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SYNTHESIS & INTEGRATION

Improving the use of early timber inventories in reconstructing historical dry forests and fire in the western United States

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Abstract. Early timber inventories in dry forests of the western United States offer detailed data sets that might provide historical information to guide restoration and preparation for future forests, but inventories have errors, biases, and limitations. We reviewed early documentation of errors and estimated errors by comparing inventory estimates to nearby tree-ring and plot estimates. In a case study in the Greenhorn Mountains, southern Sierra Nevada, California, we studied how selection and use of evidence affects findings and compared timber-inventory, land-survey, and other early evidence about historical forests and fire. Early documents showed inventories were unreliable, often with large underestimation errors from poor visual estimates, requiring correction multipliers of 2.0–2.5. Comparing inventory estimates to tree-ring estimates, we found commonly used two-chain-wide inventories required correction multipliers of about 1.4–3.2, consistent with, but wider than the 2.0–2.5 range. These needed corrections were not applied in any study. The case study showed (1) tree-density estimates from narrower one-chain-wide inventories could be more accurate, (2) data are often available, but unused, that provide quantitative evidence about historical high-severity fires consistent with nearby historical reports, and (3) differences in forest structure between inventories and land surveys may be explained by tree growth, stand development, and especially a significant fire. Our review also documented biased placement of inventories in merchantable timber, often excluding younger forests, chaparral, and other indicators of preceding mixed/high-severity fires. We found added significant bias introduced by omitting areas burned in mixed/high-severity fires, or by missing evidence of these fires on parts of forms or associated archival materials. Use of early timber inventories could be improved by (1) avoiding use of unreliable two-chain-wide inventories or applying correction multipliers to inventory estimates, (2) completing an accuracy test of one-chain-wide inventories, (3) locating and using notes, maps, and other data about small trees and high-severity fires often available in inventory archives, or omitting conclusions about these, (4) deriving an envelope model of inference space for inventories, and (5) specifying a large area, then including all available inventory data within it, or using unbiased selection criteria. These improvements could help bring timber-inventory data into congruence with other historical sources.

Key words: General Land Office surveys; high-severity fires; historical forests; mixed-severity fires; reconstructions; Sierra Nevada; Sierran mixed-conifer forests; timber inventories.

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Introduction

Reconstructions of historical vegetation can help guide ecological restoration and prepare for forests of the future, but understanding of historical dry forests of the western United States is hampered by conflicting evidence. Dry forests are ponderosa pine (*Pinus ponderosa*) and dry mixed-conifer forests that can also include firs (e.g., *Abies concolor*), incense-cedar (*Calocedrus decurrens*), and Douglas-fir (*Pseudotsuga menziesii*). Low-severity fires, which kill <20% of the basal area in dry forests (Agee 1993), were thought to have maintained open, low-density forests dominated by pines (Covington and Moore 1994). However, evidence from early historical observations, scientific reports, and photographs, and from U.S. General Land Office (GLO) surveys and modern Forest Inventory and Analysis data, showed that infrequent mixed/high-severity fires, which killed >20% of basal area, occurred historically in dry forests; these fires led to broad variation in forest structure, including large areas of dense forests and non-forest vegetation (Baker et al. 2007, Hessburg et al. 2007, Williams and Baker 2012, Odion et al. 2014, Hanson and Odion 2016*a*, *b*). High-severity fires (>70% basal-area mortality; Agee 1993) produced patches of snag jackpots, montane shrublands, and other post-fire vegetation that favored diverse birds, mammals, and plants, including spotted owls, woodpeckers, and shrub-nesting birds (DellaSala and Hanson 2015). This "complex early seral forest" is among the most biodiverse and wildlife-rich habitats in western U.S. conifer forests (DellaSala and Hanson 2015).

Evidence broadly agrees about heterogeneous historical forest structure and rates and patterns of mixed/high-severity fires when comparing GLO reconstructions with independent evidence, except early timber inventories. Agreement was found in overlapping areas between (1) early aerial photographs (Hessburg et al. 2007) and GLO reconstructions (Baker 2012), (2) early scientific reports and GLO reconstructions (Baker 2012, 2014, Williams and Baker 2012), (3) early mapping of fire severity (Leiberg 1902) and historical observations and reports of fires (Baker 2014: Appendix A) and GLO reconstructions (Baker 2014), and (4) rates of high-severity fire from GLO reconstructions and paleoreconstructions (Baker 2015*a*, *b*). Some (Fulé et al. 2014) thought corroboration was lacking, but missed available evidence (Williams and Baker 2014). Users of early timber inventories suggested GLO estimates of tree density, basal area, and fire severity are high (Hagmann et al. 2013, 2014, 2017, Hagmann 2014, Collins et al. 2015, Stephens et al. 2015).

Early timber inventories offer large, detailed data sets and spatially extensive coverage (Graves 1917), but are known to underestimate and be unreliable. Large underestimation errors were documented by more detailed accuracy checks at the time (Hodge 1911, Kotok 1916). Early timber inventories also have little cross-validation with independent historical sources. General Land Office reconstructions, in contrast, have been validated and shown to generally have relative errors less than about 25% from large modern accuracy trials (Williams and Baker 2011) and specific and general cross-validation with independent historical sources (Baker 2014). Early timber inventories also are a potential source of historical data on fire severity, but there has been debate about the availability and use of fire-severity data in these early timber inventories (Stephens et al. 2015, Collins et al. 2016, Hanson and Odion 2016*a*, *b*).

To help resolve the uncertain accuracy of early timber inventories, here we review needed corrections for documented errors in early timber inventories, and errors shown by cross-validation with tree-ring reconstructions and early plots. We also review intentional biases inherent in timber inventories and biases from selection and use of evidence. To provide more specific evidence, we use a case study to investigate the effects of selection and use of evidence on timber-inventory findings, directly compare timber inventories and GLO reconstructions, and review nearby historical forest reports in overlapping parts of the Greenhorn Mountains study area of Stephens et al. (2015) in the southern Sierra Nevada mountains of California, USA. Our goal is to improve all sources, including the timber inventories, that can help reconstruct a historical baseline for forest structure and fire in western dry forests (Williams and Baker 2014).

Background on early timber inventories

Early timber inventories, often called "reconnaissance" inventories, began general use by the

U.S. Forest Service about 1907–1908 to rapidly estimate timber for immediate sales and working plans for future sales (Marsh 1969, Tucker and Fitzpatrick 1972). Authority for reconnaissance inventories was with Forest Service regions (Margolin 1914, Silcox 1914). Marsh (1969:24) explained that timber inventories targeted large harvestable timber: "... most of the then and prospectively accessible sawtimber area was covered and the estimates were being used for timber sale and other purposes." Margolin (1914:1) similarly said about California inventories: "The object of an intensive reconnaissance is to obtain information and data to be used in Forest Utilization, principally in timber sales, and Forest Management, principally in the preparation of working plans." Working plans were for future timber sales.

Early inventories varied, but often required more intense data collection in stands with greater timber volume, and less data in younger forests or forests with perhaps high densities of regenerating conifers and less timber volume (Graves 1917). Often no tree tallies or detailed data were collected at all in very young forests, forests with little timber volume, recently burned forests, shrub fields containing scattered trees or no surviving trees, or grasslands with scattered trees, which were ignored or, at best, just mapped (Margolin 1914, Graves 1917). Incomplete spatial coverage and sampling bias, relative to larger landscapes, thus were intentional and well documented for timber inventories.

Early "extensive reconnaissance" inventories were aimed at rapidly determining forest types, timber locations, volume estimates, and where logging might occur (Recknagel 1910, Boerker 1914). Marsh (1969:24) called 1908–1912 inventories in Region 3 (Arizona, New Mexico) "rough reconnaissance estimates." These used a Vogel method, which estimated timber on a small area (e.g., 0.4 ha or 1 acre), that was extrapolated as an estimate for a "forty" (16.2 ha or 40 acres). A forty was the basic unit of study in most timber inventories (Marsh 1969). Other methods, besides the Vogel, may also have been used in extensive reconnaissance. Later "intensive reconnaissance" inventories typically tallied trees by species, diameter class, and number of harvestable logs in strip-transects (Recknagel 1910, Boerker 1914, Graves 1917).

In both types, cruisers traversed strip-transects parallel to GLO survey section lines and corners, which were surveyed and monumented where section lines met. Strip-transects were one chain wide (20.1 m/66 feet) or two chains wide (40.2 m/132 feet) in a forty (Fig. 1). Some variations on these basic designs occurred. Graves

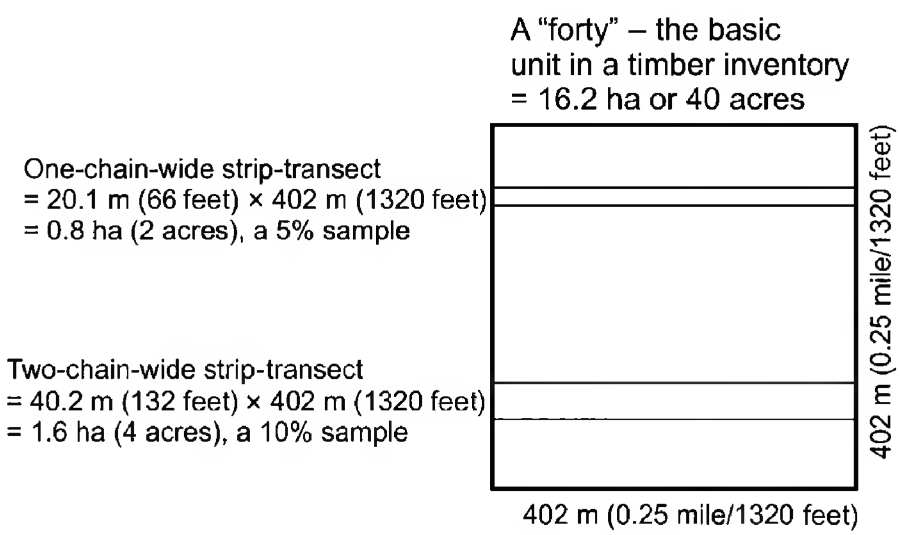

Fig. 1. Layout of strip-transects for one-chain- and two-chain-wide timber inventories inside a forty, the basic unit in a timber inventory.

(1917) specified more mapping, measurement, and accuracy standards for intensive inventories, but left extensive inventories up to districts and individual forests. Early inventories often did not meet Graves' standards for intensive inventories; he reported that up to 1916, inventories were about 69% extensive and 31% intensive (Graves 1917). It is not clear that all strip-transects were considered intensive.

An important reality of reconnaissance timber inventories was the limited time available to collect data. A timber-cruiser often paced ~400 m (~1/4 mile) segments in each of 12 forties along 4.8 km (3 miles) of line, then moved over, and did the same in return, completing 24 forties in a day (Marsh 1969). Assuming 8–12 h days, cruisers thus had about 20–30 min per forty to complete the tree tally, map topography, record and map information about non-merchantable timber and fire effects, acquire other information, and fill out forms, so only a few minutes could be spent tallying the tree data. Lots of data were collected, but this had to be done quite rapidly.

Methods

Accuracy of early timber-inventory estimates

To seek to quantify the well-known inaccuracy of early timber inventories, we reviewed historical U.S. Forest Service internal correspondence, and scientific reports and publications, regarding the accuracy of estimates from timber-inventory data, after broadly searching for literature and reports about early timber inventories. We also compared published early timber-inventory estimates to estimates from nearby tree-ring reconstructions and historical forest surveys in ponderosa pine and mixed-conifer forests of California and Oregon (Table 1).

Table 1. Cross-validations of early two-chain-wide timber-inventory estimates and GLO estimates with tree-ring and plot estimates of historical tree density.

Author	Min. dbh of trees (cm)	Timber inventory (trees/ha)	GLO (trees/ha)	Tree-ring (trees/ha)	Plot (trees/ha)	RMAE (%)	Needed correction multipliers
Scholl and Taylor (2010) Scholl and Taylor (2010)	15.2 10.0	99.4†		86.2‡		15.3	0.9
Baker (2015*b*) Merschel et al. (2014)	51.0 50.0		54.6§	48.0–52.0§		5.0–13.8	0.9–1.0
Baker (2012) Morrow (1986)	10.0 10.0		175.0¶	167.0¶		4.8	1.0
Baker (2014) Scholl and Taylor (2010)	10.0 10.0		160.0¶	160.0¶		0.0	1.0
Scholl and Taylor (2010) Scholl and Taylor (2010)	15.2 10.0	99.4		141.5		29.8	1.4
Hagmann et al. (2014) Munger (1917)	15.0 15.0	66.0			105.0–147.0	37.1–55.1	1.6–2.2
Hagmann et al. (2014) Merschel et al. (2014)	53.0 50.0	26.0§		48.0–52.0§		45.8–50.0	1.9–2.0
Hagmann et al. (2014) Morrow (1986)	15.0 15.0	66.0		133.0–152.0		50.5–56.6	2.0–2.3
Collins et al. (2011)-MC Scholl and Taylor (2010)	15.2 10.0	52.0		141.5		63.3	2.7
Collins et al. (2015) Scholl and Taylor (2010)	15.2 10.0	48.1		141.5		66.0	2.9
Collins et al. (2011)-PP Scholl and Taylor (2010)	15.2 10.0	44.0		141.5		68.9	3.2

Notes: Studies are ordered sequentially by needed correction multipliers. In Author column, the top line is timber inventory or GLO and the bottom line is tree-ring or plot. PP, ponderosa pine; MC, mixed-conifer; dbh, diameter at breast height; GLO, General Land Office; RMAE, relative mean absolute error, the absolute value of the difference between the timber-inventory or GLO estimate and the tree-ring or plot estimate as a percentage of the tree-ring or plot estimate.

† All comparisons are for just conifers unless specified otherwise.

‡ All comparisons are for the whole study area, except this one is for the timber-inventory area.

§ These estimates are for only large conifer trees, with slightly varying lower limits: 53 cm dbh for Hagmann et al. (2014), 51 cm for Baker (2015*b*), and 50 cm for Merschel et al. (2014).

¶ This estimate is for all trees, not just conifers.

Case study of the 1911 timber inventory in the Greenhorn Mountains, southern Sierra Nevada

In a case study overlapping the area of a 1911 timber-inventory study (Stephens et al. 2015), we conducted more complete assessments of historical (1) tree density, by adding quantitative data on immature tree density and (2) high-severity fire, by adding unused sources. We also reviewed nearby historical reports not used in Stephens et al. (2015).

We used data from 1911 U.S. Forest Service timber inventories analyzed by Stephens et al. (2015). We obtained copies of the 1911 timber-inventory forms, maps, and associated archival information for the area analyzed by Stephens et al. (2015) from the National Archives and Records Administration at San Bruno, California (Accession Box 33, #60-0328). The 1911 surveyors made field notes about forties with past and ongoing logging and, like Stephens et al. (2015), we excluded these forties from our analysis.

The Stephens et al. study area spanned 6120 ha of ponderosa pine and Sierran mixed-conifer forests in the Greenhorn Mountains in the southwestern-most Sierra Nevada, California. Ponderosa pine (*Pinus ponderosa* Lawson and C. Lawson) forests in this area often also include some sugar pine (*Pinus lambertiana* Douglas), Sierran white fir (*Abies concolor* (Gord. & Glend.) Lindl. Ex. Hildebr. var. *lowiana* (Gord. & Glend.) Lemmon), and incense-cedar (*Calocedrus decurrens* (Torr.) Florin). Lower elevations may include some blue oak (*Quercus douglasii* Hook. & Arn.) and gray pine (*Pinus sabiniana* Douglas ex Douglas). Sierran mixed-conifer forests typically have mixes of ponderosa pine, sugar pine, Sierran white fir, incense-cedar, California Black oak (*Quercus kelloggii* Newberry), and canyon live oak (*Quercus chrysolepis* Liebm.). At higher elevations, Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) may replace ponderosa. Montane chaparral also occurs in patches in forests, with a mix of several ceanothus (*Ceanothus* L.), manzanita (*Arctostaphylos* Adans.), and other shrubs.

To re-analyze tree density, we added data for immature trees <30.5 cm in diameter at breast height (dbh) that were included on the same 1911 timber-inventory field survey forms used by Stephens et al. (2015), but were not assessed in Stephens et al. (2015). The 1911 surveyors estimated these immature trees to have been 10–40 yr old. We analyzed these data for both mixed-conifer and ponderosa pine forests, defined as having >50% ponderosa pine by volume, based on the 1911 timber inventories.

We used the 1911 Greenhorn field notes regarding "Condition of Timber" for each timber-inventory transect, to identify the proportion of transects with evidence of past high-severity fire. We used the same criteria as Stephens et al. (2015), such as immature, regenerating conifer stands with very few or no remaining mature trees (generally with substantial fire scars), and areas of early-successional vegetation, such as montane chaparral and young oak regeneration, in unlogged forests. Stephens et al. (2015: Appendix A) reproduced field notes for the Condition of Timber category. We also used field notes for the "Underbrush" category, used rarely by Stephens et al. (2015), and the "Immature Growth Under Merchantable Timber" category, which was not used by Stephens et al. (2015), to further inform this analysis of past high-severity fire.

Field data and notes for tree-density transects used by Stephens et al. (2015) were only for 16.2-ha subsections (forties) with at least some surviving mature trees and would have missed high-severity fire areas where all trees were killed. We used 1911 timber-inventory maps, and field notes accompanying maps, to determine the extent of high-severity fire in areas with no remaining merchantable timber as of 1911. To avoid including areas of naturally persistent non-forest, we only counted areas lacking merchantable timber as having high-severity fire effects if current dominant vegetation, based on forest habitat classifications under the California Wildlife Habitat Relationships database, is either ponderosa pine or Sierran mixed-conifer forest (data available at https://www.wildlife.ca.gov/Data/CWHR).

We also searched early U.S. Forest Service reports for quantitative data regarding historical tree density, other aspects of forest structure, and qualitative descriptions of historical high-severity fire effects in ponderosa pine and mixed-conifer forests in the southern Sierra Nevada.

To further understand the historical structure of the forests in the Greenhorn study area and potential influences of fire, we used the original GLO surveys, as in the nearby western Sierra study (Baker 2014), employing the same methods, which are thus summarized here (Appendix S1).

The full GLO study area (Fig. 2) covers 49,050 ha and includes parts of the Greenhorn Mountains and the canyon of the Kern River on the Sequoia National Forest. Parts of townships T27S R32E and T28S R32E were omitted that contained different, low-elevation vegetation. General Land Office surveys were not available for the northern part of Stephens et al.'s (2015) study area; thus, our full study area overlaps 3359 ha (55%) of the approximately 6120 ha of forest analyzed by Stephens et al. (2015) using the 1911 forest-inventory data (Fig. 2). Overlap primarily covers the ponderosa pine part of the Stephens et al. study area, most of which is within our full study area, along with a smaller area of mixed-conifer forest. We also analyzed all area in the full study area above 1430 m in elevation (22,317 ha), congruent with the elevation limits of the Stephens et al. (2015) study. The original GLO surveys here were conducted between 1858 and 1885, with 54% surveyed by 1879.

Results

Documented large errors and needed correction multipliers for early timber-inventory estimates

Reconnaissance inventories had variable, but often substantial, underestimation errors from inherently imprecise visual estimation, and insufficient training and accuracy checking. Cruisers estimated the length of each strip-transect by pacing, which can introduce substantial inaccuracy, but cruisers could correct estimates using a multiplier based on the distance between their paced ending location and a monumented section corner (Margolin 1914, Silcox 1914). It is not clear how often this was done, given that only a few minutes were likely available for each tree tally.

Likely, the largest source of error was that cruisers visually estimated the width of the strip-transect. They were encouraged to periodically check their distance estimation (Margolin 1914), but unlike length correction after pacing, a width check required added time and effort since there was no nearby section corner to enable quick correction. Margolin (1914) said more checking was needed, but it is not clear how often it occurred, since cruisers were already under time pressure. At times a supervisor might do the width check, but only checked the visual estimate by pacing, also prone to error, and the check was apparently just used to refine subsequent visual estimation, not to correct previous estimates (Cornwall 1913). In some areas, reconnaissance crews were large and specifically trained, as well as overseen by a supervisor (Cornwall 1913), although just one cruiser, or a cruiser and compassman, often did each transect; in other areas, local rangers or untrained staff completed inventories (Recknagel 1910, Margolin 1914, Silcox 1914). This variability in training and supervision likely contributed to variability in inventory accuracy.

Moore (1915) reported that one of the earliest extensive inventories, in 1908 on the Coconino National Forest, Arizona, underestimated timber volume by 25%, but said later inventories with untrained crews were found to underestimate by 50–60%, requiring correction multipliers of 2.0–2.5, calculated as 1/(1.0–0.5) and 1/(1.0–0.6). Moore (1915) observed that the errors were due to a tendency to omit trees on the margin of the transect (p. 228):

> The method always gives an underestimate . . .the errors of even a single individual are very difficult to correct in the final estimate, because they vary from day to day and even within a single day. However, it is probable that a fair idea of the lump estimate over a considerable area can be secured by the prevailing system of raising the entire estimate by a certain correction factor determined by accurate methods of check estimating; but the figures on single forties will still be wholly unreliable.

Boerker (1914) reported an extensive reconnaissance inventory in 1910 on the Lassen National Forest, California, underestimated timber volume by about 2.5 times, relative to a later more intensive inventory, indicating early agreement that a 2.0–2.5 correction multiplier was needed.

However, large errors were not confined to early extensive inventories, but were large for two-chain intensive inventories as well. E. I. Kotok, who was Forest Supervisor on the Eldorado National Forest, California, explained in a 1916 letter to the District Forester in San Francisco (Hanson and Odion 2016*b*): "In checking over 10% estimates by the strip method two chains wide, once through the forty, of reconnaissance work on the Shasta, we found, invariably, very low estimates, due entirely to underestimating the width of the strip. Where the one-chain width was used, this error was considerably reduced." Hodge

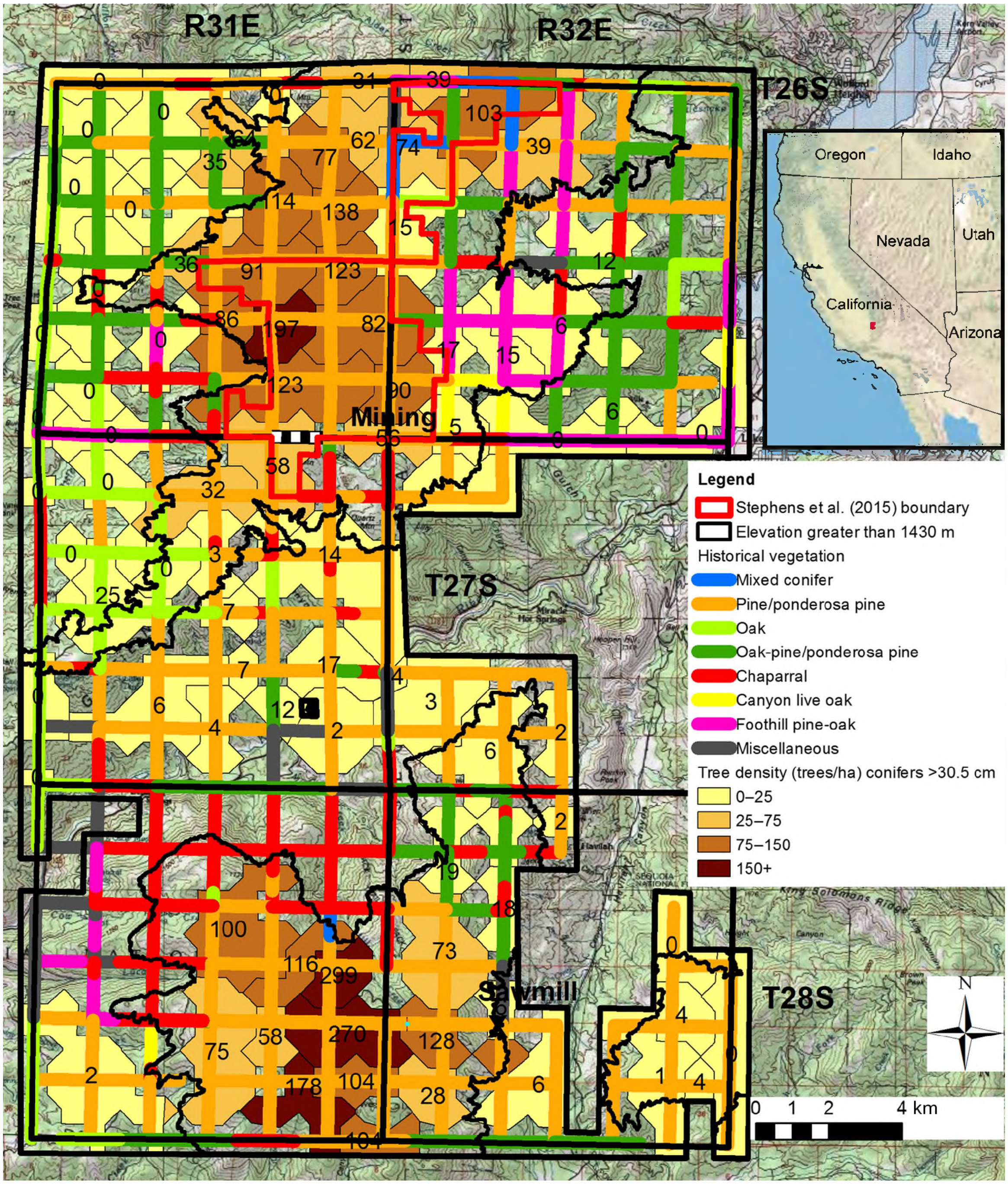

Fig. 2. Historical vegetation, based on section-line data, and tree density, based on bearing-tree data, for the Greenhorn Mountains study area. Tree density, for conifers >30.5 cm dbh, is shown as an integer on top of each reconstruction polygon. Townships, outlined in black, are 9.6 × 9.6 km (6 × 6 miles). The one recorded mining area, in the north, and the one recorded sawmill, in the south, are shown.

(1911) explained how underestimates arose (p. 7): "The tendency is strong to tally doubtful trees if they are large and to leave them out if they are small. And trees at a greater distance than 33 feet are very generally underestimated." The net effect could have been overestimation of volume in one-chain inventories from tallying large doubtful trees, but underestimation in two-chain inventories, where omission dominated.

As Kotok (1916) said, one-chain-wide inventories may have had lower error than two-chain-wide inventories. Hodge (1911) said one-chain strips had lower error because it was easier at 33 feet than at 66 feet to accurately estimate which trees were inside the transect and correctly estimate their diameters. A single check-estimate for a one-chain strip reported a 14–15% volume overestimate (Cornwall 1913). Candy (1927) found visually estimated one-chain-wide strip-transects in two areas overestimated basal area by 24.6% and 20.9%, but half-chain-wide strips had only 10% error. In another trial, of half-chain strips, one cruiser underestimated basal area by 15%, the other overestimated by 20%. One-chain-wide transects might under- or overestimate in the 15–25% error range for basal area and volume.

More accurate methods that allowed error estimation and that reduced or eliminated known errors from visual estimation appeared in the mid-1920s. For example, Candy (1927:164) said: "...any method of survey for which it is possible to calculate the accuracy of the estimate obtained, is very much superior to methods in which the accuracy of the estimate is doubtful and not at all calculable," referring to timber-inventory reconnaissance methods. In an explicit test of reconnaissance methods, he compared the accuracy of visual estimates on a one-chain-wide strip through accurately measured plots in two areas and found errors of 21–25%. Errors from using a series of fixed plots along a line, in contrast, had <1% error.

From the mid-1920s into the early 1930s, reconnaissance inventory data were disparaged as unsatisfactory, particularly in local areas, and not "authentic," and calls arose for a more accurate and systematic national forest survey (LaBau et al. 2007). Analysis by a special committee of the Society of American Foresters in 1926 said previous timber estimates "...have necessarily been based on rather **fragmentary and unsatisfactory** data. It is probable that these estimates are closer to actualities for the country as a whole **than they can be for small subdivisions**..." (boldface added; Clapp 1926:139). This special committee (Clapp 1926:140) disparaged inventory data: "The balancing of available timber supplies, imports, substitution, and growth on the one hand, with requirements, cut, drain upon the forests, and exports on the other, can only be possible in a thoroughly satisfactory way when based upon detailed, **authentic** information" (boldface added). Since this was a review by a scientific society, it was unlikely it had primarily funding or political motives. In 1932, in a related special report on the timber situation in the United States, the Forest Service repeated this disparaging term: "The present report gives the best information on the general forest situation in 1930 that could be compiled from readily available material, pending the time when **authentic** data will be supplied by intensive investigations now under way or planned by the Forest Service" (U.S. Forest Service 1932:1; boldface added). With passage of the McSweeney-McNary Forest Research Act of 1928, a formal national forest survey had begun, based on more accurate means of estimation, including fixed plot samples (LaBau et al. 2007).

Comparing early timber-inventory and tree-ring estimates expands estimated large errors

Two-chain timber-inventory estimates of tree density were generally underestimates. They had 30–69% RMAEs (relative mean absolute error, the absolute value of the difference between the timber-inventory estimate and the tree-ring estimate as a percentage of the tree-ring estimate) and in most cases needed correction multipliers of 1.4–3.2 relative to tree-ring estimates (Table 1), consistent with the 2.0–2.5 correction multipliers reviewed above, but with a larger range. The most valid comparison for the Hagmann et al. (2014) two-chain inventory estimates is with Merschel et al. (2014), for the density of large trees, which had an RMAE of 45.6–50.0%, requiring a correction multiplier of 1.9–2.0. Comparison of Hagmann et al. (2014) and Munger (1917) was made by Hagmann et al. for trees >15.2 cm dbh. The comparison is across large distances and is not specific enough to be very valid in estimating errors, although Munger (1917) aimed to characterize ponderosa pine forests in general. Hagmann et al. thought Munger's stands were atypically well stocked, and thus discounted the large underestimation by timber-inventory data (Table 1). However, directly above Munger's table 7 (p. 20), the source of the 105–147 trees/ha estimate, Munger said the data in table 7 are from "representative stands" and said the table "shows by samples the variability of Oregon's normally stocked virgin forests." Hagmann et al. (2014) did not compare their estimate of 66 trees/ha to the tree-ring reconstruction of Morrow (1986) at Pringle Falls, which is well south of their study area, but cited the Morrow estimate as 133–152 trees/ha, so it is also a less valid general cross-validation. The needed correction of Hagmann et al. (2014), derived as 133/66 to 152/66, would be 2.0–2.3 (Table 1), consistent with other correction estimates (Table 1).

In contrast, the GLO estimate of tree density for the Morrow site had a 4.8% RMAE relative to the Morrow estimate (Table 1), whereas the Hagmann et al. estimate had a 50.5–56.6% RMAE. Similarly, the GLO estimate of tree density for the Merschel et al. (2014) area had a 5.0–13.8% RMAE, whereas the early timber-inventory estimate had a 44.6–49.0% underestimation RMAE (Table 1). General Land Office estimates, in general, thus were much more accurate for tree density, relative to tree-ring reconstructions, than were early timber-inventory estimates (Table 1).

If timber-inventory estimates were adjusted using correction multipliers, they could be made more congruent with GLO and plot or tree-ring estimates that already closely agree. If Hagmann et al.'s (2014) estimate of 66 trees/ha for all trees >15 cm dbh were corrected using the documented 2.0–2.5 correction multiplier, that would yield roughly 132–165 trees/ha for their study area, which would then be more congruent with the nearby GLO reconstruction (Baker 2012) that showed a large area of mostly <143 trees/ha >10 cm dbh in a similar physical setting east and southeast of the Hagmann et al. study area. Similarly, if a 2.0–2.5 multiplier were applied to the Hagmann et al. (2013) estimates of 63–64 trees/ha in ponderosa pine and dry mixed-conifer in the southern eastern Cascades, the resulting 126–160 trees/ha estimate would roughly match nearby GLO estimates of <143 trees/ha and 143.0–214.2 trees/ha over much of the four-township area north of Klamath Falls (Baker 2012; Fig. 1). Referring to the data in Table 1, it is evident that correction multipliers of 2.0–2.5 would also bring the Hagmann et al. (2013, 2014) timber-inventory estimates into closer congruence with the plot estimates of Munger (1917), and the tree-ring estimates of Morrow (1986) and Merschel et al. (2014). Similarly, correction multipliers of 2.0–2.5 would bring the timber-inventory estimates of Collins et al. (2011, 2015) into closer congruence with the tree-ring estimates of Scholl and Taylor (2010).

In summary, available comparisons with overlapping or nearby tree-ring reconstructions show that uncorrected timber-inventory estimates of tree density had, in one case, low relative errors, but otherwise had large (37.1–68.9%) underestimation errors, requiring correction multipliers of about 1.6–3.2. However, comparisons by Scholl and Taylor (2010), in one case, had only 15–30% errors in timber-inventory estimates relative to tree-ring estimates from two-chain-wide transects. Comparisons between early timber-inventory estimates and tree-ring estimates within or nearby (Table 1) are initial comparisons, as discussed further below. General Land Office estimates in and near timber inventories had 0.0–16.2% RMAEs relative to tree-ring estimates (Table 1), and thus were much more accurate, in general, than were early timber-inventory estimates. Applying correction multipliers to timber-inventory data brings these estimates into congruence with other sources.

Two-chain timber-inventory estimates of basal area also underestimated and had RMAEs of 29–52%, requiring correction multipliers of 1.4–2.1 relative to tree-ring estimates (Table 2). However, the GLO reconstruction did not outperform the early timber-inventory estimates in one case, having a 60% RMAE relative to tree-ring estimates (Table 2). The early timber inventory used by Scholl and Taylor (2010) was less accurate (RMAE = 29.2%) than in the case of tree density (Tables 1, 2). Other early timber inventories had RMAEs of 39–52%, requiring correction multipliers of 1.6–2.1, a narrower range than with tree density, and lower than the documented correction multipliers of 2.0–2.5, but still showing large, consistent underestimation.

Inherent biases in timber inventories missed, or reported but forgotten, in comparisons

Inherent intentional biases toward large merchantable timber and against younger, denser

Table 2. Cross-validations of early two-chain-wide timber-inventory estimates and GLO estimates with tree-ring estimates of historical basal area.

Author	Timber inventory (m^2/ha)	GLO (m^2/ha)	Tree-ring (m^2/ha)	RMAE (%)	Needed correction multipliers
Baker (2014) Scholl and Taylor (2010)		48.0†	30.0†	60.0	0.6
Scholl and Taylor (2010) Scholl and Taylor (2010)	20.6‡		29.1‡	29.2	1.4
Scholl and Taylor (2010) Scholl and Taylor (2010)	20.6		29.2	29.5	1.4
Collins et al. (2011)-MC Scholl and Taylor (2010)	17.9		29.2	38.7	1.6
Collins et al. (2015) Scholl and Taylor (2010)	16.1		29.2	44.9	1.8
Collins et al. (2011)-PP Scholl and Taylor (2010)	14.1		29.2	51.7	2.1

Notes: In Author column, the top line is timber inventory or GLO and the bottom line is tree-ring or plot. PP, ponderosa pine; MC, mixed-conifer; GLO, General Land Office; RMAE, relative mean absolute error, the absolute value of the difference between the timber-inventory or GLO estimate and the tree-ring estimate as a percentage of the tree-ring estimate.

† All comparisons are for just conifers except these, which are for all trees.

‡ All comparisons are for the whole study area, except this one is for the timber-inventory area.

forests with non-merchantable timber or burned areas were reviewed in the *Background on early timber inventories* section. Inherent biases were not acknowledged in several studies (Scholl and Taylor 2010, Collins et al. 2011, Hagmann et al. 2013, Stephens et al. 2015). Hagmann et al. (2014) reported physical bias, but not the important bias against forests lacking merchantable timber: "The topography of this study area, a gentle slope…contrasts sharply with more rugged topography elsewhere in the frequent-fire forests of the Pacific Northwest." Yet, titles and abstracts of Hagmann et al. (2013, 2014) implied incorrectly that the timber inventories were representative of all ponderosa pine and mixed-conifer forests over larger areas. Collins et al. (2015) similarly reported that available data were significantly biased toward lower elevations, yet said their analysis "…may be the first study to provide robust quantification of both overstory and understory characteristics across a large historical landscape" (p. 1172), forgetting the physical bias. Collins et al. (2015) also reported that 70% of their study area had no inventory data. Forgetting that missing data can represent areas lacking merchantable timber because of high-severity fires (Hanson and Odion 2016*a*, *b*), Collins et al. concluded: "…our historical vegetation structure and composition data indicate that extensive stand-replacing disturbances were absent [in] this landscape" (p. 1173). Some data were missing because of access, topography, and ownership constraints (Collins et al. 2016). However, 1911 field data, which were available but missed by Collins et al. (2015), did provide direct descriptions of substantial high-severity fire that left little or no remaining merchantable timber in large patches (Hanson and Odion 2016*a*, *b*). Thus, inherent biases were unreported or reported and forgotten, and inappropriate inferences were then made or implied.

Case study of the 1911 timber inventory in the Greenhorn Mountains, southern Sierra Nevada

In the Greenhorn Mountains, GLO and timber-inventory estimates of mean tree density (Table 3) and basal area showed similarities and differences likely explained by fire between the GLO surveys and timber inventory. Within the pine/ponderosa pine area of the Stephens et al. part of our study area, the mean tree density for conifers ≥30.5 cm dbh was 92.8 trees/ha (standard deviation [SD] = 51.8, n = 9) for the GLO estimate, much larger than the 25.2 trees/ha (SD = 12.1) from the 1911 timber inventory. Conifers <30.5 cm dbh had a GLO-reconstructed mean of 78.2 trees/ha. In contrast, historical density of immature conifers (<30.5 cm dbh), added from the 1911 timber inventory, had a mean of 8.2 (SD = 25.0) fir/cedar trees/ha and 163.0 (SD = 189.9) pine trees/ha (ponderosa and sugar pines) for a total of 171.2 conifers/ha (n = 71). General Land Office-reconstructed mean basal area for conifers ≥30.5 cm dbh was 17.8 m^2/ha (SD = 4.4, n = 6) compared to the timber-inventory estimate of

Table 3. Comparison of early one-chain-wide timber-inventory and GLO estimates of tree density in the Greenhorn Mountains study area.

Type of forest/ category of trees	Timber inventory (trees/ha)	GLO (trees/ha)	Percentage of total trees from GLO (%)	RMAE of timber inventory relative to GLO (%)
Ponderosa pine				
Conifers ≥30.5 cm	25.2†	92.8	22.0	72.8
Non-conifers ≥30.5 cm	No estimate	151.3	35.8	
Conifers <30.5 cm	171.2‡	78.2	18.5	118.9
Non-conifers <30.5 cm	No est.	100.1	23.7	
Total conifers	196.4	171.0	40.5	14.9
Total non-conifers	—	251.4	59.5	
Total trees	—	422.4	100.0	
Mixed-conifer				
Conifers ≥30.5 cm	75.0†	87.0	17.4	13.8
Non-conifers ≥30.5 cm	No estimate	143.7	28.7	
Conifers <30.5 cm	216.8‡	220.8	44.1	1.8
Non- conifers <30.5 cm	No estimate	49.0	9.8	
Total conifers	291.8	307.8	61.5	5.2
Total non-conifers	—	192.7	38.5	
Total trees	—	500.5	100.0	

Note: GLO, General Land Office; RMAE, relative mean absolute error, the absolute value of the difference between the timber-inventory estimate and the GLO estimate as a percentage of the GLO estimate.
† From the 1911 timber-inventory data of Stephens et al. (2015).
‡ From the additional 1911 timber-inventory data for immature trees analyzed here.

11.2 m^2/ha (SD = 5.1). Historical ponderosa pine forests thus were moderately dense with conifers, with a mean of 196.4 total conifers/ha from the 1911 inventory and 171.0 total conifers/ha from the GLO reconstructions. About 60% of total trees were non-conifers, mostly oaks. Large conifers, the focus of Stephens et al. (2015), were only 22% of total trees, in forests that were quite dense overall, with a GLO-reconstructed total tree density of 422.4 trees/ha >10 cm dbh.

The 1911 timber-inventory estimate and earlier GLO estimate showed closer agreement for density of large trees (Table 3), but not basal area, in mixed-conifer forests. General Land Office-reconstructed mean tree density for conifers ≥30.5 cm dbh was 87.0 trees/ha (SD = 20.5, n = 2), but the sample is small. The Stephens et al. (2015) estimate was similar at 75.0 trees/ha (SD = 26.9). Conifers <30.5 cm dbh had a GLO-reconstructed mean of 220.8 trees/ha. Historical density of immature conifers (<30.5 cm dbh), added from the 1911 timber inventory, was quite similar, as it had a mean of 187.7 (SD = 516.7) fir/cedar trees/ha and 29.1 (SD = 76.3) pine trees/ha for a total of 216.8 immature conifers/ha (n = 71). Both sources agreed that historical mixed-conifer forests were quite dense with conifers, with a mean of 291.8 total conifers/ha from the 1911 inventory and 307.8 total conifers/ha from the GLO reconstruction. About 39% of total trees were non-conifers, mostly oaks. Large conifers, the focus of Stephens et al. (2015), were only 17% of total trees, in forests that were very dense overall, with a GLO-reconstructed total tree density of 500.5 trees/ha. The GLO-reconstructed mean basal area for conifers ≥30.5 cm dbh was 18.3 m^2/ha, less than the Stephens et al. estimate of 29.5 m^2/ha (SD = 9.9), but the GLO sample is only n = 1.

Regarding historical high-severity fire, based on information added from the 1911 timber inventories, there were 26.3 transects of 97 (27.1%) with high-severity fire effects in ponderosa pine forests, and 77.3 transects of 291 (26.6%) with high-severity fire effects in mixed-conifer forests (Appendix S2: Table S1). Early forest-survey reports for the southern Sierra Nevada also indicate substantial occurrence of high-severity fire, including both small and large patches, with some large patches spanning entire slopes and ridges, and large expanses of montane chaparral with young regenerating conifers and oaks far from the nearest surviving mature trees (Appendix S2: Tables S2, S3). Most chaparral patches were explicitly attributed to high-severity fires in forests (Appendix S2: Tables S2, S3). Some of this evidence may be from an

1880–1885 fire (Appendix S3). Early U.S. Forest Service forest-survey reports for the southern Sierra Nevada were congruent, consistent with substantial occurrence of higher-severity fire effects in the Greenhorns, leaving fewer surviving overstory trees, and facilitating dense, younger conifer regeneration (Appendix S2: Table S4). In Sequoia National Forest overall, "crown density," also described as "crown cover" (which, in context, was used as a rough equivalent of canopy cover in historical reports), had means of about 60% in mature ponderosa and Jeffrey-pine forests, and 80–90% in mature mixed-conifer forests, based on these early U.S. Forest Service reports (Appendix S2: Table S4).

Discussion

Large errors and needed correction multipliers for early timber-inventory tree-density estimates

Historical reports said early reconnaissance timber inventories commonly underestimated stand-level data (tree density, basal area, volume), requiring correction multipliers of 2.0–2.5. Two-chain-wide strip-transects were also known to have large errors from visually estimating transect widths over long distances, with estimates described as "very low" in one case, also suggesting correction multipliers of 2.0–2.5 may have been needed. Moore (1915) thought estimates would remain unreliable if corrected, because of day-to-day variability by individuals, and Candy (1927) found basal-area estimates varied by 35% among individuals, one being an underestimate and the other an overestimate, also indicating unreliability. Since even narrower half-chain strips had under- and overestimates of 15–20% (Candy 1927), one-chain-wide strip-transects could under- or overestimate by 15–25% or more. In our case study, an RMAE of 13.8% from comparing the one-chain mixed-conifer tree-density estimate of 75.0 trees/ha with the GLO estimate of 87.0 trees/ha suggests one-chain transects could be about this accurate. However, this is only one comparison in a small area, omitted from Table 1, as it is not based on comparison with a tree-ring or plot estimate.

Nearly all uses of early timber inventories (Tables 1, 2) were based on data from two-chain-wide strip-transects with stand-level underestimation errors likely approaching 50–60%, requiring reported correction multipliers of 2.0–2.5 or empirical 1.4–3.2 correction multipliers found here. Only Stephens et al. (2015) used one-chain-wide data with lower estimation errors (≥15–25%).

No recent studies using early timber inventories reported that two-chain strips had known large errors and likely required correction multipliers, as documented above, or that, even after correction, "figures on single forties will still be wholly unreliable" (Moore 1915:228). Yet, it was well known that early timber inventories were inaccurate and unreliable. The Clapp report of 1926 and U.S. Forest Service report of 1932 suggested data from early timber inventories were unsatisfactory and not authentic, particularly for small areas such as those used in recent studies.

Comparing early estimates confirms it is timber-inventory estimates that need correction

Early timber inventories had little prior cross-validation with independent historical sources, but empirical comparisons here generally showed 30–69% RMAEs and needed correction multipliers of 1.4–3.2 (Tables 1, 2) for two-chain inventory data for tree density, consistent with, but wider than documented correction multipliers of 2.0–2.5. Perhaps the one case of better accuracy, in the Scholl and Taylor (2010) comparisons, reflects what Moore (1915:228) said, quoted earlier: "...the errors of even a single individual are very difficult to correct in the final estimate, because they vary from day-to-day and even within a single day." A crew did about 24 forties in a day. We hypothesize that the 17 forties in the Scholl and Taylor (2010) sample could just indicate a good day, since the larger areas studied by Collins et al. (2011, 2015), which included the Scholl and Taylor study area, had 63–69% RMAEs for tree density, requiring correction multipliers of about 2.7–3.2 (Table 1).

The most reasonable evidence-based conclusion is that it is the timber-inventory tree-density estimates that need correction, since other sources agree more. General Land Office-reconstructed tree density had much lower errors (0.0–16.2%) relative to the same tree-ring reconstructions (Table 1). The results show that if timber-inventory estimates were adjusted using early correction multipliers or initial empirical corrections derived here, then timber-inventory estimates, tree-ring estimates, estimates from early forest surveys, and GLO estimates would be broadly congruent, showing it is just the timber inventories that need correction.

Inherently biased evidence limits valid inferences from early timber inventories

Early timber inventories were intentionally biased toward areas of large, merchantable trees and against younger, denser forests, significantly limiting evidence about both overall stand-level and landscape-level heterogeneity. Yet, as shown in the *Results* section, timber-inventory data with these known biases were often used with no mention of these biases. Timber-inventory data were also compared to data in more objective and comprehensive studies without limiting comparison to the biased topographic settings and merchantable timber covered by the timber-inventory data.

For example, Hagmann et al. (2014) mentioned that Hessburg et al. (2007) had strongly contrasting findings from the more diverse topography in their study area. However, Hagmann et al. did not explain this was likely also because Hessburg et al. was spatially comprehensive, including forests of all ages, whereas the Hagmann et al. data were inherently biased toward settings with large merchantable timber. Similarly, Hagmann et al. (2014) compared their tree-density estimates to summary estimates from Baker (2012) across a large area that, like the Hessburg et al. (2007) study area, was spatially comprehensive, including much more diverse and rugged topography, as well as forests of all ages, and made the invalid inference (p. 166): "Baker's reconstructions from GLO survey data overestimate historical densities." If Hagmann et al. had matched their specific inventory settings to similar settings and forests with merchantable-sized trees in the Hessburg et al. (2007) and Baker (2012) study areas, more agreement would likely have been found. In the *Results* section, we showed that applying correction multipliers to timber-inventory data and matching physical settings would lead to more congruence with other sources.

Also, early historical timber inventories may not include oaks or other non-conifers, which could comprise a substantial portion of tree density and basal area. Extensive areas of oaks or other non-coniferous dominance also can indicate earlier historical high-severity fires (Baker 2014). Both the GLO reconstructions and the added immature conifers from the 1911 Greenhorn timber inventory show that trees <30.5 cm dbh and non-coniferous trees, particularly oaks, neither of which were reported by Stephens et al. (2015), were abundant in these ponderosa pine and Sierran mixed-conifer forests. These forests were thus much denser than implied by timber-inventory data only for conifers ≥30.5 cm dbh, which were just 17–22% of total trees (Table 3).

Biased selection and use of evidence from timber inventories adds to their inherent biases

It is scientifically valid to use criteria to delimit a study area for a particular purpose, but this also limits the corresponding inference area and can lead to invalid inferences about stand-level and landscape-level variability. For example, substantial burned area in early timber inventories was excluded within a study area in the southern part of Oregon's eastern Cascades by Hagmann et al. (2013), as explained in Hagmann (2014): "...the timber inventory data set overlaps an area that burned in 1918 in a fire Weaver (1961) describes as covering more than 80,000 ha..." (p. 59), and "Many transects in this area include notes describing recent fire damage, including understory, reproduction, and timber burnt or fire killed. In Skellock Draw, high-severity fire effects on groundcover, understory, and overstory were recorded" (p. 61). Consistent with these inventory data, Weaver (1961:569) said that in the vicinity of Skellock Draw and Military Crossing, the fire "...crowned in patches of ponderosa pine. Extensive pole stands of this species there date back to the 1918 fire." Timber-inventory data from forests extant in 1914–1922 were assumed (Hagmann et al. 2013) to represent historical forest structure in this area; thus, the 1918 fire must similarly represent historical fire, and forests in the fire area must also represent historical forest structure.

Nonetheless, Hagmann (2014:61) explained that she omitted the 1918 burned area: "This area is not included in the summary statistics recorded in this chapter or previously (Hagmann et al. 2013)." The rationale for this omission was not provided. Hagmann et al. (2013:500) did not report this omission when they used the reduced area after removal of the 1918 fire area to conclude: "The prevalence of low-density forests composed primarily of large-diameter ponderosa pines leads us to conclude that a disturbance regime of frequent low- to moderate-severity fires was the dominant influence on the structure and composition of forests in this landscape for several centuries prior to the 1914–1922 inventory." This is inaccurate in describing the inference period, which had to include the period of the 1914–1922 inventory itself, along with the 1918 fire area. If these are included as they must be, historical fires in ponderosa pine and dry mixed-conifer forests on the Klamath Indian Reservation had a variety of fire severities, including some extensive areas of high-severity fire. That is the description of the 1918 fire by Weaver (1961), and it is supported by the timber inventory itself.

The omitted 1918 burned area also means that the forest-structure findings from the reduced area selected by Hagmann et al. (2013) do not allow inference about historical forests or fire within most of the rest of the former Klamath Indian Reservation. Excluding the 1918 fire area resulted in a small inference area on the Klamath Indian Reservation, since Weaver (1961:569) said the 1918 fire "...covered most of the central portion of the reservation..." and that area was intentionally excluded from analysis. It would take explicit research to determine the appropriate inference space in Oregon's eastern Cascades. Excluding the 1918 burned area and its inventory data belies the use of the published early timber-inventory data to guide ecological restoration of historical forests or Northern spotted owl habitat (Hagmann et al. 2017), which are also not supported due to the large underestimation errors of early timber inventories shown here.

Biased selection and use of data can occur after recognition of the data, as above, or the data may be missed, in either case leading to biased understanding of landscape-level heterogeneity in fire. We reiterate that timber-inventory transects were often simply not conducted in areas where little or no merchantable timber remained after past high-severity fire, and prior to natural post-fire regeneration to mid-successional forests. However, other historical data forms and maps documenting such high-severity fire areas, which were at times prepared alongside the timber inventories of forest with merchantable timber (and which were found in the same boxes as the timber inventories at the National Archives), must be sought and, if found, examined for a complete assessment of historical landscape heterogeneity in these forests (Hanson and Odion 2016*a*, *b*). For example, in the case of the Scholl and Taylor (2010) and Collins et al. (2011, 2015) study areas, these records of high-severity fire occurrence (Hanson and Odion 2016*a*, *b*) were written by the 1911 surveyors on light-cardboard jackets into which the timber-inventory transect data, for areas with merchantable timber, were placed by inventory staff. Thus, data on historical high-severity fire effects are available with the 1911 timber-inventory data at the National Archives in San Bruno, California (Hanson and Odion 2016*b*).

Missed or omitted data on immature conifers mean that previous inventory findings (Stephens et al. 2015) provided an incomplete understanding of the stand-level structure of historical forests. Data for immature conifers, which in our case study were roughly 10–40 yr of age and <30.5 cm dbh, were recorded on the back of the page on which the 1911 timber-inventory field notes for conifers ≥30.5 cm dbh were recorded for each forty. Immature conifers had a mean of 171.2 trees/ha in ponderosa pine forests and 216.8 trees/ha in mixed-conifer forests of the Greenhorn Mountains. Inclusion of immature conifers showed that estimates of total conifers closely agreed between timber inventory and GLO reconstructions (Table 3), and showed that historical Greenhorn forests were quite dense, similar to historical southern Sierra Nevada forests further to the north, which had a mean of 275 trees/ha >10 cm dbh and a standard deviation of 558 (Baker 2014; Table 3). Also, non-conifers (e.g., oaks) were quite abundant historically. Omission of immature conifer data and absence of data on non-conifers were quite significant, since the large-conifer data used by Stephens et al. (2015) represented only 17–22% of total trees.

Studies of early timber inventories in ponderosa pine and mixed-conifer forests of the western Sierra (Scholl and Taylor 2010, Collins et al. 2011, 2015, Stephens et al. 2015) and the eastern Cascades of Oregon (Hagmann et al. 2013, 2014, 2017) missed or omitted parts of the available timber-inventory data, including data on immature trees and on mixed/high-severity fire, and young, regenerating forests (Hanson and Odion 2016*a*, *b*, Appendix S2: Table S1). Conclusions of these early timber-inventory studies about stand-level and landscape-level historical forest structure and fire are, consequently, invalid for these forests.

Changes between expansion of industrial land uses and timber inventories or other sources

Early timber inventories began after the early 1900s and recently used inventories have extended to 1925 (Hagmann et al. 2014), often decades after the expansion of industrial land uses, leaving in question the degree to which early timber inventories represent historical forests. For example, a steam-powered sawmill was installed in 1864 in a timber-inventory area that was not fully surveyed for timber until 1924 (Hagmann et al. 2017), a period of 60 yr. Comparisons with tree-ring or GLO reconstructions may also differ by 30–60 yr or more, leaving ample time for substantive changes in forest structure. Tree growth and self-thinning alone can substantially change forests in 30–60 yr periods. For example, in the western Sierra, trees up to 30.5 cm in diameter can be only 40 yr old, as explained above. Intervening logging, fires, and other disturbances can also substantially change forests (Hagmann et al. 2017), as documented by the 1918 fire, left out of the Hagmann et al. (2013) analysis (see *Biased selection and use of evidence from timber inventories adds to their inherent biases*).

With historical low-severity fire, killing up to 20% of basal area, having historical fire rotations of <25 to >55 yr in the eastern Cascades of Oregon and western Sierra of California (Baker 2017), the full timber-inventory area would likely have burned once or more in a 60-yr period, potentially substantially changing tree populations. For example, in the Greenhorn Mountains case presented here, differences in tree density in ponderosa pine forests and in the abundance of chaparral suggest a large fire or fires likely burned in the period between 1880 and 1885 (Appendix S3). Fire likely reduced density of large trees in ponderosa-pine forests by about 52–73%, suggesting a mixed-severity fire with substantial moderate- and high-severity effects. This is also supported by the evidence added here of high-severity effects recorded in 27% of inventory transects. High-severity parts of this fire or fires likely also expanded the area of chaparral openings (Appendix S3: Fig. S1), often an indicator of high-severity fire (Baker 2014), from 0.2% to 11.8% of the landscape and expanded oak-dominated forests with surviving conifers from 6.9% to 11.7% of the landscape (Appendix S3: Table S1). Over the next few decades up to the time of the timber inventories, the density of small trees increased (Table 3), as expected during natural succession after mixed- to high-severity fire.

The large changes that can ensue from tree growth, stand development, and mixed- to high-severity fires or other disturbances between the time of expansion of industrial land uses and the time of the early timber inventories pose significant challenges. For comparisons, detailed reconstruction methods (Fulé et al. 1997) may be needed to calibrate general equations for reconstructing inventory data to a reference time period, although this would only work where significant disturbances have not occurred. Of course, this problem affects all historical sources to some degree, but the timber inventories are later and have more potential sources of change.

Summary and Suggestions for Improving the Use of Early Timber Inventories

We reviewed evidence that suggests recent interpretations and uses of timber-inventory data are generally invalid. Timber-inventory estimates were documented in early reports and scientific publications, based on accuracy checks, to have large errors, often requiring that estimates be corrected by multiplying them by 2.0–2.5. These large documented corrections are shown here to be supported and widened by empirical 1.4–3.2 correction multipliers needed to make early timber-inventory estimates match nearby or overlapping tree-ring estimates. The need for corrections and the unreliability of estimates were not mentioned or applied in any recent study. Timber inventories are also inherently and intentionally biased, focused on merchantable timber, and often intentionally omit detailed data for areas with younger and smaller trees, shrub fields with tree regeneration, and other areas of preceding high-severity fires. Researchers recently using timber inventories thus had no data available for non-merchantable timber areas, or missed available field notes and maps regarding high-severity fire effects in the same archival files as the timber-inventory data, or omitted areas that burned at mixed to high severity. This has led to invalid inferences, to larger areas, because of unavailable, missed, or omitted data, in addition to documented large underestimation errors, and substantial underestimation of landscape-scale heterogeneity.

In contrast, spatially extensive studies of larger landscapes (Hessburg et al. 2007, Baker 2012), which closely agreed in overlapping areas, also were corroborated by independent sources of evidence, including early scientific reports (Baker 2012). These studies showed that historical landscapes were more complex in both forest structure and fire severity than implied by studies using early timber inventories. Here, we showed that when the inherent biases of early timber inventories are considered or remedied, the same complex and heterogeneous picture emerges of historical ponderosa pine and mixed-conifer forests, belying evidence from uncorrected timber-inventory estimates of only larger conifers in biased settings.

These findings show that if uncorrected early timber-inventory estimates (Collins et al. 2011, 2015, Hagmann et al. 2013, 2014, 2017, Stephens et al. 2015) are used as a guide for restoring or managing forest structure in general or specific wildlife habitat, it is likely that significant adverse ecological impacts will ensue. For example, forest habitat of the Northern spotted owl, generally associated with denser forests, might be thinned to very low tree densities, damaging owl habitat, based on uncorrected timber-inventory data with large documented errors (Hagmann et al. 2017). Published uses of two-chain timber inventories are generally invalid, since they have these documented and uncorrected large errors in estimating historical tree density and basal area, or lacked or omitted significant evidence about historical forests or fire severity. In contrast, it appears that if all available timber-inventory records of historical mixed- and high-severity fire are used, early timber inventories may provide valid scientific evidence specifically for fire, and it is possible that one-chain-wide timber inventories might also do so for tree density.

Based on this review and our case study, we suggest the use of timber inventories in understanding historical forests and fire can be improved in several ways. First, one-chain-wide inventories may be more accurate, perhaps with more acceptable errors of 15–25% or more, but further accuracy testing is needed. Two-chain-wide inventories are not recommended for use due to known large underestimation errors and unreliability from day-to-day variability in accuracy. If used anyway, at a minimum the needed corrections should be applied to bracket uncertainty, described as "...the prevailing system of raising the entire estimate by a certain correction factor determined by accurate methods of check estimating" (Moore 1915:228). Early documents suggested 2.0–2.5 multipliers are appropriate, but multipliers between 1.4 and 3.2 for tree density and 1.4 and 2.1 for basal area are suggested from initial comparisons here with tree-ring and plot estimates. Our initial comparisons do not adjust for differences in tree species, tree sizes, or time periods, as we focused on whether there was general congruence with reported early corrections, which was found but over a broader range. Corrections using either set of multipliers appear to lead to bracketed estimates that are generally congruent with all other independent sources.

Second, we suggest more validation with tree-ring and plot estimates might narrow the range of needed corrections and provide more independent validation. The best validation likely would be from an accuracy assessment, with probabilistic sampling, using tree-ring reconstructions or early fixed inventory plots in timber-inventory areas corrected to the time of expansion of industrial land uses as the standard. These would allow temporal corrections for tree growth, stand development, and disturbances to be devised. There is no perfect standard, as even tree-ring methods unfortunately have error due to missing evidence from decomposition. For example, Scholl and Taylor (2010) reported that: "...small diameter trees alive in 1899 that died in the first few decades of the 20th century may have decomposed completely by 2002" (p. 375). Nonetheless, this process could possibly clarify errors and lead to more refined methods to correct or bracket estimates, although reported unreliability remains a potentially uncorrectable reality.

However, given wide agreement by about 1930 to abandon early timber inventories and replace them with a systematic national forest survey, it is reasonable to question whether useful, valid data can be retrieved about historical forests from early two-chain inventories. Certainly, the fire information is less prone to visual errors and underestimation. If a consensus arises that it is sensible, as we think, to simply abandon forest density and basal-area data from two-chain-wide inventories and early extensive reconnaissance inventories, it might still be worthwhile to work to improve the use of one-chain-wide inventories with this validation process, particularly if inventories were done by well-trained crews. Limited evidence is presented here from our case study and early literature that errors from one-chain-wide inventories might be only about 15–25% or more, similar to errors found with GLO reconstructions (Williams and Baker 2011).

Third, given that in the early timber inventories, there generally exist separate notes and maps regarding high-severity fire effects where little or no merchantable timber remained (and, thus, no timber-inventory transects were conducted), such evidence must be included in future analyses of these data sets to accurately and completely describe landscape heterogeneity in historical forests. If these data are lacking, absence of evidence should preclude any conclusions about fire severity.

Fourth, to address inherent bias, we suggest that quantitative spatial analysis in Geographical information systems (GIS) be used to analyze topographic and other inherent biases in the timber inventories, as we know they were intentionally biased to areas of merchantable timber. It is relatively straightforward in GIS to identify the biophysical envelope for a single inventory or set of inventories, and apply that envelope across adjoining landscapes to objectively identify appropriate inference areas. Similarly, envelope models of timber-inventory locations can be used to objectively identify appropriate tree-ring and GLO comparison locations, improving the validity of comparisons.

Fifth, to avoid added bias, we suggest it is best to specify a large land area, and then include all available timber-inventory evidence across the large land area, with minimal and objective a priori screening criteria (e.g., inventories must record certain information) rather than omitting some data after its examination. An appropriate scale may be on the order of 100,000 ha or more, based on the findings of Hanson and Odion (2016*a*, *b*) of varying information availability across 65,000 ha. However, if it is infeasible to use all the available data, then unbiased selection criteria (e.g., random, stratified random, or other probabilistic sampling) are needed, and explanations offered as to why some of the data were not used.

No historical source is free of limitations, and there is no reason to exclude any source from some usage, as multiple lines of evidence are needed to develop the most accurate historical baseline (Odion et al. 2014, Williams and Baker 2014). Other sources may suffer from limitations and warrant revision or new methods of reconstruction or use. Our understanding of the past will always be imperfect, but with further use, scrutiny, and suggestions for improvement, each source can be better understood, and limitations can be overcome or accepted.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.1935/full