderosa pine forests	Q41: "Yellow pine grows commonly in many-aged stands; i.e., trees of all ages from seedlings to 500-year-old veterans, with every age gradation between, are found in intimate mixture."	Ponderosa pine forests are typically uneven-aged
Munger (1917:18)	Eastern Oregon ponderosa pine forests	Q42: "In some stands there is a preponderance of very old trees; in fact, in many of the virgin stands of central and eastern Oregon there are more of the very old trees and less of the younger than the ideal forest should contain."	Ponderosa pine forests are typically dominated by old trees with a deficiency of young trees

Table A1. Continued.

Source	Location	Quote	Interpretation
Munger (1917:19)	Eastern Oregon ponderosa pine forests	Q43: "In the virgin stands throughout the State there seems to be a very large proportion of trees whose age is about 225 or 275 years, suggesting that after this age their mortality is greater."	Ponderosa pine forests often have trees up to about 225–275 years old
Langille (1903:33)	T004S R011E; 25 km southeast of Mt. Hood; north region	Q44: "The timber in this vicinity is almost all yellow pine of two classes, viz, old trees with an average diameter of 30 inches, and a younger growth about 18 inches in diameter."	Ponderosa pine forests with only two size classes of trees
Forest structure: tree density			
Munger (1917:17)	Eastern Oregon ponderosa pine forests	Q45: "In most of the pure yellow-pine forests of the State the trees are spread rather widely, the ground is fairly free from underbrush and débris, and travel through them on foot or horseback is interrupted only by occasional patches of saplings and fallen trees...On the north slopes, in draws, or in other places where mixed with other species, the yellow-pine forests are usually denser, more brushy, and therefore harder to traverse."	Ponderosa pine forests are typically low density except on moister slopes
Munger (1917:21)	Eastern Oregon ponderosa pine forests	Q46: "Yellow-pine forests are so irregular in density that figures for the average stand per acre or per quarter section are apt to be misleading."	Ponderosa pine forests are very variable in density
Munger (1917:20)	Eastern Oregon Cascades	Q47: "In pure, fully stocked stands in the Blue Mountain region there are commonly from 20 to 30 yellow pines per acre over 12 inches in diameter, of which but few are over 30 inches. Over large areas the average number per acre is ordinarily less than 20. On the slopes of the Cascades the number of trees per acre averages somewhat less than in the Blue Mountains, but the trees are larger. In mixed stands, the number of yellow pines of merchantable size is naturally less, though the total number of trees of all species is as a rule larger..."	In the Eastern Cascades, ponderosa pine forests may have <50–75 trees/ha that are >30 cm in diameter, with few trees >75 cm, but mixed-conifer stands are denser
Langille (1903:34–35, Plate IX)	T005S R010E; 30 km southeast of Mt. Hood; north region	Q48: Plate IX shows the forest being cut. The forest is obviously dense.	A dense dry forest visible in a picture from near A.D. 1900
Plummer (1903:78)	T005S to T017S; north region	Q49: "Its forests [ponderosa pine] are generally open, without much litter or undergrowth, and for these reasons are almost immune from fire."	Ponderosa pine forests generally low density
Weaver (1959:16)	Warm Springs Indian Reservation; 90 km northwest of Bend; north region	Q50: "Mr James G. Smith, an elderly member of the Warm Springs Tribe, recalls that as late as 1914 or 1915 it was possible to drive a wagon almost at will throughout most of the ponderosa pine type."	Early account suggests ponderosa pine forests were low density
Munger (1917:21)	Southern part of Eastern Oregon Cascades; central and south regions	Q51: Table 7 contains diameter-class distributions and tree-density estimates for two ponderosa pine stands: (1) Near Lapine: 32.5 trees/ha >10 cm; 29.3 trees/ha >30 cm; (2) Klamath Lake region: 151.9 trees/ha >10 cm; 87.0 trees/ha >30 cm.	Two ponderosa pine stands had 32.5 and 151.9 trees/ha

Table A1. Continued.

Source	Location	Quote	Interpretation
Weaver (1961:569)	T035S R008E, T035S R009E, T036S R008E, T036S R009E; 30 km north of Klamath Falls; south region	Q52: "In 1929 Jack Horton, an elderly cattleman of Hildebrand, Oregon, stated that in the early days the Ya Whee Plateau was 'open and grassy, like a park.'"	Early account suggests dry forests were low density
Weaver (1961:569)	20–35 km northeast of Klamath Falls; 10–20 km southeast of south region	Q53: "Harry Engle, an elderly resident of Fort Klamath, Oregon, still recalls vividly the days when he rode the range in the Sprague River–Swan Lake–Hildebrand area in the late 1880's and the 1890's... The forest was open and park-like with considerable grass..."	Early account suggests dry forests were low density
Forest structure: spatial pattern of tree regeneration			
Munger (1917:8)	Eastern Oregon ponderosa pine forests	Q54: "... yellow-pine reproduction is extremely patchy in the virgin forest; here there will be almost a thicket of young trees, and near by, under seemingly similar conditions, there will be little or no reproduction."	Ponderosa pine regeneration was highly variable
Munger (1917:18–19)	Eastern Oregon ponderosa pine forests	Q55: "Usually two or three or more trees of a certain age are found in a small group by themselves, the reason being that a group of many young trees usually starts in the gap which a large one makes when it dies."	Ponderosa pine regeneration was in small groups associated with a canopy gap
Langille (1903:36)	Northern part of Eastern Oregon Cascades; north region	Q56: "The yellow pine in some instances does good work in stocking open spots in the timber, but seldom extends far beyond the parent tree."	Ponderosa pine regeneration close to parent trees
Von Wernsted (1906) cited in Weaver (1959:16)	Warm Springs Indian Reservation 90 km northwest of Bend; north region	Q57: "The yellow pine reproduction is uneven and on the whole poor on account of ground fires which have been frequent in the past."	Ponderosa pine regeneration poor because of fires
Weaver (1961:569)	20–35 km northeast of Klamath Falls; 10–20 km southeast of south region	Q58: "Harry Engle, an elderly resident of Fort Klamath, Oregon, still recalls vividly the days when he rode the range in the Sprague River–Swan Lake–Hildebrand area in the late 1880's and the 1890's... The forest was open and park-like with considerable grass... To the specific query if there were young trees Mr. Engle replied that there were scattered groups of saplings and trees of pole size. He explained that fuel seldom accumulated in sufficient quantity to enable the fires to become very hot. Therefore, many of the young trees survived."	Dry forests had tree regeneration in scattered groups because of fire patterns
Forest structure-abundant or dense tree regeneration			
Munger (1917:11)	Eastern Oregon dry mixed conifer forests	Q59: "In certain parts of the State repeated surface fires have the effect of transforming the forest type from a stand consisting largely of yellow pine to one consisting of lodgepole pine, whose reproduction is extremely abundant and vigorous after fire."	Very dense lodgepole pine regeneration after fire

Table A1. Continued.

Source	Location	Quote	Interpretation
Munger (1917:8)	Eastern Oregon ponderosa pine forests	Q60: "... yellow-pine reproduction is extremely patchy in the virgin forest; here there will be almost a thicket of young trees, and near by, under seemingly similar conditions, there will be little or no reproduction."	Ponderosa pine regeneration was highly variable, including some thickets
Von Wernsted (1906) cited in Weaver (1959:16)	Warm Springs Indian Res. 90 km NW of Bend; N Region	Q61: "The yellow pine reproduction is uneven and on the whole poor on account of ground fires which have been frequent in the past. When there is reproduction in spots, it is, however, dense."	Where ponderosa pine regeneration occurs in spots, it is dense
Leiberg (1900:322)	T030S R010E; 45 km east of Crater Lake; 22 km east of central region	Q62: "In late years there has been fewer fires than formerly and the young growth, formerly mostly suppressed, is asserting itself everywhere. The young growth is yellow pine with a few scattered individuals of white fir."	Abundant ponderosa pine regeneration
Leiberg (1900:339)	T031S R010E; 50 km east of Crater Lake; 20 km east of central region	Q63: "Fires have not run much in later years and the young growth of yellow pine is therefore abundant."	Abundant ponderosa pine regeneration
Leiberg (1900:288–289)	Southern part of Eastern Oregon Cascades; central and south regions	Q64: "On the eastern side of the Cascades, especially, fires have run through the yellow-pine timber many times. The absence or relative scarcity of young growth and underbrush is here very noticeable and striking ... where the forest has enjoyed freedom from fire for a number of years seedling and sapling trees of the yellow pine are springing up in the greatest abundance."	Abundant ponderosa pine regeneration in places
Forest structure: shade-tolerant trees			
Langille (1903:36)	Northern part of Eastern Oregon Cascades; north region	Q65: "In the yellow-pine forests most of the young growth is red [Douglas-fir] or white fir, which, taking advantage of the shade and moisture afforded by the yellow-pine cover, is growing rapidly, and will, in time, form a larger percentage of the forest than it has in the past."	Most regeneration in dry mixed-conifer forests is Douglas-fir and white fir
Plummer (1903:102–103, Plate XVII)	Northern part of Eastern Oregon Cascades; north region	Q66: Plate XVII shows a mature stand of incense cedar	Mature incense cedar occurred in places
Leiberg (1900:446)	T039S R005E; 40 km west of Klamath Falls; south region	Q67: "Fires have run everywhere in the forest stands, suppressing the young growth, burning great quantities of the firs, and filling the forest with a great many small brushed-over tracts in place of the consumed timber."	Mixed-severity fires killed many firs
Munger (1917:17)	Eastern Oregon ponderosa pine forests	Q68: "In most of the pure yellow-pine forests of the State the trees are spread rather widely, the ground is fairly free from underbrush and débris, and travel through them on foot or horseback is interrupted only by occasional patches of saplings and fallen trees... On the north slopes, in draws, or in other places where mixed with other species, the yellow-pine forests are usually denser, more brushy, and therefore harder to traverse."	Ponderosa pine forests were fairly free of understory shrubs except on north slopes or in moister settings

Table A1. Continued.

Source	Location	Quote	Interpretation
Forest structure: understory shrubs			
Plummer (1903:78)	Northern part of Eastern Oregon Cascades; north region	Q69: "Its forests [ponderosa pine forests] are generally open, without much litter or undergrowth, and for these reasons are almost immune from fire."	Ponderosa pine forests had few understory shrubs
Plummer (1903:87)	Northern part of Eastern Oregon Cascades; north region	Q70: "In the yellow-pine region bordering the timberless area of eastern Oregon the forest floor is often as clean as if it had been cleared, and one may ride or even drive without hindrance. As the hills are approached the brush increases ... on the northern summits and on all the western slopes the underbrush is heavy, and together with the litter makes travel off the trails impossible with pack animals"	Ponderosa pine forests free of understory shrubs near lower forest border, but more shrubs in foothills
Von Wernsted (1906) cited in Weaver (1959:16)	Warm Springs Indian Reservation 90 km northwest of Bend; north region	Q71: "There is very little underbrush in the lower country and but very little grass ... with the foothills there is an increasing amount of chaparral undergrowth."	Dry forests had few understory shrubs near lower forest border, but more shrubs in foothills
Dodwell and Rixon (1903:152)	T018S to T029S; central region	Q72: "Along the eastern slope of the Cascade Mountains very little undergrowth is found, as the climate is much drier..."	Dry forests had few understory shrubs
Munger (1917:18)	Southern part of Eastern Oregon Cascades; central and south regions	Q73: "Here [southern Cascades] there is ordinarily a great deal of underbrush and chaparral, and the more open the woods the greater the amount of brush."	Dry forests in south had abundant shrubs, especially in lower-density stands
Leiberg (1900:288–289)	Southern part of Eastern Oregon Cascades; central and south regions	Q74: "On the eastern side of the Cascades, especially, fires have run through the yellow-pine timber many times. The absence or relative scarcity of young growth and underbrush is here very noticeable and striking..."	Ponderosa pine forests had few understory shrubs because of fires
Weaver (1961:569)	T035S R008E, T035S R009E, T036S R008E, T036S R009E; 30 km north of Klamath Falls; south region	Q75: "In 1929 Jack Horton, an elderly cattleman of Hildebrand, Oregon, stated that in the early days the Ya Whee Plateau was 'open and grassy, like a park.'"	Dry forests had grassy, not shrubby understories
Weaver (1961:569)	20–35 km northeast of Klamath Falls; 10–20 km southeast of south region	Q76: "Harry Engle, an elderly resident of Fort Klamath, Oregon, still recalls vividly the days when he rode the range in the Sprague River–Swan Lake–Hildebrand area in the late 1880's and the 1890's... The forest was open and park-like with considerable grass. There were clumps of manzanita (*Arctostaphylos* spp.), snowbrush (*Ceanothus velutinus*) and bitterbrush (*Purshia tridentata*), but these shrubs seldom grew very high because of the frequent fires set by cowboys and lightning."	Dry forests had considerable grass, with only clumps of shrubs, because of frequent fires

Appendix B

Table B1. Trees of the eastern Cascades, common names used by the surveyors, and abundance in the surveys, by group.†

Species	Common name	Number‡	Percentage‡
Conifers			
Calocedrus decurrens	Cedar	178	1.50
Juniperus occidentalis	Juniper	135	1.14
Larix occidentalis	Larch, tamarack	147	1.24
Picea engelmannii	Spruce	26	0.22
Pinus monticola	White pine	6	0.05
Tsuga mertensiana	Hemlock	10	0.08
Total		502	4.23
Firs			
Abies concolor/grandis	W. fir, White fir	110	0.93
Abies magnifica	Shasta fir	1	0.01
Fir sp.	Fir	1643	13.86
Pseudotsuga menziesii	Douglas-fir, Red fir	269	2.27
Total		2023	17.06
Hardwoods			
Acer circinatum	Vine maple	2	0.02
Alnus sp.	Alder	8	0.07
Fraxinus sp.	Ash	2	0.02
Populus sp.	Balm, cottonwood	3	0.03
Populus tremuloides	Aspen, quaking aspen	15	0.13
Prunus sp.	Cherry	1	0.01
Quercus sp.	Oak	22	0.19
Quercus garryana	White oak	57	0.48
Quercus kelloggii	Black oak	19	0.16
Salix sp.	Willow	7	0.06
Total		136	1.15
Pine			
Pinus contorta var. *murrayana*	B. pine, Black pine, Sassafras pine, tamarack (in one township)	783	6.60
Pinus lambertiana	Sugar pine	105	0.88
Pine sp.	Pine	6960	58.70
Pinus ponderosa	Y. pine, Yellow pine	1347	11.36
Total		9195	77.56
Grand total		11856	100.00

† These are species groups used in the reconstruction of basal area and diameter distributions.
‡ These are the number and percentage of trees recorded by the surveyors out of the grand total of 11,856 trees.

Appendix C

Table C1. Quality and consistency of information recorded by surveyors of the Oregon Eastern Cascades study area. Analysis of specific parts of section-line descriptions (e.g., understory trees and tree density) used only surveyors with entries recorded as "yes" in that column.

Surveyor	Used many density terms to describe timber	Recorded understory trees and tree density	Recorded understory shrubs and shrub density	Approximate number of townships surveyed
Major				
Perkins, Henry C.	Yes	Yes	Yes	7.5
Judkins, Thomas C.	Yes	Yes; only in 4 townships	Yes; only in 4 townships	7.0
Moore, Rufus S.	Yes	Yes	Yes	6.0
Lackland, Samuel W.	Yes	Yes	Yes	5.0
Meldrum, Henry	Yes	Yes	Yes	4.5
Chandler, Henry L.	Yes	Yes	Yes	2.5
Minor				
Applegate, Daniel W	No; only one term	Yes	Yes	0.5
Applegate, Jesse	Yes	Yes	Yes	0.7
Byars, W. H.	No; no use of terms	No	No	0.1
Campbell, Frank	Yes	No	Yes	0.8
Campbell, William B.	No; only one term	Yes	Yes	0.2
Campbell, William S.	Yes	Yes	Yes	0.3
Cartee, L. F.	No; no use of terms	No	No	0.1
Clark, Newton	Yes	Yes	Yes	0.3
Fisher, E. F. F.	Yes	No	No	0.2
Gradon, Herman D.	No; only one term	No; only rarely	No	1.0
Handley, T. B.	Yes	No	No	0.2
Howard, James	Yes	Yes	Yes	1.0
McQuinn, John A	Yes	Yes	Yes	1.0
McClung, John W.	No; no use of terms	No	No	0.1
Meldrum, John W.	No; only one term	No	No	0.5
Mensch, Fred	No; no use of terms	No	No	0.1
Mercer, George	No; only one term	No	No	0.1
Owen, Jason	No; only one term	No; only rarely	No	1.2
Pershin, George S.	No; only one term	Yes	Yes	0.4
Ransom, D. W.	Yes	No	No	0.5
Rumsey, James L.	No; only one term	Yes	Yes	1.5
Taylor, Douglas W.	No; only one term	Yes	No	0.1
Thompson, David W.	Yes	No	No	0.2
Tolman, James C.	No; only one term	Yes	Yes	1.3
Truax, Sewell	No	Yes	Yes	0.1
Turner, William M.	Yes	No; only rarely	Yes	0.4
Wilkes, Lincoln E.	Yes	Yes	Yes	0.1

Notes: Surveyors are rated as to whether they consistently used density terms (dense or heavily timbered, good, fine, and scattered) to describe timber and recorded understory trees and shrubs. To be given the rating "yes," a surveyor had to use all the terms and had to consistently record information about understory trees or shrubs.

Appendix D

Table D1. Understory species of the Eastern Cascades study area.

Species	Surveyor names
Acer circinatum, occasionally *A. macrophyllum*	Maple, vine maple
Alnus sp.	Alder, black alder
Amelanchier sp.	Serviceberry
Arctostaphylos patula	Chamise, manzanita, rhododendron
Artemisia tridentata	Sagebrush
Berberis aquifolium, *B. repens*	Barberry, bearberry, grape, wild grape
Calamagrostis rubescens	Pine grass
Castanopsis chrysophylla	Chinkapin
Ceanothus integerrimus	Lilac, heath lilac—based on color and inflorescence; no validation along section lines
Ceanothus velutinus	Annis, balm, cinnamon, elk brake, elk brush, greasewood, snowbrush
Cercocarpus ledifolius	Mahogany
Cornus sericea, or other *Cornus* spp.	Dogwood
Corylus cornuta	Hazel, Witch hazel
Fragaria sp.	Strawberry
Kraschennikikovia lanata	White sage
Populus tremuloides	Aspen, quaking aspen, quaking ash?
Prunus emarginata, and other *Prunus*	Cherry, plum
Prunus virginiana	Choke cherry
Purshia tridentata	Buck brush, chaparral, laurel, mountain laurel, myrtle, sweet laurel
Ribes cereum, occasionally other *Ribes*	Currant, gooseberry
Rosa woodsii or other *Rosa* sp.	Rose, wild rose
Rubus ursinus	Blackberry
Rubus parviflorus	Thimbleberry
Rubus spectabilis	Salmonberry
Salix sp.	Willow
Scirpus sp.	Tules
Vaccinium sp.	Huckleberry, whortleberry
Viburnum edule	Arrowwood; based on wood properties; no validation along section lines
Unknown species	Snowdrop

Appendix E

Table E1. Crown radius and Voronoi equations used in the reconstructions.

Group/species	Ln crown radius (CR)			Ln Voronoi area		
	Species equations			Group equations		
	Equation	n	R^2_{adj}	Equation	n	R^2_{adj}
Group 1				$1.470 + 0.330 \ln(CR/(1/Meandist^2))$	64	41.3
Abies concolor	$-0.163 + 0.347 \ln(dbh)$	21	53.3			
Abies grandis	$-0.576 + 0.417 \ln(dbh)$	22	34.9			
Calocedrus decurrens	$-1.000 + 0.529 \ln(dbh)$	24	38.8			
Pseudotsuga menziesii	$-0.200 + 0.409 \ln(dbh)$	25	63.0			
Quercus kelloggii	$-0.210 + 0.401 \ln(dbh)$	21	20.6			
"Fir"	$-0.573 + 0.484 \ln(dbh)$	88	47.5			
Group 2				$0.586 + 0.565 \ln(CR/(1/Meandist^2))$	33	35.2
Larix occidentalis	$-3.150 + 1.020 \ln(dbh)$	23	53.9			
Pinus monticola	$-1.320 + 0.714 \ln(dbh)$	11	80.1			
Quercus garryana	$-1.270 + 0.685 \ln(dbh)$	22	32.8			
Group 3				$0.914 + 0.628 \ln(CR/(1/Meandist^2))$	82	47.1
Juniperus occidentalis	$1.040 + 0.588 \ln(dbh)$	23	63.8			
Pinus contorta	$-1.040 + 0.572 \ln(dbh)$	24	52.2			
Pinus lambertiana	$-0.946 + 0.587 \ln(dbh)$	24	72.8			
Pinus ponderosa	$-0.896 + 0.532 \ln(dbh)$	26	75.8			
"Pine"	$-1.210 + 0.625 \ln(dbh)$	97	74.2			
Pooled equations						
All species	$-0.786 + 0.512 \ln(dbh)$	285	53.3	$1.410 + 0.428 \ln(CR/(1/Meandist^2))$	201	42.8

Notes: The three groups were created based on the similarity of slope and intercept values of Voronoi equations for individual species, not based on similarity of crown-radius equations. Group equations were fit; individual-species Voronoi equations could not be used because of insufficient sample size and poor fit; Meandist is a measure of local tree density, based on the mean distance among the four trees at the section corner. Other abbreviations are: dbh = diameter at breast height (1.37 m); CR = crown radius.