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Land surveys show regional variability of historical fire regimes and dry forest structure of the western United States

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Abstract. An understanding of how historical fire and structure in dry forests (ponderosa pine, dry mixed conifer) varied across the western United States remains incomplete. Yet, fire strongly affects ecosystem services, and forest restoration programs are underway. We used General Land Office survey reconstructions from the late 1800s across 11 landscapes covering ~1.9 million ha in four states to analyze spatial variation in fire regimes and forest structure. We first synthesized the state of validation of our methods using 20 modern validations, 53 historical cross-validations, and corroborating evidence. These show our method creates accurate reconstructions with low errors. One independent modern test reported high error, but did not replicate our method and made many calculation errors. Using reconstructed parameters of historical fire regimes and forest structure from our validated methods, forests were found to be non-uniform across the 11 landscapes, but grouped together in three geographical areas. Each had a mixture of fire severities, but dominated by low-severity fire and low median tree density in Arizona, mixed-severity fire and intermediate to high median tree density in Oregon-California, and high-severity fire and intermediate median tree density in Colorado. Programs to restore fire and forest structure could benefit from regional frameworks, rather than one size fits all.

Key words: dry forests; fire regimes; fire severity; forest structure; General Land Office surveys; geographical variation; restoration.

Introduction

Although climate is changing, evidence about historical forest structure and fire provides a baseline for understanding current forests and future forest change, yet regional variation in this baseline remains incompletely understood across dry forests of the western United States. Dry-forest landscapes have ponderosa pine (*Pinus ponderosa*) and dry mixed-conifer forests with some added trees (e.g., *Abies*, *Pseudotsuga*). Historical evidence is from tree rings, paleo charcoal, land surveys, early aerial photographs, and early historical documents and inventories (e.g., Hessburg et al. 2007, Williams and Baker 2014, Baker and Williams 2015). We contributed General Land Office (GLO) survey reconstructions for 11 dry-forest landscapes over ~1.9 million ha of dry forests in four states (Baker 2012, 2014, 2015, 2017*a*, Williams and Baker 2012*a*, *b*, 2013, Fig. 1a, Table 1). These reconstructions and others (e.g., Hessburg et al. 2007, Sherriff et al. 2014) found substantial area of open, low-density dry forests, with a history of low-severity fire, which is often considered the historical norm in dry forests (e.g., Covington and Moore 1994). However, GLO reconstructions and others also found that most dry-forest landscapes had more dense historical forests and mixed- and high-severity fire than previously known, but regional variation in forest structure and fire regimes remains poorly understood. National and local programs are underway to restore and manage fire and structure of dry forests, but a one-size-fits-all approach of lowering fuel loads, thinning forests, and reintroducing low-severity fire to recreate open, low-density forests has been common (e.g., Fulé et al. 2012).

Here we first synthesize published evidence that GLO reconstructions (Table 1) are well validated and accurate for reconstructing historical forests and fire in dry forests of the western United States, then use them in an additional synthesis to analyze variation in historical forest structure and fire regimes across dry forests. We have recently critiqued the validity of early timber inventories as sources of historical reconstructions (Baker and Hanson 2017), and our GLO reconstructions have also been critiqued (e.g., Levine et al. 2017), both part of normal scientific scrutiny of the validity of methods. Since historical reconstructions have been widely used to help guide large programs of ecological restoration and climate-change resilience, it is very important that all methods be validated. Here, we synthesize the details of published validations, that together allow overall errors from our GLO reconstructions to be calculated.

Reconstructions Using the General Land Office (GLO) Survey Data

The GLO surveys were mostly done near EuroAmerican settlement to lay out section lines and corners for land

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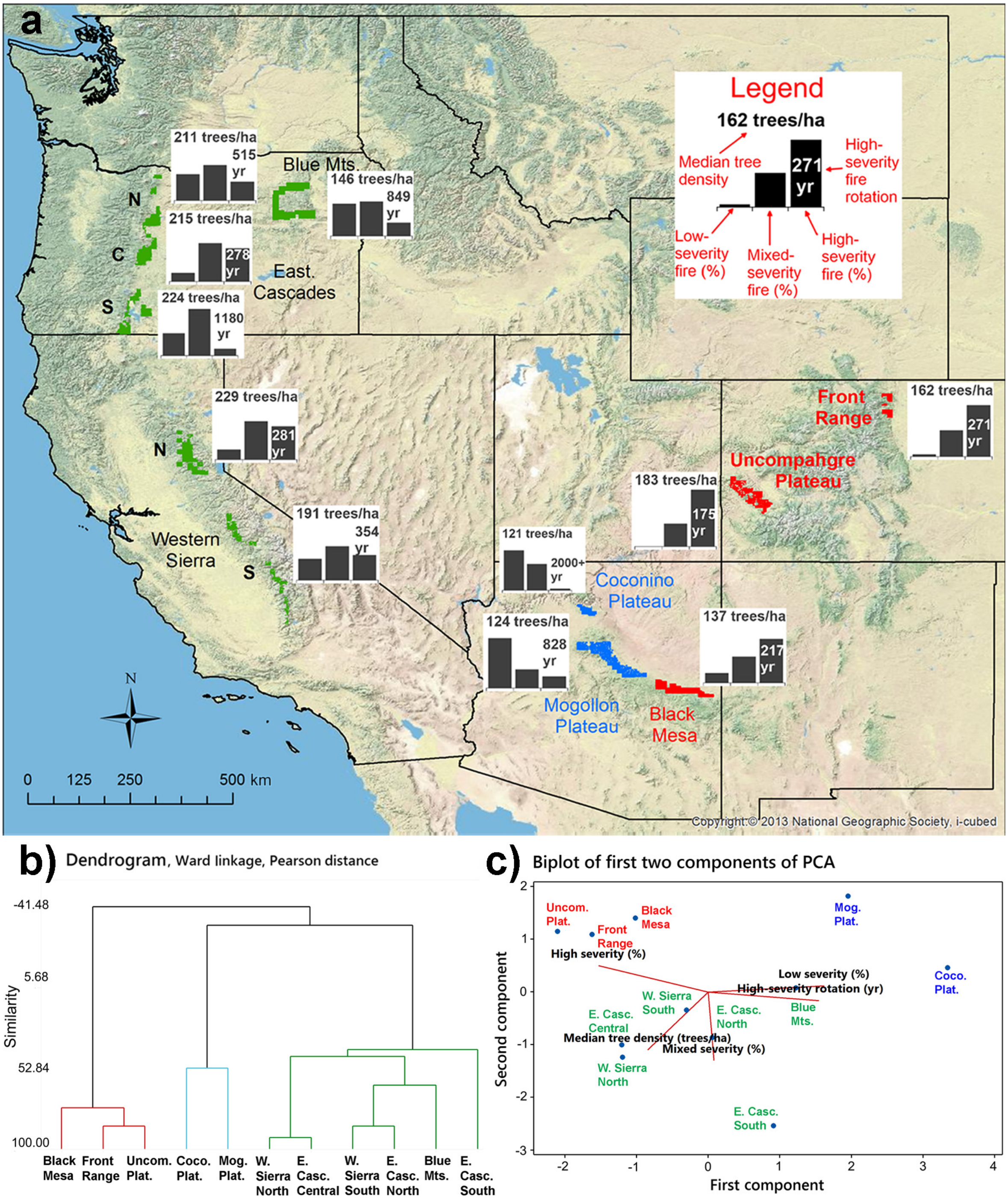

FIG. 1. Results of the analysis of historical fire regimes across 11 dry-forest landscapes in the western United States: (a) the 11 landscapes, color-coded to show the groups identified by cluster analysis, and associated bar graphs showing the data for the five basic parameters in the analysis, (b) the dendrogram from the cluster analysis, showing in color the three groups, and (c) a biplot showing the locations of the 11 landscapes and the directions of influence of the five basic parameters in the analysis relative to the first two components of the principal components analysis, that together explain about 93% of the variation in the data set. Abbreviations are Mts., Mountains; Uncom., Uncompahgre; Plat., Plateau; Coco., Coconino; Mog., Mogollon; W., Western; E., Eastern; Casc., Cascades.

allocation. They provide ecological data in the form of bearing-trees at section corners and quarter corners (Fig. 2a), spaced 805 m apart along 1,609-m section lines (Williams and Baker 2011). Bearing-tree data include the distance from the corner to each tree (i.e., tree spacing), the tree's diameter, and its common name. Usually, a set of one section corner (four bearing trees) and two quarter corners (each two bearing trees), representing ~259 ha, is repeated (Fig. 2b). These provide systematic and spatially extensive data. Bearing-tree data were measured and recorded with

Table 1. The 11 landscapes studied using General Land Office surveys.

Study area	Source	Area (ha)	Low severity (%)	Mixed severity (%)	High severity (%)	High-severity fire rotation (yr)	Median tree density (trees/ha)
Black Mesa, Arizona	Williams and Baker (2012*a*)	151,080	12.0	32.8	55.2	217	137
Coconino Plateau, Arizona	Williams and Baker (2013)	41,214	58.8	38.7	2.5	2,000†	121
Mogollon Plateau, Arizona	Williams and Baker (2012*a*)	405,214	62.4	23.1	14.5	828	124
Western Sierra, California, North	Baker (2014)	133,482	12.6	48.2	39.2	281	229
Western Sierra, California, South	Baker (2014)	196,461	26.4	42.5	31.1	354	191
Front Range, Colorado	Williams and Baker (2012*a*)	65,525	2.5	32.9	64.6	271	162
Uncompahgre Plateau, Colorado‡	Baker (2017*a*)	227,036	0.0	28.7	71.3	175	183
Blue Mountains, Oregon	Williams and Baker (2012*a*)	304,709	40.3	43.2	16.5	849	146
Eastern Cascades, Oregon, North	Baker (2012)	146,555	32.5	44.2	23.3	515	211
Eastern Cascades, Oregon, Central	Baker (2012)	147,502	10.4	48.2	41.4	278	215
Eastern Cascades, Oregon, South	Baker (2012)	104,160	29.4	61.7	8.9	1,180	224
Total		1,922,938					

†This estimate was not reported in Williams and Baker (2013) because so little (about 2.5%) high-severity fire was found. In order to have complete data, a rough estimate of 2,000 yr was used here.
‡All estimates are the mean between the ponderosa pine and dry mixed-conifer estimates in Baker (2017*a*).

low bias and error in western dry forests (Williams and Baker 2010). We use bearing-tree data to estimate its Voronoi area (VA), the area closer to the tree than to other trees. The inverse of mean VA among trees equals tree density. Empirical models, rooted in probability theory (i.e., Horvitz-Thompson; Delincé 1986), provided the statistical foundation to estimate VA with GLO data (Williams and Baker 2011). In our method, the VA is estimated initially from the estimated crown radius of the tree, derived from the recorded tree diameter at stump height (DSH, about 0.3 m), and this initial VA

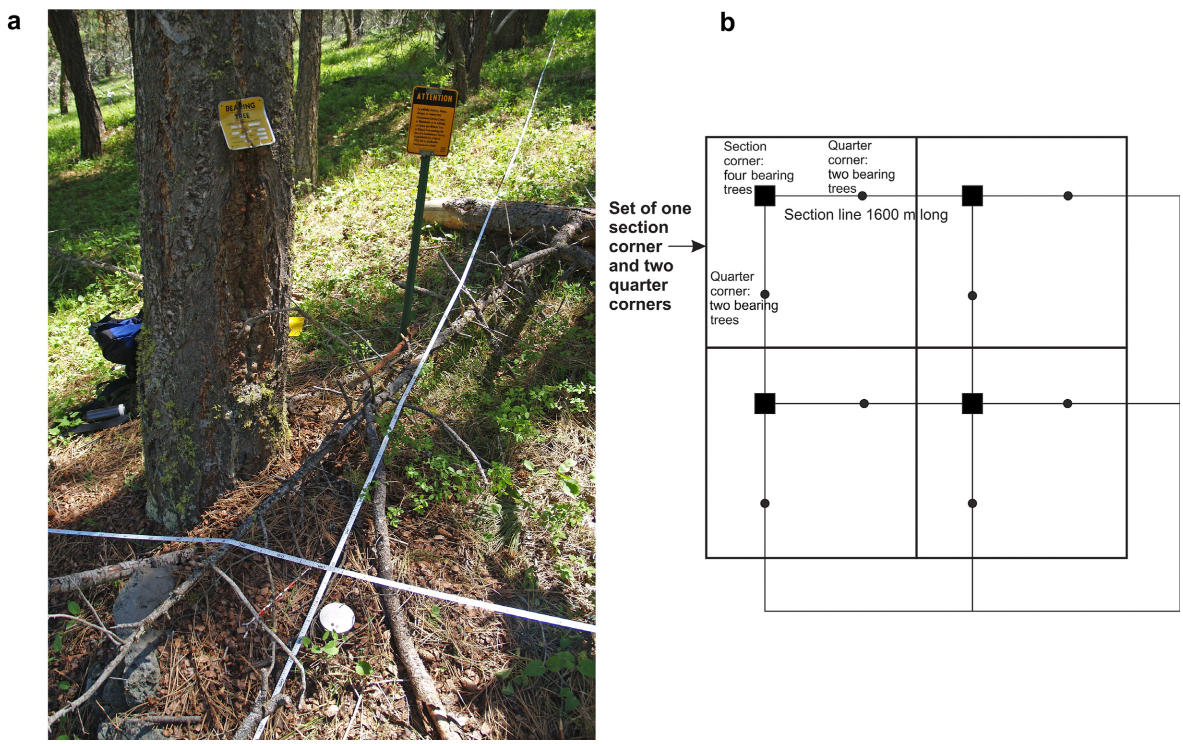

Fig. 2. Land-survey protocols. (a) Section corners and bearing trees have often been relocated and monumented with brass caps at the corner and signs on bearing trees. We laid out north-south and east-west tapes to help relocate and remeasure bearing trees. (b) The 1,600-m section lines lead to repeating sets containing one section corner, with four bearing trees, plus two quarter corners, each with two bearing trees. Four sets are shown.

is then adjusted up or down by the mean distance of other trees at the corner from the corner. Estimating the VA of a tree, from GLO data, sets our method apart from previous methods, which generally used distance-based estimators (e.g., point-centered quarter; Cottam and Curtis 1956) to calculate forest attributes. Distance-based estimators are biased when the spatial pattern of trees deviates from random, but Voronoi-based estimation is distribution-free and is accurate under a wider range of tree patterns (Delincé 1986).

We use the estimated VA to reconstruct tree density, basal area, and quadratic mean diameter. Tree composition and diameter distributions are directly from bearing-tree records; fire-severity proportions and high-severity fire rotation, the expected period required for fire to burn across a landscape one time, are modeled from tree density and diameter distributions, calibrated with tree-ring reconstructions (Williams and Baker 2011, 2012*a*, *b*). Methods were initially validated in a modern accuracy trial and reconstructions were cross-validated with other sources (Williams and Baker 2011). GLO records provide data for eight trees per 259 ha across large landscapes; the most extensive tree-ring reconstructions averaged about seven trees per 259 ha (Williams and Baker 2013), thus can reach comparable data density. GLO data have been used in historical reconstructions across the United States (Schulte and Mladenoff 2001).

A Synthesis of Published Validations of GLO Reconstructions in Dry Forests

Validations include (1) 20 *modern validations* that replicated the original land-survey method at modern section corners, then compared survey estimates to the truth, represented by data from a rectangular plot centered over the corner (Appendix S1: Tables S1–S3), (2) 47 *specific historical cross-validations* from overlaying GLO reconstruction polygons on locations where other historical sources (e.g., tree-ring reconstructions) provided estimates of the truth; GLO estimates were averaged, if more than one polygon (Appendix S1: Tables S4–S8), (3) six areas with *general historical cross-validations* in which we compared the mean from independent estimates, in or near our GLO study areas, that could not be precisely overlaid, to the mean for our study area (Appendix S1: Tables S9, S10), and (4) 99 corroborating observations and estimates from early scientific studies and seven corroborating paleo-reconstructions (Appendix S1: Tables S11, S12). These validations span the scales from single reconstruction polygons to means across large land areas.

Modern validations in Arizona, Colorado, Oregon forests

Williams and Baker's (2011) field-based modern validation included 499 corners across study areas in the Blue Mountains, Oregon, on the Mogollon Plateau, Arizona, and in the Colorado Front Range (Fig. 1a, Appendix S1: Table S1). Data were obtained for multiple 21-corner grids to allow analysis of accuracy achievable from pooling bearing-tree data in a 2:1 ratio of quarter corners to section corners (Fig. 2b) at 3- to 21-corner pooling levels.

We evaluated 15 estimators for accuracy and bias, and new Voronoi-based estimators were shown to be most accurate, using relative mean absolute error (RMAE), the absolute difference between the estimate and the truth as a percentage of the truth. RMAE for tree density was lowest at the six-corner pooling level (~519 ha) at 21–23% across the three study areas. A small accuracy check was also made in the eastern Cascades, Oregon (Appendix S1: Table S1; Baker 2012). In addition to dry forests, small initial accuracy trials showed the potential of GLO reconstructions using three-corner pools in piñon–juniper and subalpine forests on the Uncompahgre Plateau (Appendix S1: Table S1; Baker 2017*a*). For basal area, RMAE was the lowest at the nine-corner level at about 21–25% for two study areas (Blue Mountains, Front Range), and for quadratic mean diameter, RMAE was also lowest at the nine-corner level at 12–16% for these two study areas (Appendix S1: Table S2). Accuracy of reconstruction of species composition, based on a similarity measure, the percent similarity of communities (PSC) was 89–94% for the two study areas at the nine-corner pooling level (Appendix S1: Table S3). Accuracy of diameter reconstructions, using 10-cm bins, was 87–88% (Appendix S1: Table S3).

An incorrect modern validation in Sierran mixed-conifer forests

A study purportedly tested our method and reported it failed (Levine et al. 2017), but their test did not replicate our method (details in Appendix S1: Section S1). Levine et al. reported main results using diameter at breast height (DBH, 1.37 m height) to estimate VA, not diameter at stump height (DSH, ~0.30 m height), which is essential to our method and its testing (Williams and Baker 2010, 2011). DBH is ~23% smaller than DSH and yields smaller VA estimates and higher tree density, resulting in overestimation. Levine et al. approximated DSH in an appendix using an insufficient equation. Levine et al. also examined unpooled corner data, and did not replicate our key method of pooling GLO data. We use GLO data in six-corner pools, each with two sets of one section corner (each with four bearing trees) plus two quarter-corners (each with two bearing trees) for a total of 16 bearing trees (Fig. 2b). Also key is the harmonic mean of pooled data. If correct DSH data, pools, and a harmonic mean in the pools are used, our method accurately estimates tree density (RMAE = 19%; Appendix S1: Section S1). We show this for data in a Levine et al. plot where they found our method failed, showing the failure is from Levine et al. not replicating our method.

Calculation of a tree's Voronoi area is central to our method and in a separate "MHVD deconstruction" section Levine et al. explicitly studied this. However, they inexplicably did not adjust the estimated Voronoi area of each bearing tree using the density of adjoining bearing trees at the same corner, as our method requires, but instead used the density of distant trees that have no influence on the bearing tree. When done correctly (Appendix S1: Section S1), our method estimated Voronoi areas accurately (R^2_{adj} = 0.872) and tree-density estimates had low errors (24.5%). Levine et al. had fundamental design and calculation flaws, and is not a valid test of our method.

Specific and general historical cross-validations

A key test of the accuracy of our method was to do specific and general historical cross-validations. Cross-validations were with independent reconstructions from tree-rings or paleo records, or from independent records in early aerial photos, scientific reports, plots, or inventories. Early timber-inventory estimates are in Appendix S1, and we cross-validated tree density with one-chain-wide (Stephens et al. 2015; one chain = 20.1168 m), but not two-chain-wide estimates (Collins et al. 2011, 2015, Hagmann et al. 2013, 2014, 2017). Validation with tree-ring reconstructions and early plot data showed one-chain-wide inventories could have low error, but two-chain-wide inventories are unreliable and often substantially underestimate tree density, requiring correction multipliers of 1.4–3.2 (Baker and Hanson 2017). This is also evident here; in California, two-chain-wide estimates of tree density were <20% of the mean of 19 other sources; in Oregon, two-chain-wide estimates were <32% of the mean of five other sources (Appendix S1: Table S9). However, fire evidence from two-chain-wide inventories can be reliable, if available and fully incorporated (Baker and Hanson 2017), and is thus used here.

For historical tree density, 18 specific cross-validations in three states, with historical tree density from 47.0–294.3 trees/ha, had mean RMAE of 10.4–11.2% (Appendix S1: Table S4), showing high accuracy in this key test at the scale of 6-corner pools (~519 ha). General cross-validations of historical tree density with 39 independent sources, ranging from 56.2 to 684.0 trees/ha, showed RMAEs of 16.0% on the Mogollon Plateau, Arizona, 6.0% in the western Sierra, 27.8% in the Blue Mountains, Oregon, and 14.2% in the Eastern Cascades of Oregon (Appendix S1: Table S9); in three other areas, only one or two sources were available, limiting their value. These general cross-validations show GLO reconstructions accurately estimate tree density over large land areas. Together, these 57 sources validate the high accuracy of GLO tree-density reconstructions across spatial scales.

For historical basal area, five specific cross-validations in two states, where historical basal area ranged from 9.1 to 52.0 m^2/ha, had mean RMAE of 34.9% (Appendix S1: Table S5). General cross-validations from four independent sources in two states showed mean RMAE of 13.8–20.7% (Appendix S1: Table S10). Together, these nine independent sources show that basal-area reconstructions may have lower accuracy than tree-density reconstructions, but still provide RMAEs averaging in the <35% range. For quadratic mean diameter, four specific cross validations, in two states, had mean RMAE of 30.2% (Appendix S1: Table S5), but we have no general cross-validations yet.

Composition and diameter distributions have five specific cross-validations, which show only modest accuracy of 62.3% PSC for composition and 67.5% for diameters, based on Appendix S1: Table S6. These are lower than modern validations with 91.3% and 87.7% PSC (Appendix S1: Table S3). We suggest more cross-validation is needed. Most applications have not used the details of composition and diameters, but only broad discrimination, such as the percentage of the landscape with >30% firs or abundance of small/large trees (e.g., Williams and Baker 2012*a*).

For historical fire severity, 10 specific cross-validations in six study areas in four states had high mean accuracy of 89.1–90.1%, based on PSC (Appendix S1: Table S7). There is also substantial corroborating evidence that moderate/mixed-to-high-severity fires occurred and were extensive in some areas, based on evidence for five study areas in four states (Appendix S1: Table S11). These include 99 quotes from early forest-reserve and other reports, four tree-ring reconstructions, two paleo studies, and two using early photographs (Appendix S1: Table S11).

The rate at which high-severity fires burned historically in dry forests, measured by the fire rotation (the expected time to burn an area of interest one time), was specifically cross-validated at five sites in four states, which had mean RMAE of 15.8–26.5% (Appendix S1: Table S8). Independent estimates are from forest-reserve reports, timber inventories, direct observations, and early aerial photos. These validate that high-severity fire rotations can be accurately reconstructed using our method. The currently known range of GLO estimates for historical high-severity fire rotations in western dry forests is 175 to roughly 2,000 yr (Table 1), a range generally congruent with charcoal-based paleo reconstructions (Appendix S1: Table S12), providing further corroboration.

These tests against numerous, diverse, independent sources show that our reconstruction methods are valid, with known and relatively low error rates, for use in reconstructing historical forest structure and fire and guiding ecological restoration across dry forests of the western United States.

Variation in Historical Forests and Fire Regimes Across Dry Forests of the Western United States

The tree-ring reconstructions and early inventories used in the cross-validations together show the large historical variability in forest structure among dry-forest regions. Combining specific (Appendix S1: Table S4) and general (Appendix S1: Table S9) cross-validation data, historical mean tree density was 106 trees/ha (n = 23) in northern Arizona, 131 trees/ha (n = 4) in the Blue Mountains, Oregon, 211 trees/ha (n = 5) in the eastern Cascades, Oregon, and 257 trees/ha (n = 30) in the western Sierra. Independent estimates of median tree densities from GLO reconstructions were congruent (Table 1). Using the tree-ring reconstructions and early inventory data, one-way ANOVA (Minitab, State College, Pennsylvania, USA) followed by Tukey pairwise comparisons, showed Arizona and California means to be significantly different ($F_{3,58} = 12.2$, $P < 0.001$) at $\alpha = 0.05$, with Oregon means intermediate. Other areas had insufficient data for an ANOVA, but GLO data show that Colorado was also intermediate in tree density (Table 1). Mean basal area, combining specific (Appendix S1: Table S5) and general (Appendix S1: Table S10) cross-validation data were sparse, but also differed significantly ($F_{1,7} = 8.5$, $P = 0.022$) between Arizona (13.4 m^2/ha, n = 4) and California (33.8 m^2/ha, n = 5). Historical dry forests of the western USA were not uniform in structure, but instead were low density in Arizona, intermediate in Oregon and Colorado, and high density in California, with low basal area in Arizona and high basal area in California.

Variation in climate, combined with these variations in tree density and basal area, as well as other fuels, should lead to different fire regimes across a large land area like the western United States. We analyzed variation in historical fire regimes by clustering and ordinating four parameters (percent low, mixed, and high-severity fire, high-severity fire rotation) and one forest-structure parameter (median tree density) across the 11 landscapes (Fig. 1a, Table 1). We used cluster analysis with Ward's linkage, and with Pearson correlation as a distance measure, and a principal components analysis, also using correlation, both done in Minitab 18 (Minitab). To help with interpretation, we used evidence about rates of historical low-severity fire in and near these areas (Baker 2017*b*). Our purpose was to determine whether there were spatially coherent patterns in these basic historical parameters that might help resolve incomplete understanding of regional variation in historical forests and fire.

Cluster analysis suggested three groups (Fig. 1b) shown by colors on the map, dendrogram, and biplot of the principal components analysis (Fig. 1c). All groups had a mixture of fire severities, but differed in which severity dominated. The blue group in northern Arizona was dominated by low-severity fire, had little high-severity fire, a long high-severity fire rotation, and had the lowest median tree density of 121–124 trees/ha. The green group in California and Oregon was dominated by mixed-severity fire and had intermediate to high median tree density of 146–229 trees/ha. The red group in Colorado and Arizona was dominated by high-severity fire, with little low-severity fire, and had intermediate median tree density of 137–183 trees/ha (Fig. 1a). About 93% of total variation was captured in the first two principal components (Fig. 1c). The first is associated with the percentage of low- and high-severity fire and the high-severity fire rotation (all with $|r|$ = 0.54–0.57), and the second is associated with the percentage of mixed-severity fire ($r = -0.72$) and median tree density ($r = -0.62$). Higher median tree density is associated with more mixed-severity fire; tree density is also part of the GLO-based calibrated model that separates low- from mixed- and high-severity fire (Williams and Baker 2011).

High tree densities along the Cascade-Sierran axis, probably supported by higher winter precipitation, likely restricted the area of pure low-severity fire and allowed for a diversity of severities, favoring mixed severity (Fig. 1a). Tree-ring reconstructions of low-severity fire support this; historical fire rotations ranged from <25 yr to >55 yr within the Cascade-Sierran axis, allowing varying levels of understory fuels and tree densities (Baker 2017*b*). Low tree density and associated dominance by low-severity fire in drier northern Arizona landscapes (Fig. 1a) are also supported by short (<25 yr) low-severity fire rotations from tree-ring reconstructions (Baker 2017*b*). Finally, dominant high- and mixed-severity fire and moderate tree densities in southern Rocky Mountain landscapes (Fig. 1a) are consistent with often long (>40 yr) historical low-severity fire rotations, based on tree-ring reconstructions (Baker 2017*b*).

Historical high-severity fire rotations ranged widely among the six California-Oregon landscapes, but were longer (515–1,180 yr) in Oregon and shorter in California (281–354 yr), from a higher percentage of high-severity fire. The Eastern Cascades Central area (Table 1) was anomalous, but its shorter high-severity fire rotation is likely explained by co-dominance by short-stature Sierran lodgepole pine (*Pinus contorta* var. *murrayana*) on pumice (Baker 2012). Another anomaly is Black Mesa in Arizona (Fig. 1a), which did not have the nearby Coconino-Mogollon pattern of dominant low-severity fire, but instead had high-severity fire like Colorado landscapes (Fig. 1a). We hypothesize the region from Colorado to northern Arizona could be a tension zone, vulnerable to episodes of large severe fires that could overcome and transform landscapes that perhaps had dominantly low-severity fire regimes for extended periods. Evidence of two or more historically large, severe fires was found on the Uncompahgre Plateau in the 19th century (Baker 2017*a*), but unfortunately without evidence about the prior fire regime. Data from other unstudied large landscapes in this region may help resolve this hypothesis.

Summary

Use of GLO survey data expanded landscape-level reconstructions of historical forest structure and fire, revealing substantial variability across landscapes and between regions, which challenged past theories that suggested more stable forest dynamics across dry-forest landscapes. Here we show our GLO methods for reconstructing historical forest structure and fire are well validated and have low errors, from comparison with numerous, diverse, independent sources.

GLO reconstructions provide unique evidence about historical fire regimes across the 11 large dry-forest landscapes, covering about 1.9 million ha in the western United States. These show that historical fire regimes were generally congruent within regions, but different among regions. All had a mix of severities, but dominance by low-severity fire and the lowest median tree density were found only in Arizona. California and Oregon were dominated by mixed-severity fire and had intermediate to high median tree densities. Colorado and a part of northern Arizona were dominated by high-severity fire, with little low-severity fire, and had intermediate tree density. We hypothesize that the area from northern Arizona to Colorado was a tension zone historically vulnerable to transformation from century-scale episodes of large, severe fires. If the goal is to restore and manage contemporary forests and their fire regimes using historical forests as a guide, then region-specific historical frameworks can improve on a common one-size-fits-all approach.

Acknowledgments

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Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1688/full