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

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IS IT TIME TO AGAIN ABANDON EARLY TIMBER INVENTORY DATA?

Early U.S. Forest Service timber inventories began around 1907–1908. By 1911–1916, underestimation and unreliability were commonly known, by 1926 abandonment was suggested, and by the 1930s they were replaced by better methods. Hagmann et al. Comment (2018; "Hagmann et al." hereafter) and other recent users of these data appeared unaware of this history and assumed these data were accurate, but these data had been documented for a century to be unreliable and to underestimate tree density and timber volume. There is no disagreement between Hagmann et al. and Baker and Hanson (2017; "B&H" hereafter) regarding most of the central findings of B&H, including this history, most of our corroboration of underestimation by early timber-inventory data, and our documentation of omission of key available data in recent uses.

Here, in reply to the points that Hagmann et al. did dispute, we show that: (1) reconstructions

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from 19th century land-survey data, critiqued by Hagmann et al., do provide accurate estimates of historical tree density, (2) quality control checks published in Hagmann et al. do not document the tree density accuracy of timber inventories, (3) using correction multipliers for underestimation and including data on immature conifers remain essential if early timber inventory data are used, (4) early timber inventories were inherently biased toward areas of merchantable timber, and bias was added by recent omission of key evidence, (5) B&H did not ignore relevant cross-validation as Hagmann et al. said, and (6) an apparent ad hominem attack by Hagmann et al. did not cite our rebuttals. We acknowledge some of Hagmann et al.'s critiques of our specific corroborative evidence and make some adjustments. However, this revised evidence still corroborates large underestimation and the need for correction multipliers to estimate tree density from early timber inventory data.

Not long after the early timber inventories began, underestimation and unreliability were commonly reported by senior U.S. Forest Service managers and scientists (e.g., Hodge 1911, Moore 1915, Kotok 1916). In the mid-1920s and early 1930s these data were criticized as "not authentic," "fragmentary," and "unsatisfactory" by the Society of American Foresters and U.S. Forest Service (e.g., Table 1, further details in B&H), leading to abandonment and replacement. This history was neither reported nor addressed in recent uses of these data (Scholl and Taylor 2010, Collins et al. 2011, 2015, Hagmann et al. 2013, 2014, 2017, Hagmann 2014, Stephens et al. 2015, Hanson and Odion 2016a).

Subsequently, details about patented lands were reported in Collins et al. (2016), and evidence of high-severity fire on omitted inventory forms was reported in Hanson and Odion (2016a). Finally, key documents on the early history (Hodge 1911, Kotok 1916) were found and made available in Hanson and Odion (2016b). The recent historical findings of Hanson and Odion (2016b) stimulated further historical research in B&H, which was followed by Hagmann et al., which focused on our new corroborating evidence, to which we are now replying.

Table 1. Some 1911–1916 reports of underestimation and unreliability of two-chain-wide timber inventories.

Source	Quote
Hodge (1911: page 7) in Hanson and Odion (2016b: Appendix B)	"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"
Moore (1915:228)	"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"
Kotok (1916: page 1) in Hanson and Odion (2016b: Appendix B)	For two-chain-wide transects, the Forest Service ". . . found, invariably, very low estimates, due entirely to underestimating the width of the strip"
Clapp (1926: page 139)	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: page 139)"

B&H reviewed why early timber-inventory data were shown to underestimate and be unreliable by 1911–1916 (Table 1) and were invalidated and abandoned after about 1930. The central problem was underestimation and unreliability from visual estimation. Surveyors visually underestimated the width of two-chain-wide (66 feet or 20.1 m on each side) transects and undercounted or missed smaller trees relative to larger ones, both causing underestimates of tree density (Table 1; B&H: pages 6, 8). Correction multipliers were tried, but data were still inconsistent and unreliable at both transect and study area scales (Table 1). In 1926, a specially assigned committee of the Society of American Foresters (Clapp 1926: page 139) concluded these early timber inventories were based on "fragmentary and unsatisfactory data." The McSweeney-McNary Forest Research Act of 1928 helped initiate abandonment and replacement by better methods.

Hagmann et al. did not acknowledge or comment on this history of these data or our proposals for testing and possibly resurrecting some parts of them. Instead, Hagmann et al. critiqued portions of our corroboration. Even if the new corroborative evidence in B&H had been refuted by Hagmann et al., which we show is not the case, substantial evidence would have been needed to show it is possible to overcome the early documented history of underestimation and unreliability. We showed in B&H that underestimation could be roughly offset using documented early correction multipliers or our empirical estimates, both of which would bring estimates from early timber inventories into congruence with other historical sources (e.g., Appendix S1: Table S1). Unreliability, however, would be difficult to overcome, requiring a large validation and likely individual corrections of many transects and overall inventories, since unreliability was documented at the transect level, from day to day, and at subdivision or study area scales (Table 1, B&H). This seems to be a nearly impossible task. Thus, we ask—is it time to again abandon early timber inventory data?

Here, we first present matters in B&H not contested by Hagmann et al. Then, we focus on rebutting or accepting details that Hagmann et al. disputed, followed by a summary and answer to this question.

CENTRAL FINDINGS OF BAKER AND HANSON (2017) NOT CONTESTED BY HAGMANN ET AL. (2018)

It is possible that there is more agreement than disagreement over the evidence, because Hagmann et al. did not express disagreement with the following central findings of B&H:

First, that early timber inventory data, particularly from two-chain-wide transects, were documented between 1911 and 1916 to underestimate and be unreliable and were abandoned and replaced by more accurate methods by the 1930s, as discussed in B&H.

Second, that comparisons between timber inventory estimates and other sources (i.e.,

Appendix S1: Table S1; B&H: Table 1; B&H: page 9) showed that it is timber inventory estimates, not other sources, that underestimate and need correction.

Third, that comparison of historical U.S. General Land Office (GLO) data and a one-chain-wide timber inventory in the Greenhorn Mountains showed that one-chain-wide inventories, if all available data are used, could be fairly accurate, but further validation is needed, as discussed in B&H.

Fourth, that in the 1911 Greenhorn timber-inventory dataset in the southern Sierra Nevada, surveyors provided quantitative estimates of "immature" conifer density in 69% of transects, but these data were not included in Stephens et al. (2015). Hagmann et al. also did not dispute that non-conifer trees (mostly oaks) were ~60% of all trees in ponderosa pine and ~39% of all trees in mixed-conifer forests. When these are included, historical tree density in these forests was ~17 times higher than the 25 trees/ha reported in ponderosa pine, and ~7 times higher than the 75 trees/ha reported in mixed-conifer forests (B&H: pages 10–11) by Stephens et al. (2015).

Fifth, that in 1912 the Forest Service estimated mean crown cover of 60% and 80–90% in mature ponderosa pine and mixed-conifer forests, respectively, of the southern Sierra Nevada, as in B&H. This is far higher than estimates in timber inventory studies (Collins et al. 2011, 2015, Stephens et al. 2015), because these studies omitted most trees (see above).

Sixth, that there is abundant evidence of high-severity fire in ponderosa pine and mixed-conifer forests of the southern/central Sierra Nevada, as presented in Hanson and Odion (2016b), including their Table 1 with explicit field notes from 1911 timber-inventory surveyors about numerous entire forties (16.2-ha subsections) in which "severe" fires killed merchantable timber, resulting in early-successional vegetation (immature conifers and chaparral).

Seventh, that numerous detailed descriptions of high-severity fire, including large patches, in ponderosa pine and mixed-conifer forests were presented in several historical U.S. Forest Service reports that B&H cited and quoted (B&H Appendix S2: Tables S2–S4). These included a 1912 Forest Service report (current Sequoia National Forest) that estimated that 25% of the ponderosa pine forest was in a "young unmerchantable" stage of succession and that only 1% of this area was the result of logging (B&H Appendix S2: Table S4). These also included another early report, found in the same file boxes as the 1911 timber inventory data at the National Archives in San Bruno, California, in which the Forest Service reported that high-severity fire in ponderosa pine forests had resulted in "large areas of pure brush within the timberline and the extension of brush into the zone at the lower edge of the former timber belt" (B&H Appendix S2: Table S2). The Forest Service noted that "under dense chaparral cover charred down-timber and shells of pines burned to the ground are to be noted, where no pine now stands" (B&H Appendix S2: Table S2). In mixed-conifer forests, these early reports noted that "frequently" there were "great areas of openings" where severe fire "denuded ... the cover formerly occupying the site as evident from charred logs and occasional stubs of trees left standing," and observed that dense "thickets" of immature fir and cedar were "common" (B&H Appendix S2: Table S3).

Finally, that, as summarized in B&H, use of early timber-inventory data can 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" (B&H: page 1).

Detailed Replies or Acceptance of Hagmann et al. (2018) Critiques

Hagmann et al. began their paper: "Early timber inventories in western ponderosa pine and mixed-conifer forests (Collins et al. 2011, 2015, Hagmann et al. 2013, 2014, 2017, Stephens et al. 2015) document forest conditions that are

consistent with other records and reconstructions of historical vegetation patterns and fire regimes on landscapes that experienced frequent low- to moderate-severity fires." This statement lacked any corroborating citations or evidence at all, and we also show here that it is not supported as a summary of the available evidence.

Accurate, validated estimates of historical tree density from GLO land-survey data

Hagmann et al. (in the section titled *Biased estimates of historical tree density...*) said: "The method used by B&H to estimate historical tree densities (column labeled "GLO" [General Land Office] in B&H Tables 1–3) overestimates known tree densities." The basis for this was a paper purporting to show errors in our method of reconstructing tree density from GLO surveys conducted in the mid/late 1800s (Levine et al. 2017). Baker and Williams (2018) showed that Levine et al. (2017) lacked the required tree diameter data needed to use our method, used inadequate taper equations to attempt to correct for this lack, and made significant calculation errors, so that their study was not a valid test of our method at all. The details of the methodological and calculation errors were explained in Baker and Williams (2018). Hagmann et al. did not meaningfully explain the nature of the errors in Levine et al. (2017) that we reported, and Hagmann et al. cited unpublished material that had not been peer-reviewed. Levine et al. (2017) and Hagmann et al. both did not report that our method had been extensively validated with tree ring reconstructions and plot data and was shown to produce accurate estimates. That alone should have led Levine et al. to explore and find that it was their erroneous diameter estimates and calculation errors, not a flaw in our method, that led to their erroneous results.

Baker and Williams (2018) updated and reviewed validations of the accuracy of GLO land survey reconstructions. These included 20 modern validations with plot data, 47 specific historical cross-validations in small areas, six large areas with general cross-validations, 99 corroborating observations from scientific studies, and general corroboration from seven paleo-reconstructions. For tree density, modern validations showed that the relative mean absolute error (RMAE), the absolute difference between

the estimate and truth as a percentage of the truth, was 21–23% across study areas in three states. Eighteen specific cross-validations of GLO reconstructions of historical tree density in three states had RMAEs of 10.4–11.2%. General cross-validations of historical tree density with 39 independent sources had RMAEs of 16.0% on the Mogollon Plateau, 6.0% in the western Sierra Nevada, 27.8% in the Blue Mountains, and 14.2% in the eastern Cascades. These many corroborating "sources validate the high accuracy of GLO tree-density reconstructions across spatial scales" (Baker and Williams 2018: page 288).

Similarly, B&H Table 1 showed that GLO reconstructions had much lower error (0.0–13.8% RMAEs) than did timber inventory estimates (37.1–68.9%, except 15.3% in one case) when compared with tree ring reconstructions. This is still the case in our updated table (Appendix S1: Table S1). Evidence is thus substantial that GLO reconstructions are valid and quite accurate.

Accuracy of early timber inventories: quality control checks and time spent on inventories

Hagmann et al. (in the section titled *Incorrect assumptions about the accuracy...*) referenced "quality control records" for historical timber inventories in three study areas; they suggested these were "checks" on "accuracy" of tree density estimates, but none was an accuracy check of tree density. Table 1 of Hagmann et al. stated that the Stanislaus National Forest example pertained to timber volume, not tree density. Very different densities of trees, depending on tree size, can comprise the same timber volume, so this check is not relevant to the accuracy of historical visual estimates of tree density. Moreover, Table 1 of Hagmann et al. stated that the standard deviation of the Stanislaus check cruise was 46%. Thus, if true timber volume was, for example, 20,000 board feet per hectare (bf/ha), 68% of estimates would range from 10,800 to 29,200 bf/ha, and 95% of estimates would range from 1600 to 38,400 bf/ha, given a standard normal distribution. Table 1 of Hagmann et al. showed that check cruises on the other two sites were not accuracy checks, comparing visual timber inventory estimates to measured values, but instead were just repeats of the same visual estimation methods documented to be inaccurate and underestimate tree density. Standard deviations

at these two sites were also high—28% and 32%. With a standard deviation of 28%, if actual density was 100 trees/ha, 95% of estimates would range from 44 to 156 trees/ha. Wide confidence intervals indicate substantial inaccuracy.

We appreciate new evidence from Hagmann et al. about time spent on transects, including correction of B&H's description of methods used, and we endorse this reporting in general. However, if crews of 2–3 had roughly 30–60 min to complete each transect, but had to work together on parts, then closer to 15–30 min could be available for tallying, particularly since topographic work could take considerable time. Detail about how work was shared could help resolve this.

Comparisons show correction multipliers and data on immature conifers remain essential

Need for correction multipliers, documented by early sources, remains.—Early timber inventory data were found to underestimate and were abandoned and replaced a century ago; it is Hagmann et al., and other studies that used these data, that needed to provide matching cross-validation evidence that showed these abandoned data had any scientific value. None was provided in Hagmann et al., which focused instead on our initial comparisons and said B&H's Tables 1–3 were invalidated by "differences in scale, sampling bias, minimum diameter, and site quality" which they asserted "invalidate B&H's assertion that timber inventories require correction multipliers for tree density." However, Hagmann et al. aimed at the wrong target. We were not the source of the assertion that timber inventories require correction multipliers; it was early senior Forest Service officials and scientists who documented the need for correction multipliers of 2.0–2.5 (e.g., Table 1).

B&H made it clear that our Tables 1–3 were initial corroborating empirical comparisons only, did not fully match, and that further refinements are ultimately needed: "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..." (B&H: page 16). All that Hagmann et al. really raised about our initial comparisons were minor matters, some we accept and some we refute, but we put these all in Appendix S1.

These updated initial comparisons still corroborate the early documented need to apply correction multipliers to early timber inventory data. B&H also showed that if correction multipliers were applied to timber inventory estimates, they would become roughly congruent with other historical sources (this is not disputed by Hagmann et al.), and early timber inventory data were the only source that needed correction multipliers.

Moreover, we recently added more general cross-validations which further showed that early two-chain-wide timber inventories require correction multipliers >2.0. Two timber inventory estimates of tree density in California dry forests (Collins et al. 2011, 2015) were <20% of the mean (i.e., estimates of historical tree density from other sources were more than 5 times higher) and well below the range of 19 other historical sources and tree ring reconstructions of tree density mostly from 1900 to 1909, near the 1911 timber inventory dates (Baker and Williams 2018: Appendix Table S9). Similarly, early timber inventory estimates of tree density in two Oregon areas (Hagmann et al. 2013, 2014, 2017) were <32% of the mean (estimates from other sources were more than three times higher) and well below the range of five other early inventory and tree ring reconstructions of tree density, two from 1908 and 1917, near the time of the timber inventories (Baker and Williams 2018: Appendix Table S9). These add evidence that two-chain-wide timber inventory data require large correction multipliers.

We agree with Hagmann et al. that better matched and more extensive validations would be needed to possibly resurrect these abandoned early timber inventory data. Until evidence is published showing acceptable accuracy from comparisons between independent sources and timber inventory data in closely matched samples (e.g., sampling area, spatial scale, time period, diameters, site quality, etc.), all uses of two-chain-wide early timber inventories remain invalid.

Accurate estimates of tree density and fire severity require all available evidence.—Hagmann et al. (in the section titled *Inappropriate comparisons of studies*) said quantitative estimates of immature conifers were not included by Stephens et al. (2015) because the "diameter limits" of these trees "were not recorded." However, both B&H and Hagmann et al. agree immature conifers were <30.5 cm in diameter at breast height (dbh), and surveyors

noted they were at least 10 yr old, as discussed in B&H. Empirical data generally place the lower limit of 10-yr-old trees at ~2.5 cm dbh (Hanson and Odion 2016*a*), consistent with the lower limit of saplings in current and historical definitions.

Hagmann et al. cautioned against assuming that 100% of transects, cited in Appendix S2: Table S1 of B&H, that had widely scattered surviving trees and high levels of shrub cover and young conifer or oak regeneration, resulted from past high-severity fire. However, Hagmann et al. did not contest the 38% of transects classified as high-severity fire where there were no live, surviving mature trees, and only immature, regenerating conifers/oaks and chaparral. Nor did Hagmann et al. contest that surveyors did not conduct tree density transects in 16.2-ha subsections in which high-severity fire killed all the merchantable timber, but only where at least some merchantable trees survived.

In the other 62% of transects classified as high-severity fire by B&H—transects with some surviving, heavily fire-damaged, mature conifers—we agree with Hagmann et al. that some could have been from repeated moderate-severity fires. However, Hagmann et al. do not make the argument that most of these transects resulted from lower-severity fire, so we do not necessarily see a meaningful dispute on this point. Hagmann et al. suggested B&H categorized these transects as high-severity fire based on *either* widely scattered surviving conifers *or* presence of shrub patches *or* snags, but as explained in the *Methods* section of B&H, these required a combination of these factors. Also, Hagmann et al. cited research indicating mature mixed-conifer forests historically had ~29% shrub cover, but the transects with widely scattered surviving trees B&H classified as high-severity fire generally had considerably higher shrub cover levels than this, based on surveyor notes. Even assuming some level of dispute about the proportion of the transects with some surviving trees that indicate high-severity fire, Hagmann et al. did not contest the findings of B&H that evidence indicates considerably more high-severity fire in these forests historically than reported in Stephens et al. (2015), due to this additional evidence.

Hagmann et al. stated that they "find no evidence" that early timber inventories underestimated tree density or that any of the studies

using the timber inventories omitted high-severity fire areas or evidence of high-severity fire. However, as discussed above, there are several lines of evidence, not contested with evidence by Hagmann et al., that show underestimation of historical tree density and extent of high-severity fire. Missing or omitting available evidence is not lack of evidence.

Substantial bias inherent in early timber inventories and more added from omitting data

Intentional bias toward areas of large, merchantable trees with mostly low-severity fires.—The burden of proof is with studies that use early timber inventory data to analyze whether there was intentional bias in the placement and sampling of timber inventory areas or in the characteristics of the sampled forest. But, it is self-evident that timber inventories were placed where there was merchantable timber—why do an expensive timber inventory where there was little or no merchantable timber? In B&H, we cited early documents that explained that timber inventories were located where there were large areas of trees suitable for timber sales. As cited earlier, timber inventories in California and Oregon had atypically low tree densities that were <20% and <32%, respectively, of densities (i.e., threefold to fivefold underestimations) recorded in independent inventories and tree ring studies (Baker and Williams 2018). A large part of this is likely underestimation error, but even after applying 2.0–2.5 correction multipliers, it is clear that early timber inventories were placed where trees were large, in lower-density older forests with a long history of primarily low-severity fires.

Hagmann et al. denied that timber inventories were preferentially placed in areas containing large, merchantable trees with a history of primarily lower-severity fire: "We find no evidence in either historical records or in the studies that used these early timber inventories...of (1) bias toward areas of large, merchantable trees..." However, evidence of bias was clearly reported in one of their own studies that used early timber inventories (Hagmann et al. 2014: page 167): "Greater homogeneity in fire behavior may be expected in areas with simpler topography ... like this study area, when compared to more topographically complex areas, like some of the

subwatersheds in northern Washington studied by Hessburg et al." Hessburg et al. (2007) "found widespread evidence of partial and stand-replacing fire" (Hagmann et al. 2014: page 167) in mixed-conifer and ponderosa pine forests, and the "…area was dominated by forest structures that were intermediate between new and old forests, i.e., by pole to medium-sized, rather than large trees" (Hessburg et al. 2007: page 19). Hagmann et al. (2014) clearly explained that their timber inventory was preferentially placed where large, merchantable timber was favored, in gentler topography where fires were often lower in severity. Timber inventory data are thus a biased sample, only partly representing historical forest landscapes. B&H's fourth proposal for improving the use of early timber inventory data was to use quantitative methods to analyze inherent biases in the timber inventories. Hagmann et al. denied there was intentional bias and did not endorse this proposal.

Hagmann et al.'s comment (in *Unsubstantiated criticism of bias: Bias toward areas of large, merchantable trees*) about patented lands is baseless, as we did not assume, in B&H, anything about high-severity fire based on whether lands were patented. In Hanson and Odion (2016*b*), we thanked Collins et al. (2016) for bringing to our attention the patented lands, which pertained to only a small portion of the data, and we corrected and re-ran analyses for the Stanislaus/Yosemite study area (Hanson and Odion 2016*b*). Our results changed very little.

Hagmann et al. (in *Unsubstantiated criticism of bias: Bias toward areas of large, merchantable trees*) implied that high-severity fire patches may not have occurred in certain areas of ponderosa and mixed-conifer forests, claiming a California vegetation database ("CWHR") can only be applied at coarse scales. However, Hanson and Odion (2016*b*) showed that areas, described in timber inventories as having high-severity fire in subsections formerly comprised of merchantable timber, were reliably in ponderosa and mixed-conifer forest types, not chaparral or oak woodland. Hagmann et al. did not dispute this or cite Hanson and Odion (2016*b*).

Added bias from intentional exclusion of burned areas.—Hagmann et al. (2013) selected a 38,651-ha timber-inventory area out of a larger available dataset, then concluded that "frequent low- to

moderate-severity fires was the dominant influence… in this landscape…" (quoted by B&H on page 14 upper left corner). But Hagmann et al. (2013) did not report at all that they omitted an adjoining much larger (roughly 80,000 ha) area that had a fire that burned at moderate to high severity over substantial area. That was only reported later in Hagmann's (2014: page 61) dissertation: "This area is not included in the summary statistics recorded in this chapter or previously (Hagmann et al. 2013)." Hagmann et al.'s (2013) conclusions about historical fire and about the nature of the historical forest would likely not have been supported if the 80,000-ha fire area had been included in Hagmann et al.'s (2013) study area as it should have been. Hagmann et al. responded that they did not exclude records of fire *within* the 38,651-ha study area they chose, but that is not the issue. They did not admit that they intentionally excluded the 80,000-ha fire area itself. Our fifth proposal for improving objective use of early timber inventory data was to first choose a large land area, then include all available timber inventory data within it or sample it objectively prior to looking at the data. Hagmann et al. did not acknowledge that Hagmann et al. (2013) excluded the 80,000-ha burn part of available timber inventory data, after examination and did not endorse our proposal.

As discussed in B&H (p. 14), Scholl and Taylor (2010) and Collins et al. (2011, 2015) omitted evidence of large high-severity fire patches in these forest types, despite the fact that such evidence was located on the cardboard jackets in which the timber inventory transect data were placed in the files at the National Archives. We think it is not physically possible to avoid this evidence of historical high-severity fire while accessing the timber inventory transect data.

Inclusion of logged areas.—B&H made no erroneous claims about logging, as Hagmann et al. said. All B&H said about logging (page 15) was that its duration between the time of onset of logging and the time timber inventories were completed could reach 60 yr, it could have substantial effect, and it must be addressed.

Cross-validation with other sources not ignored or ignored because weak and irrelevant.—Again, the burden of proof lies with Hagmann et al. and other published studies to have provided closely

matching validation evidence that showed that discarded early timber-inventory data abandoned a century ago were valid to use today. Hagmann et al. said B&H "ignored abundant published material that demonstrated similarity between timber inventories cross-referenced with early records and reconstructions of historical forest conditions," but this evidence was neither closely matched nor abundant, as discussed both above and below. Moreover, two cited examples were not ignored by us, others were not used because they are not relevant to tree density estimates from two-chain-wide inventories, or they were weak, insufficient comparisons.

First, Stephens et al. (2015) is a study that used one-chain-wide inventories that we showed in B&H could be more accurate, although all available data were not included by Stephens et al.; most important, that study did not use two-chain-wide timber inventories that were documented to underestimate and be unreliable, that are the central issue raised in B&H. Second, we did not ignore comparisons with Hagmann et al. (2014) at all—our comparisons are the ones discussed by Hagmann et al. in this section of their manuscript. The cited case of Hagmann et al. (2017) is not about tree density, the issue here, so we did not use it. We included Scholl and Taylor in our Table 1—it was not ignored. Finally, some studies Hagmann et al. cited for comparison are not in the California/Oregon regions covered by timber inventories, but in northwestern Mexico. Forests in Mexico have mean annual precipitation of ~58 cm (Minnich et al. 2000), with lower potential for dense forests than timber inventory areas in California and Oregon that have ~60–125 cm (Collins et al. 2011; https://wrcc.dri.edu/Climate/precip_map_show.php?simg=ca_south.gif). In conclusion, evidence Hagmann et al. cited was not ignored, or was weak or irrelevant and should not have been used, and none was closely matched.

Appropriate cross-referencing and representation of high-severity fire

Hagmann et al. said "B&H misrepresent cross-validation" on B&H page 2, citing two critiques that we did not cite. We agree we did not cite those, but that is not "misrepresentation," since the broad introductory statements in B&H are not refuted by these two uncited critiques. We addressed comments about fire severity in the

Greenhorn Mountains in the second section of detailed rebuttals above. Hagmann et al. said: "B&H erroneously compared percentage of high-severity fire in their studies ... with Hessburg et al. (2007)." B&H did not compare the percentage of high-severity fire in these studies, but did say: "These studies showed that historical landscapes were more complex in both forest structure and fire severity than implied by studies using early timber inventories" (B&H: page 16), and this finding is further validated here, as explained above.

An apparent ad hominem attack

Hagmann et al. said "...previous publications have also documented errors in methodology or misrepresentation of the work of others" in our papers, citing a string of 11 studies. This appears to have been an ad hominem attack, since Hagmann et al. presented no evidence of purported errors or misrepresentation, and did not cite or explain evidence in our published replies to these 11 studies either. These published replies include (in the same chronological order as the 11 studies listed by Hagmann et al.): Odion and Hanson (2008), Hanson et al. (2010), Odion et al. (2014), Williams and Baker (2014), Hanson and Odion (2015, 2016b), Odion et al. (2016), Baker and Hanson (2017), and Baker and Williams (2018).

Conclusions

We posed the question–is it time to again abandon early timber inventory data? Our answer is that it likely would be good to again abandon two-chain-wide timber inventory data on forest structure (e.g., tree density, basal area), because underestimation and the need for correction multipliers were documented early, remain corroborated, and documented unreliability makes these problems likely difficult or impossible to correct. It remains the responsibility of studies that used these early timber-inventory data to address their early history, but this was not acknowledged or done by Hagmann et al. Validation would likely be difficult, costly, and still fail.

We suggest refocussing on: (1) whether early timber-inventory data on fire severity are sufficiently accurate, as they seem to be, how much error they have, and how they should be used, since this research is already underway, (2)

whether one-chain-wide timber inventory data on tree density are as accurate as they seem to be (provided that immature trees and oaks are included) from early literature and B&H's one comparison, with a goal of estimating how much error they have, and how they should be used, (3) ensuring data on immature conifers and fire are found and included, and (4) analyzing inherent biases and determining valid inference spaces and locations, avoiding added bias in selection of study areas, and ensuring inclusion of data on forest structure or fires.

In the meantime, it is not advisable to use information about historical forest structure (i.e., tree density, basal area, canopy cover) in published studies (cited in the introduction) that were based on two-chain-wide early timber inventories as a guide to ecological restoration or land management. These invalidated and abandoned data, which were determined by the Forest Service itself to be unreliable and underestimate, could lead to forests atypical of historical forests and have significant adverse effects on biological diversity and ecosystem functioning.

Acknowledgments

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SUPPORTING INFORMATION

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2325/full