Supplementary Information for:

Effects of recent wildfires on giant sequoia groves were anomalous at millennial timescales: a response to Hanson et al.

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SUPPLEMENTARY TEXT:

Giant sequoia fire ecology

Determining trunk diameters of millennial sequoias

Our approach to determining the trunk diameter that best segregates sequoias ≥1000 years old from those <1000 years old is conceptually simple. First, we use ages from ring counts on hundreds of cut sequoia stumps to determine, within each of 23 trunk diameter classes, the relative proportions of sequoias that are ≥1000 years old. For each diameter class we then multiply the actual number of Redwood Mountain Grove sequoias in that diameter class by the relative proportion of millennial sequoias (those ≥1000 years old) expected to be found in that class. For example, if ring counts from stump tops indicated that 45% of sequoias in a given size class would typically be expected to be ≥1000 years old, and if 500 sequoias in the Redwood Mountain Grove fell in that size class, we would estimate that 0.45 x 500 = 225 sequoias in that size class are ≥1000 years old and that the remaining 275 sequoias are <1000 years old . Finally, we assess the results from all diameter classes to determine which trunk diameter in Redwood Mountain Grove is expected to yield a total number of false-positive millennial sequoias (those estimated to be ≥1000 years old that are actually <1000 years old) that is comparable to the total number of false-negative millennial sequoias (those estimated to be <1000 years old that are actually ≥1000 years old). That trunk diameter then becomes our benchmark for estimating which individual sequoias are ≥1000 years old and which are <1000 years old.

Data came from two primary sources. Age data for trunks of different diameters came from ring counts on 458 giant sequoia stump tops measured by Huntington (1914); the stumps ranged from 222 to 3210 years old and from 53 to 652 cm in diameter inside the bark (detailed methods are reported in Huntington [1914] and Stephenson and Demetry [1995]). By crossdating six of Huntington's stumps to the exact year, Douglass (1919, p. 45) provided a limited check of the accuracy of the tree ages we derived from Huntington's measurements (which were the same ages used in Stephenson and Demetry 1995). Error in the sequoia ages ranged from -1.65% to +0.06% of Douglass' crossdated age for the six stumps, with an average error of -0.54%. We therefore deemed Huntington's data to provide sufficiently accurate estimates of actual ages at the height of the stump top, although the comparison with Douglass' data suggested that the ages derived from Huntington's data may have tended to slightly underestimate actual ages.

Numbers of Redwood Mountain sequoias by diameter class, in turn, were determined in the summer of 1968, when sequoias in those portions of Redwood Mountain Grove inside of Kings Canyon National Park (about 79% of the 1059-ha grove) were mapped and measured for diameter at breast height (DBH, at 1.37 m [4.5 ft] above ground level). All living sequoias were mapped and recorded regardless of size, even including sequoias <1 m tall. Diameters of sequoias >1.5 ft (45.72 cm) DBH were recorded in 1-ft (30.48-cm) classes (e.g., 1.5-2.5 ft, 2.5-3.5 ft, etc.). In 2019, a skilled vegetation mapping and remote sensing analyst (Rodney Hart, U.S. Forest Service) used remotely sensed images to precisely georectify the original 1968 Redwood Mountain sequoia stem map.

Although our approach to defining a trunk diameter cutoff for millennial sequoias is conceptually simple, four issues needed to be addressed: (1) estimating the number of years it took the Redwood Mountain sequoias to grow to their height of diameter measurement (1.37 m), (2) accounting for the fact that Huntington's trunk diameters were inside the bark, whereas the 1968 Redwood Mountain sequoia inventory diameters were outside the bark, (3) determining how to treat the subset of Redwood Mountain sequoias with fused trunks, and (4) determining how to treat cut stumps from past logging in the grove. We address each of these issues in turn.

To estimate the number of years it took each Redwood Mountain sequoia to grow to 1.37 m tall (the height at which their diameters were measured), we used an equation that estimates height growth from radial trunk growth: $y = 178x^{-0.957}$, where y is the number of years it takes a sequoia seedling to grow 1 m taller and x is the cumulative width, in mm, of the innermost ten tree rings abutting the sequoia's pith near breast height (1.37 m) (Stephenson 2000). But because we had no way of knowing the cumulative widths of the ten innermost rings of individual Redwood Mountain sequoias, we assumed the width was 27.5 mm, based on the average of 451 of Huntington's sequoia stumps (Table A in Huntington 1914). Using $x = 27.5$ mm, we thus estimate that each Redwood Mountain sequoia took 7.5 years to grow 1 m taller as a seedling (Stephenson 2000), or about 10 years to reach breast height (1.37 m). That is, we assumed that a 1000-year-old Redwood Mountain sequoia had 990 growth rings at breast height. (NOTE: Our estimated ten years to breast height applies only to sequoia seedlings that subsequently survived to become large trees, which tend to have grown more rapidly than most seedlings. Slower-growing sequoia seedlings are initially abundant but have a greatly reduced probability of surviving to become large trees [e.g., see Harvey et al. 1980, Harvey and Shellhammer 1991, Shellhammer and Shellhammer 2006, Stephenson et al. 2024].)

Next, because all of Huntington's trunk diameters were inside the bark, but all Redwood Mountain trunk diameters were outside the bark, meaningful comparisons of the two data sets

required us to estimate the Redwood Mountain sequoias' diameters inside the bark and, conversely, the diameter of Huntington's stumps outside the bark. We estimated bark thicknesses using the appropriate giant sequoia-specific equation from Appendix C of Sillett et al. (2015): $z = 100(0.007635x^{0.59052} - 0.006841y)$, where z = bark thickness (cm), x = trunk diameter outside the bark (cm), and y = height above ground level (m) (for our purposes, y = 1.37 m above ground level). For example, for Redwood Mountain's 320.02 to 350.50 cm (10.5 to 11.5 ft) diameter class, estimated bark thicknesses are 22.09 and 23.36 cm for the endpoints (for 320.02- and 350.50-cm diameter sequoias, respectively), yielding diameters inside the bark of 275.85 and 303.79 cm. Thus, the proportion of sequoias in the 320.02 to 350.50 cm diameter-outside-the-bark class that is ≥1000 years old is calculated as the proportion of Huntington's sequoias in the 275.85 to 303.79 cm diameter-inside-the-bark class that had ≥990 counted rings (because ≥990 rings plus the estimated ten years of seedling height growth yields ≥1000 years old). Specifically, Huntington's data set has 31 stumps ranging from 275.85 to 303.79 cm diameter inside the bark (Table S1), 14 of which have ≥990 rings, meaning that the proportion of millennial sequoias in the corresponding 320.02 to 350.50 cm (10.5 to 11.5 ft) diameter-outside-the-bark class is 14/31 = 0.4516. Based on this approach, we estimated proportions of millennial sequoias for each outside-the-bark diameter class (Table S1).

In smaller sequoias, Huntington's sample sizes fall below ten stumps for each 30.48-cm diameter class between 45.72 and 198.11 cm diameter outside the bark, with no data at all for sequoias <45.72 cm diameter outside the bark (Table S1). However, Fig. 1 of Stephenson (1994) shows ages determined from increment cores for hundreds of sequoias ranging from <5 cm to 218 cm diameter outside the bark. All these cored sequoias were <900 years old, reinforcing Huntington's data showing no millennial sequoias in diameter classes <228.59 cm outside the bark. Similarly, in the largest sequoias Huntington's sample sizes also fall below ten stumps for each 30.48-cm diameter class between 624.81 and 746.72 cm outside the bark, with no data at all for sequoias >746.72 cm outside the bark (however, no Redwood Mountain sequoias were >746.72 cm). Although we are unaware of any published data that could supplement Huntington's data for large sequoias, we suspect that additional data would simply confirm that sequoias >624.81 cm diameter outside the bark are overwhelmingly ≥1000 years old.

Next, to determine which trunk diameter best distinguishes millennial from non-millennial sequoias, we multiplied the number of Redwood Mountain sequoias in each diameter class by the expected proportion of millennial sequoias in the same diameter class (Table S1). This analysis includes only living, single-stemmed Redwood Mountain sequoias; later we will address multi-stemmed sequoias and cut stumps.

Our analysis estimated that, in 1968, the inventoried and stem-mapped portion of Redwood Mountain Grove contained 2003 living, single-stemmed millennial sequoias (the sum of the "≥1000 yrs old" column in Table S1). The optimum single trunk diameter for distinguishing millennial from non-millennial sequoias was 320 cm (10.5 ft), which yielded an estimated 2040 millennial sequoias (Table S2). Using the 320-cm trunk diameter cutoff therefore trivially overestimated (by 37 trees, or <2%) the estimated actual number of living, single-stemmed millennial Redwood Mountain sequoias in 1968; but even then, this slight overestimation was more than compensated for by our exclusion of potential millennial multi-stemmed sequoias (see below). Using the 320 cm cutoff yielded nearly equal proportions and numbers of false positives (17.1%, or 349 trees <1000 years old that were classified as ≥1000 years old) and false negatives (15.3%, or 312 trees ≥1000 years old that were classified as <1000 years old) (Table S2).

Available diameter cutoffs other than 320 cm would yield substantially poorer classifications of millennial and non-millennial sequoias. Using the next larger diameter-class cutoff, 351 cm (11.5 ft), would yield 101 false positives and 516 false negatives, or a ~21% underestimation of millennial sequoias. Using the next smaller diameter-class cutoff, 290 cm (9.5 ft), would yield 645 false positives and 129 false negatives, or a ~26% overestimation of millennial sequoias.

Of the living Redwood Mountain sequoias ≥46 cm (1.5 ft) DBH inventoried in 1968, 271 (~2.4%) were recorded as multi-stemmed – that is, they comprised adjacent sequoias whose trunks had grown together and were fused to heights above breast height. Most of these multi-stemmed sequoias (~92%) comprised two fused stems, and all but one of the remainder comprised three fused stems (~8%). From the reported DBH of each group of fused sequoias we calculated basal area, divided this basal area by the number of fused stems, then back-calculated the diameter equivalent for the individual stems within the fused group. From this we crudely estimated that 88 stems (44 sets of two fused stems, and no sets of three or four fused stems) may have had diameter equivalents of millennial sequoias (i.e., ≥320 cm). However, given inherent geometric uncertainties associated with this approach (such as effects of the degree and shape of fusing on the DBH measurement, and the unknown relative sizes of each of the fused stems) and the relatively small change it would make in our results (88 stems would increase the number of millennial sequoias by only ~4%), we conservatively chose to leave multi-stemmed sequoias out of all analyses and mapping of millennial sequoias.

The 1968 Redwood Mountain inventory also included 455 cut sequoia stumps ≥46 cm (1.5 ft) DBH (Table S1). We wished to include these stumps in our analyses because (1) they were more abundant than the multi-stemmed sequoias (which we ultimately chose to exclude; see above), and especially (2) unlike the multi-stemmed sequoias, which were scattered widely throughout the grove, the stumps were heavily concentrated in the western part of the grove. That is, we wished to see what the full distribution of millennial sequoias across the grove would have been if the logging had never occurred.

Virtually all the stumps likely date from between ~1875 (Buchanan et al. 1966) and 1915 (Meyer and Safford 2011). That is, the stumps were mostly 53 to 93 years old when they were inventoried in 1968. Thus, the diameter cutoff used to define millennial and non-millennial stumps must be reduced from 320 cm to account for two things: (1) the additional 53 to 93 years of growth the sequoias would have experienced if they had never been cut, and (2) the loss of bark and sapwood from the stumps over the decades after they were cut. We address these issues sequentially.

Using the appropriate bark-thickness equation from Sillett et al. (2015, Appendix C), we know that sequoias 320 cm DBH in 1968 would have had wood diameters inside the bark averaging ~275.8 cm (Table S1). Table A of Huntington (1914) indicates that, for a sequoia that has achieved a diameter of 275.8 cm inside the bark, average wood diameter growth rate during the immediately preceding decades would average about 0.19 cm/year. This growth rate suggests about 10.1 cm to 17.7 cm of lost potential wood-diameter growth from the time the stumps were cut (between 1875 and 1915) to the time the stumps were measured in 1968. That is, sequoias between about 258.1 cm and 265.7 cm diameter inside the bark would have achieved 275.8 cm diameter inside the bark (and 320 cm outside the bark) by 1968 if they had never been cut. Sequoias 258.1 cm and 265.7 cm diameter inside the bark at the time they were cut would have had average bark thicknesses of roughly 21.3 to 21.6 cm (from Sillett et al. 2015, Appendix C), with corresponding diameters outside the bark of 300.7 to 308.9 cm.

Little information is available on rates of bark and sapwood loss from sequoia stumps. Huntington (1914, p. 143) noted that for the cut stumps he studied, sapwood "decays rapidly, so that at the end of 20 to 30 years it is often quite rotten, although enough generally remains to permit the counting of the rings." Referring to fallen sequoia trunks (not stumps), Douglass (1928, p. 19) said that the bark "lasts 10 years or so after the tree has fallen," and that the sapwood "weathers off in something over half a century." Referring to a cut sequoia trunk that had been on the ground for 60 years, Douglass (1936, caption to Plate 2A) noted "bark gone, sapwood mostly gone." During a field trip to Case Mountain Grove on 6 May 2024, one of us (N. L. Stephenson) opportunistically supplemented Huntington's and Douglass' observations. While they were still on private land, many large Case Mountain sequoias were logged beginning "in the 1940s" and continuing into the "mid 1950s" (Elliott-Fisk et al. 1996). We assumed the Case Mountain logging began immediately after the end of World War II, and thus potentially spanned 1945-1955. That is, at the time of observation in 2024 the stumps were likely 69-79 years old, with a midpoint age of ~74 years – comparable to the midpoint age of ~73 years for the Redwood Mountain stumps when they were measured in 1968. Of six Case Mountain stumps examined, Stephenson found that four had no remaining bark at breast height (or, if the stump had been cut below mid-slope breast height, no remaining bark just below the cut where diameter would most likely be measured). The two remaining stumps still retained one or two relatively narrow standing strips of bark, although nearly all sapwood had rotted away from behind the standing strips. Sapwood that remained on all six stump exteriors was very soft and spongy from rot (unlike the solid heartwood) and mostly had estimated thicknesses of roughly <1 cm to perhaps 2 cm, in alignment with Douglass' (1936) assessment that sapwood was "mostly gone" from a cut trunk that had been on the ground for 60 years.

Based on the preceding, we roughly estimated that average losses of combined bark and sapwood thicknesses from Redwood Mountain stumps might have ranged from 70-100%, depending in part on individual stump ages when measured in 1968. Bark of the living sequoias before they were cut would have averaged ~21 cm thick (see the preceding paragraphs) and sapwood would have averaged at least 10 cm thick (unpublished data; also see Huntington 1914, p. 143, and Sillett et al. 2015, Appendix C), for a total of ~31 cm of bark plus sapwood thickness. A 70-100% loss would therefore amount to a ~22-31 cm loss of radius, or a ~44-62 cm loss of stump diameter at breast height. Thus, the stumps of sequoias that had diameters outside the bark ranging from 300.7 to 308.9 cm at the time of cutting (see the preceding paragraphs) would likely have stumps averaging ~239 to 265 cm DBH at the time they were measured in 1968. The 1968 Redwood Mountain diameter class boundary that best corresponds to this ~239 to 265 cm diameter range would be stumps 259 cm (8.5 ft) DBH in 1968.

We therefore judged that if the Redwood Mountain sequoias had never been cut and had thus grown for an additional 53-93 years and had retained all their sapwood and bark, stumps that were ≥259 cm (≥8.5 ft) DBH in 1968 would likely have been living trees ≥320 cm (≥10.5 ft) DBH in 1968, qualifying for classification as millennial sequoias. Adding the 198 stumps ≥259 cm DBH to the 2040 living single-stemmed sequoias ≥320 cm DBH thus yields 2238 total mapped sequoias judged to be ≥1000 years old, about 9% of which were stumps.

The spatial distribution patterns of Redwood Mountain millennial sequoias as inventoried in 1968 (Fig. 4) can be expected to broadly reflect the spatial distribution patterns immediately preceding the 2021 KNP Complex wildfire. Between 1968 and 2021 the grove experienced no severe disturbances large enough to kill groups of millennial sequoias. Even the 1987 Pierce wildfire in the grove – which until recently was the most severe modern wildfire recorded in a

sequoia grove – killed only two millennial sequoias (see the main text). Certainly, other scattered millennial sequoias died between 1968 and 2021 – most of them by falling (personal observations) – but they were almost certainly replaced by comparable numbers of sequoias that newly recruited from smaller diameter classes to diameters ≥320 cm, maintaining something close to the near-stationary age distributions found in old-growth sequoia groves (York et al. 2013).

Non-fire disturbances that kill groups of sequoias

The largest recorded non-fire disturbance in a sequoia grove was the "great sequoia avalanche" of 20 December 1867, as reported by Fry (1931). A major rain-on-snow event caused the saturated soils on a large portion of the steep northern slope of Dennison Mountain (within the future Sequoia National Park) to slip in a combined avalanche and landslide, which ultimately caused the Garfield Grove of giant sequoias to be "reduced by about one-third of its former size" (Fry 1931), corresponding to a loss of perhaps 150-250 ha of the grove. According to Fry (1931), some of the sequoias lost ranged from 20 to 30 feet (~600-900 cm) in diameter. No studies have attempted to determine how much of the devastated area might subsequently have been recolonized by sequoias.

Groups of large sequoias can also be knocked down by wind. For example, Sequoia National Park's 1941 Superintendent's Annual Report states that on 8 January 1941, a windstorm "apparently of almost hurricane velocity" struck the Garfield Grove of sequoias, where "upward of a thousand trees were leveled [presumably a thousand trees of all species, not just sequoias], including some sequoias which reached 20 feet [~600 cm] in diameter" (NPS 1941). An associated photograph shows an area of damage concentrated along a low ridge. More recently, on 18 January 2021 the Mariposa Grove in Yosemite National Park lost 15 mature sequoias in a windstorm, eight of them grouped together in a wet area and along a creek and seven of them near ridges.

Deriving millennial sequoia densities for Table 1

As with Redwood Mountain Grove (see "**Determining trunk diameters of millennial sequoias,**" above), between 1964 and the mid-1970s virtually all giant sequoias that were within Sequoia and Kings Canyon national parks' boundaries at that time were mapped and had their trunk diameters at breast height recorded by 1-ft (30.48-cm) diameter class (for sequoias >1.5 ft DBH). All living sequoias and cut stumps were mapped and recorded regardless of size. During the late 2010s and early 2020s, a skilled vegetation mapping and remote sensing analyst (Rodney Hart, U.S. Forest Service) used remotely sensed images to precisely georectify the original sequoia stem maps. Hart's final grove boundary polygons reflected the presence of any sequoias of any size, even sequoias that were <1 m tall when mapped in the original census.

The censused and stem-mapped areas of a grove were sometimes smaller than total grove area, usually because parts of the grove were outside of park boundaries at the time of the census (i.e., sections of grove that fell within other federal or state jurisdictions, or on private property). In the case of the large Dillonwood Grove (420.9 ha), none of the grove was within park boundaries at the time of the censuses, although 330.0 ha is now within park boundaries. Occasionally field crews simply overlooked parts of a grove, with the most extreme example (by far) being the 9.1-ha Surprise Grove, of which only 2.4 ha was censused and mapped (see Table 1 in the main text).

As with Redwood Mountain Grove, for all censused and mapped sequoia groves in Table 1 we classified living sequoias ≥320 cm DBH and cut stumps ≥259 cm DBH as millennial sequoias. As with Redwood Mountain Grove, the ≥259 cm stump diameter – which accounts for the stumps' lost diameter growth, lost bark, and lost sapwood – is appropriate for the logged parts of Atwell Grove and Big Stump Grove (Table 1) because the bulk of the logging in those groves took place in the 1880s and 1890s (Elliott-Fisk et al. 1996), suggesting at least a 70-100% loss of bark and sapwood by the time of the censuses (see "**Determining trunk diameters of millennial sequoias,**" above).

Determination of sequoias scorched, torched, killed by KNP Complex

In early September 2022, one year after the KNP Complex wildfire, field crews assessed the fate of all previously mapped sequoias found within a 50 m radius of each of the 46 seedling plot centers (randomly located using the Generalized Random Tessellation Stratified [GRTS] algorithm with an equal probability stratified sampling design; Stevens & Olsen 2004) within the previously stem-mapped areas of Redwood Mountain Grove that burned at high severity (i.e., RdNBR >640) (Soderberg et al. 2024). Total sample area was thus ~36.1 ha, or about 14% of the stem-mapped high-severity burned area of Redwood Mountain Grove. For each sequoia in the surveyed areas, Soderberg et al. (2024) recorded whether the tree was alive (retaining any green foliage) or dead (no green foliage), and the percentage of its crown that was live, scorched, or torched. Foliage was classified as "live" if green, "scorched" if dead and brown (i.e., killed by convective heat of the fire), and "torched" if foliage was blackened (charred) or missing (e.g., only blackened, bare branches remained) but presumably consumed during the fire. Diameters at breast height of the individual sequoias were taken from the 1968 sequoia tree inventory of Redwood Mountain Grove (described in "**Determining trunk diameters of millennial sequoias**," above).

Methodological problems

Assessing apparent data bias

Comparing Soderberg et al.'s (2024) and Hanson et al.'s (2024) seedling densities

Although most of Hanson et al.'s (2024) data are publicly available in their paper's Supplementary Material, we wished to use their full data set, which we obtained directly from the paper's designated data contact. Using Soderberg et al.'s (2024) and Hanson et al.'s (2024) data from the high-severity burn areas of Redwood Mountain Grove, we estimated mean giant sequoia seedling densities and compared the estimates to assess the probability that the estimates were statistically different from one another (i.e., ANOVA). We used a Bayesian methodology that allowed us to directly describe the uncertainty in our estimates as probability distributions (see Fig. 8 of the main text), where the quantifiable uncertainty can be used to calculate the probability of the true mean from either dataset being above or below the other, given the data.

Our models are structured with normal prior distributions and are described as follows:

$$y_i \sim \mathrm{NB}(m,q) \qquad \text{(eq. S.1)}$$

where $y_{i,}$ is the seedling count for the ith observation and m and q are the mean and the shape parameter of the negative binomial distribution, respectively. The mean parameters are related to the seedling density (per hectare; '*SDens*') for ith observations using the following link function:

$$\log(m_i) = \alpha + \log(T_i) + (SDens_i)\beta + e_i \quad \text{(eq. S.2)}$$

where $\log(T_i)$ is an 'offset', which corrects for the variation in surveyed area amongst *i*th observations, α is the intercept, β is the parameter estimate, and e_i is the residual error associated with the *i*th observation. The model parameter was drawn from normal distributions centered around the mean and estimated variances of the data (eq. S.3) and was given a normal, diffuse prior with a wide distribution (eq. S.4), with the exception of the variance parameter, which was given a modest, Student's-t prior distribution (eq. S.5).

$$\mu SDens_i \sim \text{Normal}\ (\mu SDens, \mu SDens\sigma^2) \quad \text{(eq. S.3)}$$
$$\mu SDens \sim \text{Normal}\ (0,1000) \quad \text{(eq. S.4)}$$
$$SDens\sigma^2 \sim \text{Student-t}\ (0.3) \quad \text{(eq. S.5)}$$

We conducted all analyses in R version 4.3.1 (R Core Team, 2023) by computing Bayesian parameter estimates using Markov chain Monte Carlo (MCMC) sampling. Statistical package 'rstanarm' (Goodrich et al. 2022, Stan Development Team 2024) was used to compute five MCMC chains for 4000 iterations, discarding the first 2000 iterations as burn-in and sampling each iteration thereafter. All models were checked graphically for convergence and Rhat ($\hat{r}$) values (i.e., the Gelman-Rubin convergence diagnostic [Gelman and Rubin 1992]), a ratio of variation within and between MCMC chains, were less than 1.01, indicating thorough MCMC sampling and convergence of the posterior distribution.

Plot sizes and density differences

Compared to Hanson et al.'s (2024) high-severity Redwood Mountain seedling plots, all of Soderberg et al.'s (2024) seedling plots were quite large: 45 of Soderberg et al.'s 46 plots had an 11.35-m radius (0.0405 ha) and one had a 17.84-m radius (0.1 ha). In contrast, Hanson et al.'s (2024) variable-radius plots ranged from 1 m radius (0.000314 ha) up to 10 m radius (0.0314 ha). Specifically, if Hanson et al. (2024) found no sequoia seedlings within their initial 1-m radius plot, they expanded the plot to a 2 m radius. If there were still no seedlings, they expanded the plot to a 5 m radius, and finally up to a 10 m radius. Of Hanson et al.'s 43 plots that fell in high-severity burn areas (MTBS RdNBR >640), 30 (69.8%) had 1 m radius, 7 (16.3%) had 2 m radius, 3 (7.0%) had 5 m radius, and 3 (7.0%) had 10 m radius. Any one of Hanson et al.'s 1-m radius (0.000314 ha) plots (comprising ~70% of their plots) had an area less than 1% of one of Soderberg et al.'s ≥0.0405 ha plots, and the remaining ~30% of Hanson et al.'s plots (those with ≥2 m radius) had a mean plot area about 23% that of Soderberg et al.'s mean plot area.

Because low seedling densities triggered expansions of Hanson et al.'s (2024) plots, their 15 lowest-density plots (35% of their plots) included all 13 of their expanded plots (those ≥2 m radius), plus two 1-m radius plots. In these low-density plots, Hanson et al.'s data show a mean density of 1963 seedlings ha^{-1}, which is 2.7-fold greater than the 738 seedlings ha^{-1} found by Soderberg et al. in their equivalent 35% of lowest-density plots (16 plots). In contrast, Hanson et al.'s 28 highest-density plots (65% of their plots) all were of 1 m radius, with a mean density of 90,263 seedlings ha^{-1}. This density is 6.4-fold greater than Soderberg et al.'s mean density of 14,105 seedlings ha^{-1} in their equivalent 65% of highest-density plots (30 plots). Thus, the greatest disparity between the Hanson et al.'s (2024) and Soderberg et al.'s (2024) mean seedling

densities is found in plots with the greatest seedling densities, which in Hanson et al.'s case solely comprise their smallest, 1-m radius plots.

Seasonal timing of censuses

Most sequoia seedlings germinate by late spring or early summer, with substantial net losses to mortality after that (Hartesveldt and Harvey 1967, Hartesveldt et al. 1967). For example, earlier studies in Redwood Mountain Grove found 17%, 55%, and 70% mortality of a newly germinated cohort of sequoia seedlings by 20 July, 1 September, and 21 October, respectively (Hartesveldt and Harvey 1967, Hartesveldt et al. 1967). Thus, *a priori* we would expect Soderberg et al.'s (2024) early-season 2023 seedling censuses (22 June to 20 July [mean 29 June]) to find higher, not lower seedling densities than Hanson et al.'s (2024) later-season 2023 censuses (30 June to 5 August, and 29 September to 11 October). We can thus dismiss differences in the seasonal timing of the censuses as a cause of the large density difference between the data sets; if anything, the difference in seasonal timing may have reduced the density difference between the data sets.

Bias introduced by variable-radius plots

Hanson et al.'s (2024) use of variable-radius plots was inherently biased toward density overestimation. Specifically, if no sequoia seedlings were found within one of Hanson et al.'s initial 1-m radius plots, they expanded the plot to a 2 m radius. If there were still no seedlings, they expanded the plot to a 5 m radius, and finally up to a 10 m radius. Thirty percent of their high-severity plots had their sizes increased in this manner. But this approach rejects legitimate density values of zero, instead re-sampling until density values greater than zero are finally encountered.

To quantify the magnitude of this bias, for Hanson et al.'s (2024) high-severity plots with radii ≥2 m we replaced all density values with zero. We found that the magnitude of bias introduced by variable-radius plots was trivial (a <1% increase), because plot expansion was only triggered in areas of low seedling densities where the expanded plots accordingly encountered few seedlings. Thus, Hanson et al.'s variable-radius plot approach was not a meaningful contributor to the substantial density differences between their data and those of Soderberg et al. (2024). Regardless, best practices will normally include the use of fixed-radius plots rather than variable-radius plots.

Plot edge effects

Different rules for counting a seedling as inside or outside of a plot can lead to bias (Elzinga et al. 1998). Soderberg et al.'s (2024) rule for inclusion was that the point at which a seedling's stem met the ground had to be inside the plot radius. A more lax rule of inclusion, such as including a seedling if any part of its crown fell within the plot radius, would effectively increase the sampled plot radius (without changing the nominal plot radius) and would thus contribute to inflated densities. However, neither the lead author of Hanson et al. (2024) nor the paper's designated data contact responded to our April 2024 email query regarding their rules of inclusion or exclusion of seedlings near plot edges.

But for Hanson et al.'s (2024) 6-fold greater mean seedling density to have been caused solely by such edge effects, their effective plot radii would have had to have been >2.4-fold greater than their nominal plot radii; for example, their 1-m radius plots would have needed an effective radius of >2.4 m. Lax inclusion criteria for small sequoia seedlings (most of which

would likely have crown radii <15 cm) could not reasonably be expected to cause such a large effective sample radius. Thus, we can reasonably assume that potentially lax rules of inclusion were not the primary source of 6-fold greater densities found by Hanson et al. (2024).

Trampled seedlings

Unlike Hanson et al. (2024), Soderberg et al. (2024) censused each of their plot locations twice: once in early September of 2022 (their first-year census) and once largely in late June of 2023 (their second-year census). We thus considered whether seedlings that may have been trampled and killed during Soderberg et al.'s first census could have depressed seedling densities enough during their second census to account for the 6-fold density differences reported by Hanson et al. and Soderberg et al.

For two reasons, we can dismiss this possibility as a meaningful source of bias. First, by the time of the first Soderberg et al. (2024) census in early September 2022, most sequoia seedlings that had survived their first summer would typically be at least a few cm tall and have roots extending many cm into the soil (Harvey et al. 1980). That is, the seedlings would be (1) easy to see and thus easy to avoid stepping on (especially for field crew members who had extensive prior experience and training to avoid harming seedlings), and (2) large enough to be relatively resistant to fatal damage even if they were accidentally stepped on.

Second, of Soderberg et al.'s 2022-cohort seedlings that were censused in early September 2022, 69% survived until the second census in late June 2023. This exceeds the independently derived ~50% survival from early September through June indicated by the seasonal survival of thousands of individually marked and tracked sequoia seedlings reported by Hartesveldt and Harvey (1967) and Harvey et al. (1980). We suspect the comparatively higher September through June survival of the Soderberg et al. (2024) seedlings relative to the Hartesveldt and Harvey seedlings was a consequence of the exceptionally wet and snowy winter of 2022-2023. Regardless, even if we were to assume (unrealistically) that all seedling mortality between early September 2022 and late June 2023 was caused by trampling (i.e., if we assume that all the seedlings would have survived if there had been no 2022 census), total seedling density (2022 + 2023 cohorts) in late June 2023 would still have been only 12,784 seedlings ha^{-1}, rather than the observed 9455 seedlings ha^{-1}. That is, Hanson et al.'s (2024) reported 2023 density of 59,461 seedlings ha^{-1} would still be ~4.7-fold larger than that of Soderberg et al.

Hanson et al.'s (mis)use of medians

To produce a concrete example of how median seedling density varies with plot size, we used data from Demetry's (1995, 1998) study of sequoia seedlings in fire-created forest gaps. Within her largest study gap (Gap 1, spanning 1.164 ha), Demetry used a total station to precisely survey the locations of all 2364 giant sequoia seedlings that were >10 cm tall 10 years post-fire (Fig. S2). For each of 1000 computer iterations, we sampled seedlings in the gap with 15 randomly located, non-overlapping circular plots, calculating mean and median seedling densities for each iteration and then averaging results of the 1000 iterations. At intervals of 1 m radius, the process was repeated for plot radii ranging from 1 m (the size of the majority of Hanson et al.'s [2024] plots) to 11 m (approximating the 11.35-m radius of the majority of Soderberg et al.'s [2024] plots). We limited our sample to 15 non-overlapping plots per iteration so that a sample using our largest plots (11 m radius) would cover a total area not exceeding one half of the gap area. Even then, the irregular shape of the gap meant that our algorithm was sometimes unable to randomly place 15 non-overlapping 11-m radius plots completely within the

gap's boundary. Thus, regardless of plot size, we accepted all randomly placed plots having at least 75% of their area inside of the gap boundary, and this consistently allowed 15 of our largest plots to be placed on the study landscape. Because seedling abundances and locations outside of the gap boundary were unknown, we only calculated seedling densities based on the portion of each plot that fell within the gap boundary. For example, if 90% of an 11-m radius (0.038 ha) plot fell within the gap boundary, seedling density was calculated as the number of seedlings within that 90% of the plot divided by (0.9 x 0.038) ha.

The relatively low density of seedlings in the gap (2031 ha^{-1}) was likely a consequence of three things. First, Demetry (1995, 1998) surveyed the seedlings 10 years post-fire, at a time when seedling densities would already have been greatly reduced by natural mortality (Harvey and Shellhammer 1991, Stephenson et al. 2024). Second, Demetry only mapped seedlings >10 cm tall, even though some 10-year-old seedlings can be as short as 4 cm (Harvey et al. 1980, p. 59). Finally, the gap had a seedling density lower than the average of Demetry's six large study gaps, likely a consequence of natural variation and local contingencies.

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Table S1. Data used to determine the optimal trunk diameter for distinguishing giant sequoias ≥1000 years old from those <1000 years old.

									Proportion of	Living, single-stemmed Redwood Mtn sequoias in 1968			Total number
Diameter class (outside the bark)				Bark thickness *		Diameter inside bark		Number of	stumps >=990 yrs	Total numbers	Estimated numbers that were:		of cut stumps
Start (ft)	End (ft)	Start (cm)	End (cm)	Start (cm)	End (cm)	Start (cm)	End (cm)	stumps **	at stump top **		>= 1000 yrs old	<1000 yrs old	in 1968
1.5	2.5	45.72	76.20	6.36	8.93	33.00	58.34	1	0	4015	0.0	4015.0	10
2.5	3.5	76.20	106.67	8.93	11.10	58.34	84.48	2	0	1376	0.0	1376.0	21
3.5	4.5	106.67	137.15	11.10	13.02	84.48	111.11	3	0	592	0.0	592.0	32
4.5	5.5	137.15	167.63	13.02	14.78	111.11	138.07	9	0	448	0.0	448.0	44
5.5	6.5	167.63	198.11	14.78	16.41	138.07	165.29	8	0	457	0.0	457.0	51
6.5	7.5	198.11	228.59	16.41	17.94	165.29	192.71	13	0	538	0.0	538.0	40
7.5	8.5	228.59	259.07	17.94	19.39	192.71	220.30	14	0.0714	591	42.2	548.8	59
8.5	9.5	259.07	289.55	19.39	20.76	220.30	248.02	19	0.1579	550	86.8	463.2	41
9.5	10.5	289.55	320.02	20.76	22.09	248.02	275.85	21	0.3810	479	182.5	296.5	51
10.5	11.5	320.02	350.50	22.09	23.36	275.85	303.79	31	0.4516	452	204.1	247.9	26
11.5	12.5	350.50	380.98	23.36	24.58	303.79	331.82	38	0.8947	395	353.4	41.6	40
12.5	13.5	380.98	411.46	24.58	25.77	331.82	359.92	64	0.8906	348	309.9	38.1	15
13.5	14.5	411.46	441.94	25.77	26.92	359.92	388.10	66	0.9394	262	246.1	15.9	12
14.5	15.5	441.94	472.42	26.92	28.04	388.10	416.34	46	1	197	197.0	0.0	5
15.5	16.5	472.42	502.90	28.04	29.13	416.34	444.64	41	1	181	181.0	0.0	3
16.5	17.5	502.90	533.37	29.13	30.19	444.64	472.99	27	0.9630	82	79.0	3.0	2
17.5	18.5	533.37	563.85	30.19	31.23	472.99	501.39	18	1	59	59.0	0.0	0
18.5	19.5	563.85	594.33	31.23	32.25	501.39	529.84	14	1	31	31.0	0.0	2
19.5	20.5	594.33	624.81	32.25	33.24	529.84	558.33	10	0.9000	22	19.8	2.2	0
20.5	21.5	624.81	655.29	33.24	34.22	558.33	586.86	8	1	7	7.0	0.0	1
21.5	22.5	655.29	685.77	34.22	35.17	586.86	615.42	2	1	3	3.0	0.0	0
22.5	23.5	685.77	716.25	35.17	36.11	615.42	644.02	2	1	0	0.0	0.0	0
23.5	24.5	716.25	746.72	36.11	37.04	644.02	672.65	1	1	1	1.0	0.0	0

* Bark thickness was derived from the appropriate equation in Appendix C of Sillett et al. (2015).
** Data derived from Huntington (1914), as described in Stephenson and Demetry (1995) and in the Supplementary Text.

Table S2. Contingency table of numbers of giant sequoias in Redwood Mountain Grove, California, USA by estimated age and trunk diameter at breast height.

		Estimated sequoia age (including 10 years to breast height)		
		<1000 years	≥1000 years	TOTAL
Trunk diameter at breast height (outside the bark)	46 to 320 cm	8,734.5	311.5 (false negative millennials)	9,046
	≥320 cm	348.7 (false positive millennials)	1,691.3	2,040
	TOTAL	9,083.2	2,002.8	11,086

NOTE: Table S1 was the source of these summary data.

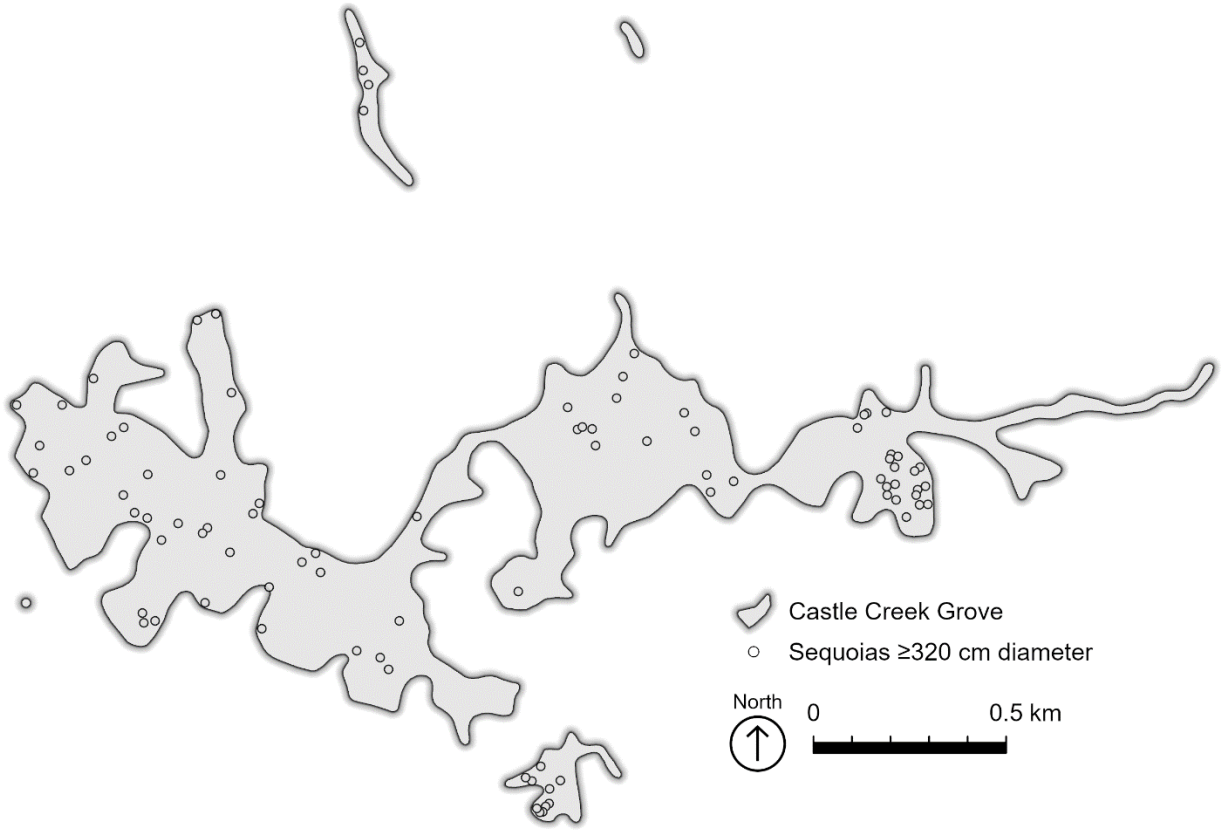

Figure S1. Distribution of millennial sequoias (those estimated to be ≥1000 years old) in the 88.5-ha Castle Creek Grove, Sequoia National Park, California, USA. Despite the low density of millennial sequoias in this grove (the lowest density of the 22 stem-mapped groves that were >10 ha; Table 1), the scattered distribution of millennial sequoias within the grove's boundaries shows that no extensive crown fires – nor any fires severe enough to kill most sequoias – had occurred in at least the preceding 1000 years. In contrast, as a consequence of the 2021 KNP Complex wildfire a 141-ha portion of Redwood Mountain Grove – an area larger than the Castle Creek Grove shown here – now has an estimated millennial sequoia density that is 5- to 14-fold lower than that of Castle Creek Grove (see "**Recent high-severity wildfires were anomalous at millennial timescales**" in the main text).

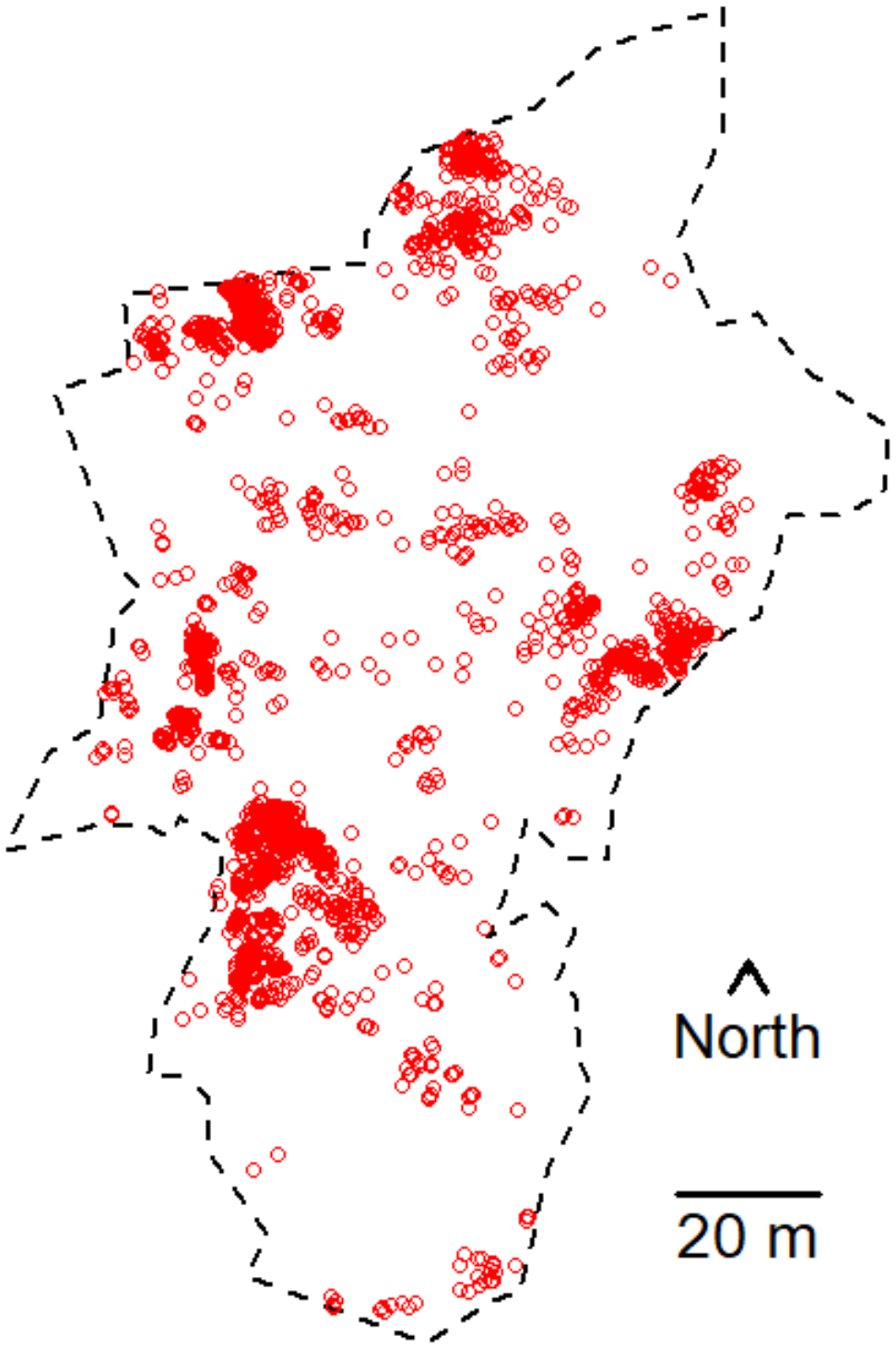

Figure S2. Map of 10-year post-fire sequoia seedlings >10 cm tall (red circles) within Demetry's (1995, 1998) fire-created Gap 1. The substantial fine-scale spatial variation in seedling densities is typical of natural post-fire sequoia regeneration.