National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

A Natural Resource Condition Assessment for Sequoia and Kings Canyon National Parks

Appendix 11 – Giant Sequoia

Natural Resource Report NPS/SEKI/ NRR—2013/665.11

ON THE COVER
Giant Forest, Sequoia National Park
Photography by: Brent Paull

A Natural Resource Condition Assessment for Sequoia and Kings Canyon National Parks

Appendix 11 – Giant Sequoia

Natural Resource Report NPS/SEKI/ NRR—2013/665.11

Robert A. York
Dept. of Environmental Science, Policy, and Management
Center for Forestry, UC Berkeley
4501 Blodgett Forest Road
Georgetown, CA 95634

Nathan L. Stephenson
U.S. Geological Survey, Western Ecological Research Center
Sequoia - Kings Canyon Field Station
47050 Generals Highway #4
Three Rivers, CA 93271

Marc Meyer
USDA Forest Service, Pacific Southwest Region
1600 Tollhouse Road
Clovis, CA 93611

Steve Hanna
USDA Forest Service, Giant Sequoia National Monument
1839 South Newcomb Street
Porterville, CA 93257

Tadashi Moody
Spatial Informatics Group
www.sig-gis.com

Anthony C. Caprio
Division of Resources Management and Science
Sequoia and Kings Canyon National Parks
47050 General's Highway
Three Rivers, CA 93271

John J. Battles
Dept. of Environmental Science, Policy, and Management
UC Berkeley
137 Mulford Hall
Berkeley, CA 94720

June 2013

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This document contains subject matter expert interpretation of the data. The authors of this document are responsible for the technical accuracy of the information provided. The parks refrained from providing substantive administrative review to encourage the experts to offer their opinions and ideas on management implications based on their assessments of conditions. Some authors accepted the offer to cross the science/management divide while others preferred to stay firmly grounded in the presentation of only science-based results. While the authors' interpretations of the data and ideas/opinions on management implications were desired, the results and opinions provided do not represent the policies or positions of the parks, the NPS, or the U.S. Government.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available in digital format from the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

Please cite this publication as:

York, R. A., N. L. Stephenson, M. Meyer, S. Hanna, T. Moody, A. C. Caprio, and J. J. Battles. 2013. A natural resource condition assessment for Sequoia and Kings Canyon National Parks: Appendix 11 – giant sequoia. Natural Resource Report NPS/SEKI/NRR—2013/665.11. National Park Service, Fort Collins, Colorado.

NPS 102/121034, June 2013

Contents

Page

Figures v

Tables vii

Appendices vii

Scope of analysis 1

Critical questions 3

Reference conditions 5

Predicted stationary age distribution for giant sequoia 5

Repeated prescribed fire effects on giant sequoia regeneration 9

High severity disturbance effects on regeneration 10

Burned substrate effects on recruitment 12

Spatial and temporal analyses 17

Grove locations 17

Fire Return Interval Departure – the primary metric of grove condition 17

Snow-dominated precipitation 18

Ozone concentration 19

Precipitation and maximum/minimum average temperature 19

Climatic water deficit 19

Size structures within groves 20

Size structure by agency 20

Departure index shifts- An approach for detecting change in grove size structure 24

Size structures of individual groves 24

Analysis of Uncertainty 27

Interactions with other focal resources 27

Contents (continued)

Page

Stressors 27

Air quality 28

Land use/fragmentation 29

Climate change 31

Invasive species 34

Altered fire regimes 35

Emergent disease complexes 36

Giant sequoia in a novel environment 39

Inter-grove assessment 40

Groves at elevation extremes 40

Small groves 40

Groves with extreme fire return interval departures 41

Groves with persistent and large climatic water deficit 41

Level of confidence in assessment 43

Monitoring and Inventory 45

Basic research 45

Active adaptive management experiments 46

Literature Cited 47

Figures

Page

Figure 1. Predicted and actual age distributions from two locations not experiencing fire during the 20th century (top graph; Atwell grove and the periphery of the Giant Forest grove), and from two locations that experienced prescribed fires in the 1970's (Mariposa Grove) and 1982 (central Giant Forest Grove)..... 7

Figure 2. Change in mean giant sequoia density prior to and following repeated burns within SEKI 10

Figure 3. Density of giant sequoia following disturbances of different quality and severity in the Bearskin, Black Mt., Case Mt., and Redwood Mt. groves..... 13

Figure 4. Average biomass of seedlings two years after planting in ash and bare soil substrates at Whitaker's Forest (Redwood Mountain Grove)..... 14

Figure 5. Giant sequoia growth trends of seedlings planted inside, on the edge of, and outside of ash substrates following the burning of debris piles in a Sierra Nevada mixed conifer forest 15

Figure 6. Size structure of giant sequoia by agency in the southern Sierra Nevada..... 22

Figure 7. Trend in the number of giant sequoia greater than 244 cm dbh since 1915 at Whitaker's Forest..... 23

Figure 8. Mean surface soil compaction (top) and mean organic matter (bottom) in reference and restoration treatment areas within the Giant Forest grove 31

Figure 9. Predicted relative growth as a function of light availability and distance from gap edge (used as a soil resource availability index) at Whitaker's Forest Research Station, CA. 33

Tables

Page

Table 1. Data sources, non-published material, and conference proceedings used for this assessment. 4

Table 2. Integrity metrics and condition assessments 42

Appendices

Page

Subappendix 1: Methods for the developing the hypothetical stationary age distribution for giant sequoia 55

Subappendix 2: – Spatial analysis data and maps 61

Subappendix 3: Inventory and monitoring methods of agencies managing giant sequoia groves 79

Subappendix 4: Size structures of groves within SEKI as of ~1970 83

Subappendix 5: Size structures of groves within GSNM as of ~2005 89

Scope of analysis

For natural resource managers in the southern Sierra Nevada, giant sequoia requires very little introduction. It receives great attention as an icon of western forests and as a common namesake with the areas where it occurs. While it is a single component of a very complex system, its attention in this assessment and in general is well deserved. Giant sequoia is one of the few "destination species" that attracts a wide swath of the public by nature of it simply being present. It draws people, who otherwise may not travel, to a natural environment. The result is an expansion of the public's sense of natural resource stewardship. Because park managers could not achieve their mission without public support, this fostering role of giant sequoia is critical for park natural resources and is important for natural resources in general.

Despite its social relevance and physical size, we re-emphasize here that the giant sequoia resource is a relatively small component of the ecosystems of the southern Sierra Nevada. As is the case with all of the resources assessed in the NRCA, we focus on giant sequoia with the understanding that other resources will be considered simultaneously when evaluating management decisions that impact giant sequoia. While we attempt to explicitly address the interaction of giant sequoia with other resources and stressors, we also realize that ultimately managers will integrate much more information than is presented here when making decisions that influence giant sequoia.

The autecology and management issues surrounding giant sequoia have been thoroughly reviewed elsewhere (Harvey et al. 1980, Aune 1994, Stephenson 1996). Stephenson (1996), in particular, should be reviewed when considering any management decisions that potentially impact giant sequoia. For those who may not be familiar with giant sequoia ecology, a summary of basic information is provided in a table below. In some parts of this assessment, we reproduce text from Stephenson's review because it is still relatively current for addressing some of the stressors. Numerous recent studies reported since 1996 have confirmed and expanded the understanding of giant sequoia, especially in areas related to ecophysiology and the effectiveness of restoration treatments. These recent studies are integrated into this assessment. Additionally, much unpublished work has been done that is useful for establishing baselines and evaluating trends. This work is presented in detail in order to expand upon previous work and to inform the final assessments. Instead of providing an introductory description of giant sequoia distribution and the various landowners who manage groves, we refer readers to the more recent descriptions provided by Stephenson (1996) and Willard (2000). Some of the relevant points from these descriptions with respect to giant sequoia within SEKI and Giant Sequoia National Monument (GSNM) include:

- Of the native giant sequoia grove area in SEKI and GSNM approximately 38% is within SEKI and 62% is within GSNM.

- 35 of the groves that make up the entire population are all or partially managed by SEKI and 33 are managed by GSNM[1].

- As we have done above, reviewers addressing giant sequoia widely recognize its transcendence beyond an ecologically important species to one with considerable added cultural value.

Giant sequoia geography and autecology: In a nut shell

- The native population exists in disjunct groves, numbering 65 to 75 depending on whether adjacent groves are lumped into one or split into two

- Cumulative grove area is approximately 14,600 hectares

- Potential longevity of individual trees is at least 3,200 years, likely more

- Past expansions of grove boundaries may have been constrained by cold at upper elevations and drought at lower elevations

- While giant sequoia can be the dominant species within parts of groves in terms of basal area, it is often relatively uncommon in terms of density of individuals

- Trees have several adaptations to fire (e.g. thick and non-resinous bark, serotinous cones banks, scorch-resistant foliage, epicormic sprouting)

- Its life history strategy is a combination of pioneer (e.g. light seeds, rapid post-disturbance colonization, rapid growth) and late-seral species strategies (longevity, large size). It is perhaps best classified as a "long-lived pioneer"

[1] The administrative partitioning of the population into groves has and will continue to evolve. Here, we refer to the 35-grove accounting reported by Stohlgren (1991) for NPS groves. For GSNM groves, we use the 33-grove accounting used during the most recent surveys by GSNM staff.

Critical questions

Questions that were derived from the NRCA process and are addressed in this report:

1. What does a sustainable age distribution look like in terms of the relative number of old versus young giant sequoia trees?
2. How effective have prescribed fire treatments been in promoting giant sequoia regeneration? How have wildfires influenced regeneration?
3. How will repeated prescribed fires influence giant sequoia?
4. How does size structure differ between groves, both within SEKI and within the GSNM?
5. How do other conditions relevant to giant sequoia resilience differ between groves?

Questions that were derived from the NRCA process, but are not addressed in detail here because of a lack of information. They identify areas of uncertainty to be addressed with further studies and with management experiments:

1. For enabling the prediction of where giant sequoia might regenerate in the future, what are the differences in soils (i.e. origin, physical, chemical properties) within and surrounding giant sequoia groves? How do soil properties interact with underground hydraulic dynamics?
2. How will long-term recruitment patterns that follow restoration treatments interact with climate?
3. What insects and pathogens, both native and non-native, might emerge as major problems in the face of climatic changes?
4. What are the climatic thresholds for sequoia die-back?
5. How will all known (and unknown) stressors interact with one another, and with what effects?
6. Where, if anywhere, are potential climatic refugia for giant sequoias?

Data sources and types used in analysis

Several publications were integrated throughout this analysis. Data came from unpublished sources, SEKI databases, and from other publicly available databases (Table 1).

Table 1. Data sources, non-published material, and conference proceedings used for this assessment.

Data description and source	Purpose
Sequoia ages and mortality rates (Stephenson, unpublished)	Establishing a reference for treatment effectiveness in restoring sequoia cohorts
Sequoia regeneration surveys following prescribed burns (Caprio and Keifer, unpublished)	Discussing repeated fire effects on sequoia regeneration
Sequoia regeneration surveys following wildfires and retention harvesting (Meyer and Safford, unpublished)	Evaluating regeneration and recruitment following high severity disturbances
Ash substrate effects on growth of sequoia at Whitaker's Forest (York, unpublished)	Potential role of fire in the recruitment of giant sequoia
Ash substrate effects on growth and survival of sequoia at Blodgett Forest (York, unpublished)	Potential role of fire in the recruitment of giant sequoia
Sequoia Tree Inventory Database	Reference conditions for grove structure within SEKI
Giant Sequoia National Monument (GSNM) monitoring and inventory database	Reference conditions for grove structure within GSNM
California Dept. of Forestry and Fire Protection inventory and monitoring database for Mt. Home Demonstration Forest	Reference conditions for grove structure within the Mt. Home grove
University of California at Berkeley, Center for Forestry monitoring database (York, unpublished)	Reference conditions and trends for grove structure at Whitaker's Forest (Redwood Mountain grove)
Giant Forest restoration study (Demetry 1998)	Restoration treatment effects in severely compacted areas
GSNM research program (Hannah, unpublished)	Discussion of giant sequoia regeneration
Long Term Soil Productivity Study (Busse and Powers, unpublished)	Decadal effect of compaction on planted giant sequoia growth
University of California at Berkeley, Integrated Biology (Dawson and Ambrose, unpublished)	Water source for large giant sequoia
University of California at Berkeley, Center for Forestry (Fahey and York, unpublished)	Interactions between mycorrhizae and restoration treatments
SEKI grove boundaries	Spatial (inter-grove) analyses
GSNM grove boundaries	Spatial (inter-grove) analyses
Fire Return Interval Departure (NRCA data)	Condition assessment
Ozone concentration (NRCA data)	Condition assessment
PRISM temperature and precipitation (NRCA data)	Condition assessment
Climatic water deficit (NRCA data)	Condition assessment
Areas of groves with precipitation dominated by snow (NRCA data)	Condition assessment

Reference conditions

For a thorough analysis of reference conditions that are informed by past patterns of structure and processes, and their potential use for restoration treatments within giant sequoia groves, readers are referred to Stephenson (1999). While we recognize the importance of using past conditions to assist with defining management goals, here we focus mainly on recent studies and databases to assist with informing how giant sequoia might be made more resilient in the face of novel stressors. These novel stressors will continuously lead to unprecedented conditions, a reality that makes it insufficient to rely upon past conditions alone as guides for treatments since the ecological and social stage upon which giant sequoia interacts with its environment is fundamentally new. Ideally, systematic monitoring would continuously enable recent trends assessments for evaluating the success of recent management decisions. Unfortunately, it is difficult to establish modern baseline conditions from current data, as there has been no systematic monitoring program for giant sequoia within SEKI or GSNM. Given these limitations, we focus on the data that do exist for making inferences. Fortunately, there have been numerous recent studies that, when integrated together, provide adequate information for developing suites of viable treatment options. Published studies are referred to throughout this assessment, but we made a deliberate effort to compile and interpret data from non-published sources (Table 1). We place emphasis on recent studies and using the data that are available to establish baselines for assessing future trends. This in turn implies a need for monitoring future trends in giant sequoia in what will be highly uncertain environments. Future assessments may then focus more on how giant sequoia interacts with treatment options and the novel stressors that have occurred. In this light, we provide analyses below from recent studies that have evaluated giant sequoia response to the cornerstone process that has heavily influenced its evolution- fire. Future fires within groves, whether they are prescribed or wildfires, will occur as an outcome of the physical processes that make up dry western forests. These fires will continue to play a key role in giant sequoia's future. Despite many uncertainties, this we at least know with great certainty.

Predicted stationary age distribution for giant sequoia

Since human lifespans are far too short to observe cohorts of most tree species from birth to death, the only reasonable way to understand population dynamics is to use quantitative demographic models to determine the relative balance between birth rates and death rates compounded over time. This reliance on long-term demographies instead of individual observations is especially important for giant sequoia, which can persist for millennia. Scattered observations of patches of regenerating giant sequoia, for example, reflect successful giant sequoia on a very small spatial and temporal scale. But groves or indeed the entire population may still be declining despite some perceived "successes." The conclusion of a declining population and not the simple observation of giant sequoia regeneration occurrence would of course be much more relevant for making management decisions. Sustainable age distributions may take several forms- from unimodal (i.e. "bell-shaped") to exponential curves. The shape of a given curve depends upon the rates of birth and death on large enough time and spatial scales that are relevant for an inter-breeding population and its given disturbance regime (e.g. "stand-replacing" fires may create sustainable unimodal age distributions in boreal forests, while mixed-severity fires may create multi-modal or exponential distributions that are also sustainable).

Here we present the results of the first demographic model for giant sequoia. A predicted age distribution was derived from empirical data to describe what a long-term stationary population of giant sequoia looks like[1]. This is a relevant reference for management decisions influencing giant sequoia, considering the emphasis of recent studies and treatments on encouraging giant sequoia regeneration as a means for addressing regeneration failures associated with fire suppression over the past century. Additionally, it provides a reference, not from reconstructed past conditions, but from modern era data and calculations that rely on basic demographic information about giant sequoia. While there remains uncertainty in precisely how dense new giant sequoia cohorts need to be in order to sustain local populations, the shape of the expected distribution can be used as an important reference for evaluating whether treatment options (i.e. burning frequently, infrequently, or not at all) move the age structure closer or farther from an expected stationary distribution.

[1] Data provided by Stephenson, unpublished

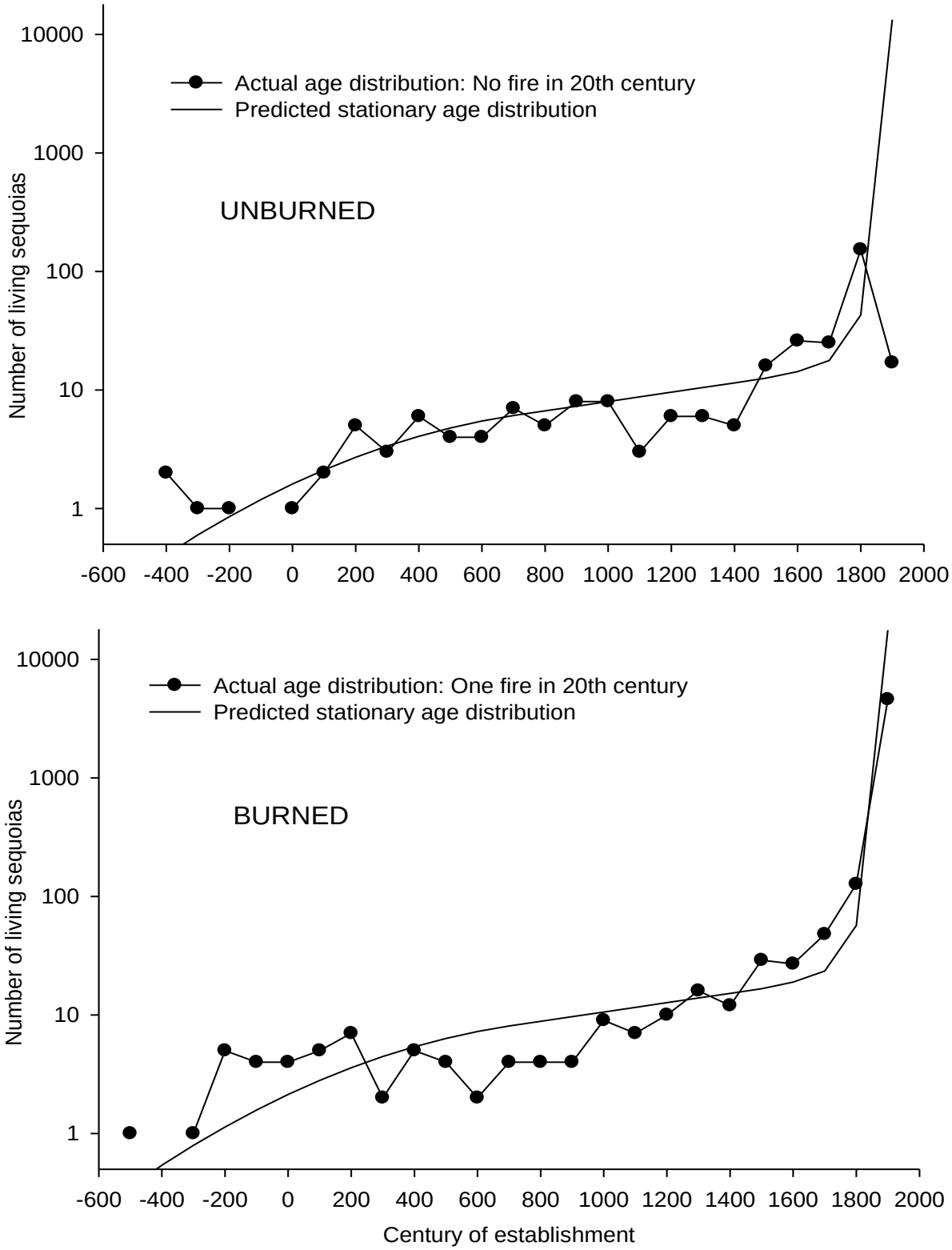


Figure 1. Predicted and actual age distributions from two locations not experiencing fire during the 20th century (top graph; Atwell grove and the periphery of the Giant Forest grove), and from two locations that experienced prescribed fires in the 1970's (Mariposa Grove) and 1982 (central Giant Forest Grove). The Y-axis is on a log-scale. From Stephenson, unpublished.

Predicted age distributions for a stationary giant sequoia population were derived from a demography study that tracked seedlings for 20 years (Harvey and Shellhammer 1991), and from a 22-year demography study of older trees (Lambert and Stohlgren 1988). Actual age distributions were obtained from two plots that were unburned within the last century (Figure 1, top) and two plots that were burned once in the last century (Figure 1, bottom). The methods of aging and calculation of the stationary age distribution are provided in Subappendix 1. Changes in survival rate as giant sequoia trees age explain the shape of the predicted distribution. Once established (i.e. after surviving the first year), seedling survival is relatively high over the first two decades (90% per year), but this survival rate is still considerably lower than the survival rate of trees between 500 to 1000 years old (99.96% per year). This change in survival explains the dramatic change in the stationary age distribution curve between trees that are 100 to 500 years old (the J-shaped section on the far right side of the curve). The shallow decline on the left hand side of the curve is explained by a very slow decrease in survivorship as tree ages approach a millennium and beyond.

The actual age distributions found in two burned areas and two non-burned areas (see methods in Subappendix 1 for more detail) appear to follow the predicted stationary distribution fairly well for older giant sequoia. Century-scale deviations from expected occur both above and below the curve with similar degrees of magnitude. As has been pointed out elsewhere (Stephenson 1994), this suggests that the giant sequoia population was either at an equilibrium or was expanding prior to Euroamerican settlement[1]. The importance of the comparison between the predicted distribution and the actual distribution highlighted here occurs when evaluating the relative departure from expected in the youngest age class (<100 years old). The burned areas resulted in the establishment of younger cohorts that move the overall structure closer toward what is expected (Figure 1, bottom). While the unburned areas do have trees in the youngest age class, the relative decline in the number of young trees moves the distribution in the opposite direction that is expected from a sustainable distribution. The smaller trees in the unburned areas also tended to have very tightly compacted rings from long periods of suppressed growth, which likely led to a higher rate of missing rings during aging. Many of the suppressed trees aged as germinating in the 1900's in reality likely germinated in the 1800's. This measurement error makes the departure from the expected distribution in unburned areas even more dramatic than shown in Figure 1. We interpret the negative departure from expected in the top graph of Figure 1 as an "at least" scenario.

Regeneration following prescribed fires is highly variable because of variation in both burn severity (Mutch and Swetnam 1995) and soil moisture conditions following burns (Harvey et al. 1980). The two burns used in this study do not nearly represent the wide range of possible prescribed fire and regeneration conditions that exist. As more prescribed fires are conducted and greater ranges in both burn severity and repetition are observed, the predicted age distribution in Figure 1 can provide a useful reference for judging the success of burns in initiating cohorts of giant sequoia that have meaningful densities for encouraging long-term persistence. Permanent

[1] The data suggesting an equilibrium or expanding population come from four groves and do not cover the entire population. It is possible that some other groves may have been contracting, but there are no data to suggest this. See Stephenson 1994 for details.

and long-term monitoring of recruitment and mortality can also hone the shape of the predicted age distribution.

Repeated prescribed fire effects on giant sequoia regeneration

True to its pioneer life history strategy, giant sequoia is capable of colonizing canopy openings created by locally severe[1] fires with very high densities of seedlings (as long as parent trees are nearby). As demonstrated above, high seedling densities following disturbances are essential to its long-term persistence even considering sequoia mortality rates that are low compared to its associated tree species. While many of the details of the fire-giant sequoia relationship have been brought to light through management experience and studies, other details remain uncertain. Of foremost importance is how giant sequoia will regenerate and recruit as prescribed burns are repeated over time. Whether the purpose of prescribed fire is to maintain low surface fuel loads or to restore past fire return intervals, the result is that numerous fires would be expected to occur at any given location before giant sequoias recruit into mature canopy trees. SEKI is well-positioned to provide information about repeated fire effects by continuing its fire program and by closely monitoring results with permanent plots. Two recent studies described below demonstrate the variability in giant sequoia response to repeated fires, and also demonstrate the need for the continuation of burning and monitoring. The studies are from T. Caprio and M. Keifer (unpublished) and Webster and Halpern (2010).

Webster and Halpern monitored giant sequoia occurrence following first and second entry burns for one to two decades. For all species combined, burns reduced tree density by greater than 58 % while having relatively little effect on basal area (see their Figure 1A and 1C). Such fire effects would seem beneficial and perhaps ideal for reducing surface fuels, decreasing small tree density, and increasing average tree size. Although they found a tendency for giant sequoia to be more frequent following burns (especially 5 to 10 years following 2nd entry burns- see Appendix in their paper), giant sequoia frequency was still very low when considering the expected age distribution from Figure 1 above. Frequency was not high enough to detect giant sequoia as a "fire indicator species," even though giant sequoia's tendency to occur following local high severity fire is well understood. It certainly is a fire indicator species by many accounts, but only when the fire is hot enough and when establishment conditions are adequate (and when sampling intensity is high enough to detect it statistically).

Caprio and Keifer's study was very similar in that they also tracked vegetation composition following 1st and 2nd entry fires. Some of the same plots were used for both studies, but the response variables (frequency versus density) were different (the Caprio and Keifer study also has the advantage of tracking the same set of individual plots over time for trees > 1.37m tall). Fire behavior of the initial burn was very similar, reducing tree density of all species by 60% while basal area remained constant and average tree size increased. The giant sequoia response, however, was more pronounced in this case (Figure 2). Giant sequoia density in the 0 to 10 cm dbh class increased following the 1st burn, and then increased again following the second burn.

---

[1] Throughout this chapter, we call fires that create discrete canopy gaps but leave most of the surrounding canopy intact as fires with "local" high severity. Fires that consume most of the canopy on larger scales (i.e. the "stand scale" or larger) are referred to as fires with "extensive" high severity.

Further, recruitment of giant sequoia into larger tree sizes occurred following the second burn. Whether densities are high enough to facilitate long-term recruitment and then persistence, however, is uncertain given the age structure information provided above (Figure 1). While average seedling densities following first burns were indeed very high (>30,000 seedlings per hectare; Fig. 2 inset), mortality in subsequent years was also high (although some of these seedlings recruited out of the size class and into the 0-10 cm size class). Spatial variability in seedling density is also expected to be very high and important for tracking long-term recruitment patterns. These two studies demonstrate that although general frequency of giant sequoia might be low (Webster and Halpern 2010), seedling density in areas where establishment does occur may indeed be very high. These "sweet spots" of giant sequoia regeneration should also be expected to shrink over time as edge effects limit recruitment (Demetry et al. 1995, York et al. 2003). Continuing burning in an experimental fashion and following up with monitoring can track recruitment patterns and distinguish the important relationship between repeated prescribed fires and giant sequoia recruitment.

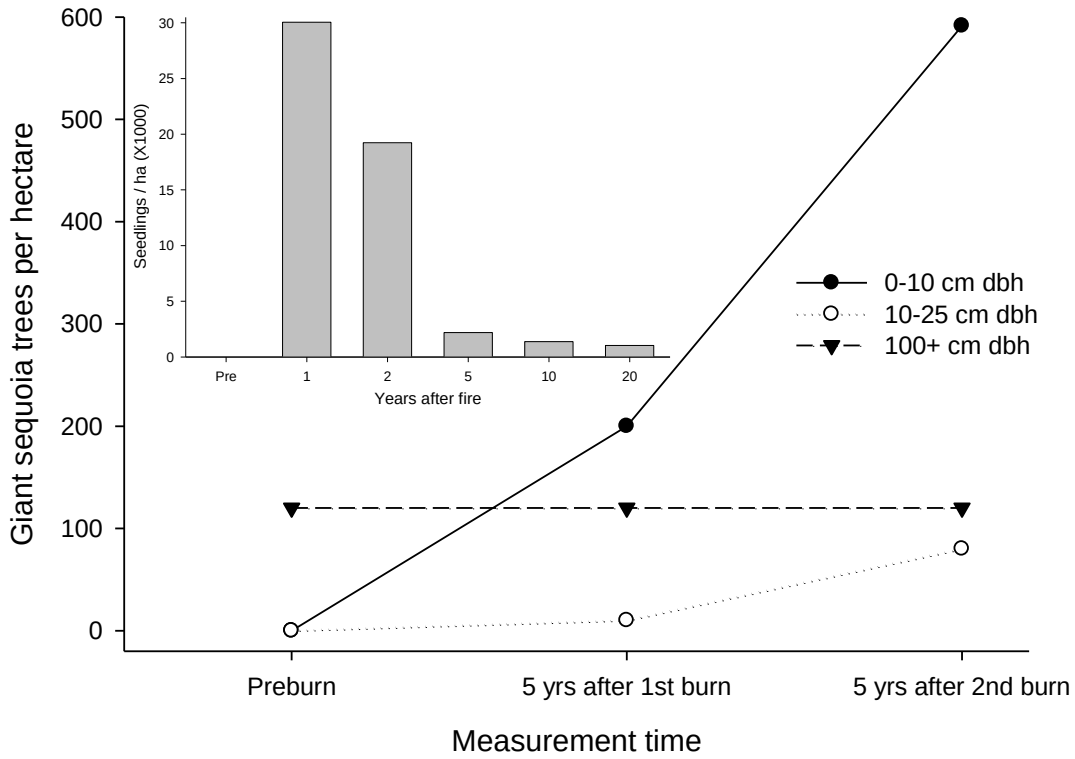


Figure 2. Change in mean giant sequoia density prior to and following repeated burns within SEKI. For trees taller than 1.35 m (line graphs), the same plots were measured repeatedly following the burns. The inset graph shows average seedling densities at different times following a single initial prescribed burn. Seedling data were compiled from several different plots that were burned at various times. Although sample size (and therefore certainty in the mean) decreases with time, there is a clear initial pulse of seedling establishment followed by a steep decline during the first 5 years following fire. From Caprio and Keifer, unpublished.

High severity disturbance effects on regeneration

Recent surveys done within Bearskin, Redwood Mountain, Black Mountain, and Case Mountain groves have assessed the response of giant sequoia regeneration to two forms of moderate to

high severity disturbance (M. Meyer and H. Safford, unpublished data). The study provides recent information on the relationship between fire severity and regeneration, but also compares the qualitatively different disturbances of fire and harvesting. The fires that occurred in this case were wildfires, while harvesting included the removal of most trees of all species except for large diameter giant sequoia followed by burning and planting of giant sequoia and other species. Harvesting occurred in the mid 1980's in Black Mountain and Bearskin groves, while moderate- and high-severity wildfires occurred in 1987 in Case Mountain and Redwood Mountain groves. A low severity wildfire also occurred in early December of 2008 in the Black Mountain grove. Although the disturbances occurred at different times and locations, they provide a wide gradient in both disturbance severity and quality for assessing giant sequoia regeneration response to disturbance.

Approximately 25 years following moderate/high severity fires and harvesting, seedling density is clearly much higher in areas where wildfire occurred compared to harvested areas (Figure 3A, gray bars from Redwood Mt. and Case Mt. versus black bars from Bearskin and Black Mt). All control areas (relatively undisturbed canopies) had zero seedlings. The seedlings in the harvested areas are from a combination of planted seedlings and germination from local tree seed dispersal which was likely enhanced by pile and broadcast burning following the harvest. In this case, seedling densities were much higher following the moderate severity fire (25-75% basal area mortality one year following fire) in Case Mountain compared to the high severity (>75% basal area mortality) fire in Redwood Mountain. The Case Mountain fire was also much more spatially patchy in terms of fire severity, with high severity patches occurring within a matrix of mixed severity fire. Several factors besides fire severity (e.g. soil moisture conditions following the fires, density of overstory surviving the fires) were responsible for the high variability, but the results demonstrate that the fire severity-seedling density relationship is not a simple linear one.

The differences in regeneration response between disturbance severity and quality are less pronounced when isolating the larger giant sequoias (>140 cm tall and < 30 cm dbh) that regenerated (Figure 3B). Presumably, these are the trees most likely to recruit into the canopy and eventually replace the parent trees. While seedling density is to a large degree a function of disturbance quality (fire versus harvest), rate of recruitment (i.e. growth) appears to be primarily a function of resource availability (Hannah unpublished, Meyer and Safford unpublished; York et al. 2003, Shellhammer and Shellhammer 2006, York et al. 2011).

Considered together, the Caprio and Keifer study and the Meyer and Safford study suggest the following:

- Mechanical disturbances, even when high in severity, do not nearly lead to the high densities of giant sequoia that are often observed following moderate and high severity fires, although dense planting could result in roughly similar magnitudes of trees likely to recruit into the canopy.
- Cohort densities following fires are extremely variable, ranging by two orders of magnitude between these two studies.
- While there is a generally positive relationship between regeneration density and fire severity at the stand scale, other factors are important as well (e.g. substrate quality, seed supply, soil moisture, and light availability) for both establishment and recruitment.

Burned substrate effects on recruitment

As demonstrated above, fires have distinct roles in seed dispersal and seedling establishment. Three recent studies (York unpublished, Shellhammer and Shellhammer 2006, York et al. 2009) further explain the potential role that fire has in enhancing the recruitment that occurs following regeneration. Considered individually, each study has limitations in its applicability for conducting prescribed or allowing wildlfire (i.e. the studies involve either planting seedlings or burning debris piles instead of natural regeneration and broadcast burns). But when considered together, they are applicable. Each study compared growth and survival of seedlings growing in ash substrates compared to bare mineral soil substrates. In the first study (York unpublished), seedlings paired in ash and soil substrates were planted beneath distinct canopy gaps ranging in size from 0.04 to 0.4 hectares in a controlled experimental fashion. The biomass of seedlings planted in ash substrates was more than double the biomass of adjacent seedlings planted on bare soil after just 2 years of growth (Figure 4). The stark difference in biomass between ash and soil substrate seedlings remains at least as large after 5 years (York, personal observation).

In a similar study, seedlings were planted within, on the edge of, and beyond ash substrates and then tracked for 10 years (York et al. 2009). The seedlings were planted beneath a sparse overstory of mature conifer trees (59% light availability). A positive ash substrate influence on both height and diameter growth was detectable after just one year. The difference between the faster growing ash substrate seedlings and those planted on the edge or beyond ash substrates then increased over the next 10 years (Figure 5). There was no difference between seedlings planted on the edge of the ash substrate and those planted on the bare soil after 4 years and beyond.

Finally, Shellhammer and Shellhammer (2006) tracked seedlings established in burned and non-burned substrates for 40 years and found survival to be considerably higher for seedlings that established in burned areas. Although the comparison is likely confounded by the fact that ash substrate seedlings were in higher light environments than soil substrate seedlings, the difference in 40 year survival was large enough (almost 7 times greater) to at least suggest a positive substrate effect on survival, especially considering the growth results of the other two studies, which did control for differences in light availability between substrate treatments.

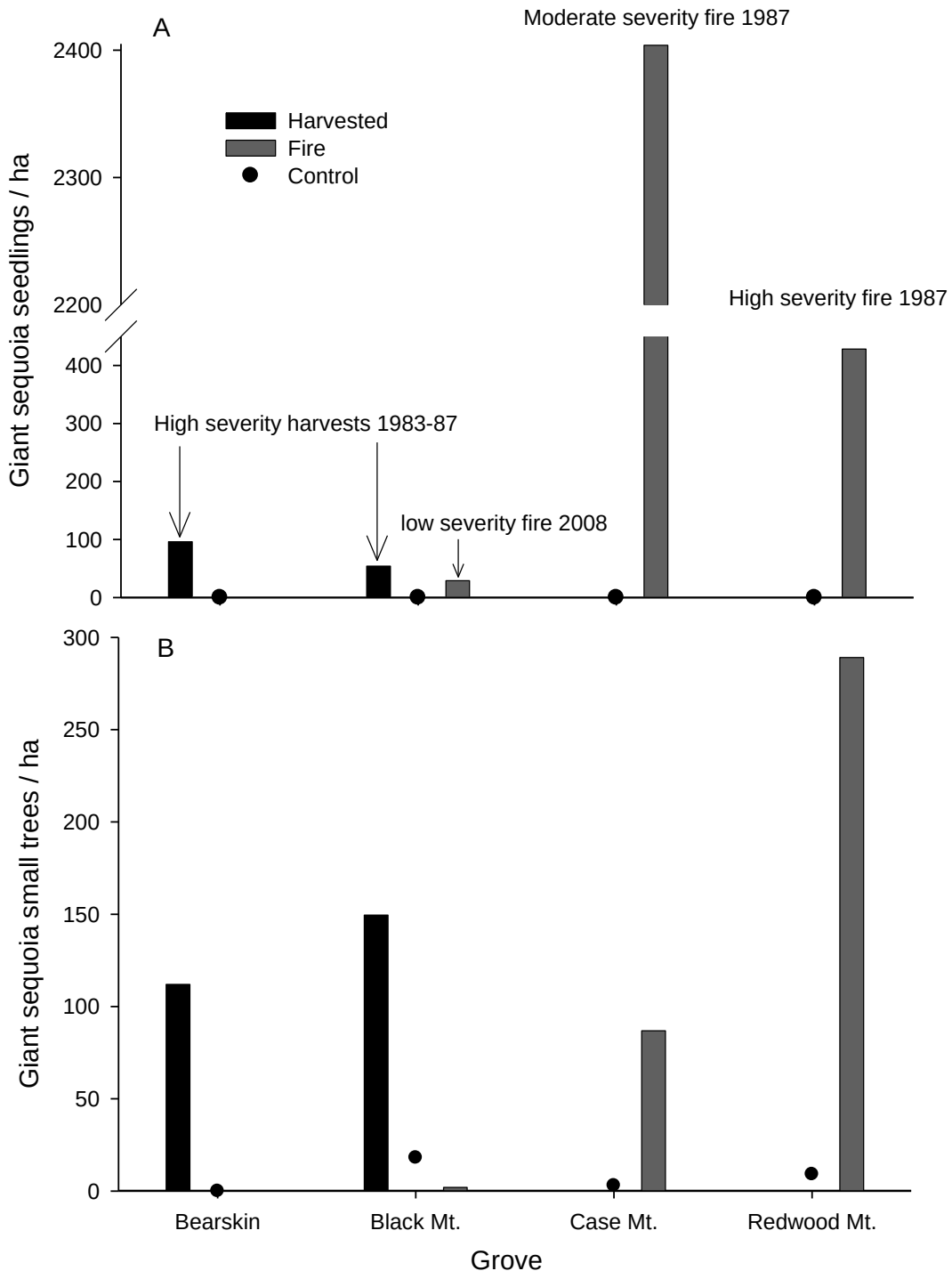


Figure 3. Density of giant sequoia following disturbances of different quality and severity in the Bearskin, Black Mt., Case Mt., and Redwood Mt. groves. Fires were wildfires. The low severity fire in Black Mt. occurred in early December. The harvests were followed by either pile or broadcast burns. Giant sequoia were planted in Bearskin Grove at roughly 394 seedlings/ha and in Black Mt. at roughly 37 seedlings/ha. A. Density of seedlings (<50cm tall). B. Density of small trees (> 140cm tall and <30cm dbh). Saplings (50-140cm tall) were also measured but are not reported here.

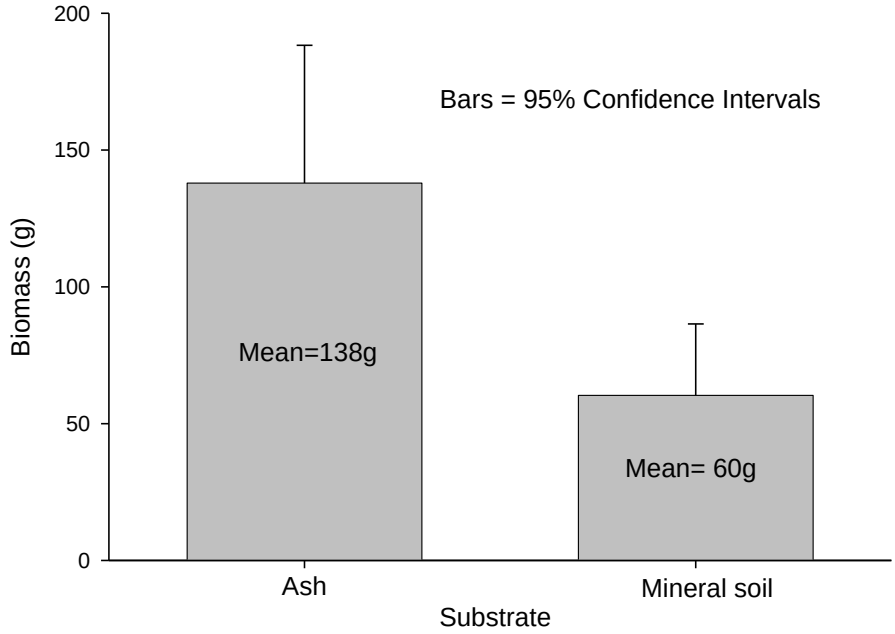


Figure 4. Average biomass of seedlings two years after planting in ash and bare soil substrates at Whitaker's Forest (Redwood Mountain Grove). 31 pairs of seedlings were planted adjacent to each other in either ash or bare soil within gaps. All within-gap locations (south edge, center, and north edge) were sampled. From York, unpublished.

When considered together, these studies suggest fire's role as an enhancer of giant sequoia recruitment. York et al. (2009) suggested an increase in available nitrogen as a cause for the increased growth in ash substrates (differences in competing vegetation were controlled for in the analysis). If this is the case, any increase in growth from ash substrates created by prescribed burns may diminish with successive prescribed burns, as the amount of biomass consumed (and nitrogen made available) per burn declines and because of cumulative volatilization losses related to fires. Where fires have not occurred for extended periods, there may even be exceptionally high buildups (compared to past periods with frequent fires) of nitrogen in biomass, suggesting a possible decline in nutrient-related growth increases following repeated fires. Fire-induced nitrogen volatilization could be at least partially compensated for following fires by rapid establishment of nitrogen fixing species (primarily *Ceanothus spp.*), but long-term nutrient fluxes and their interaction with giant sequoia in the context of repeated fires is uncertain. Other possible mechanisms for how fires can increase seedling growth include fire-induced chemical and physical changes in the soil (Certini 2005) and possibly reductions in soil pathogens that would otherwise kill giant sequoia seedlings (Stephenson 1996).

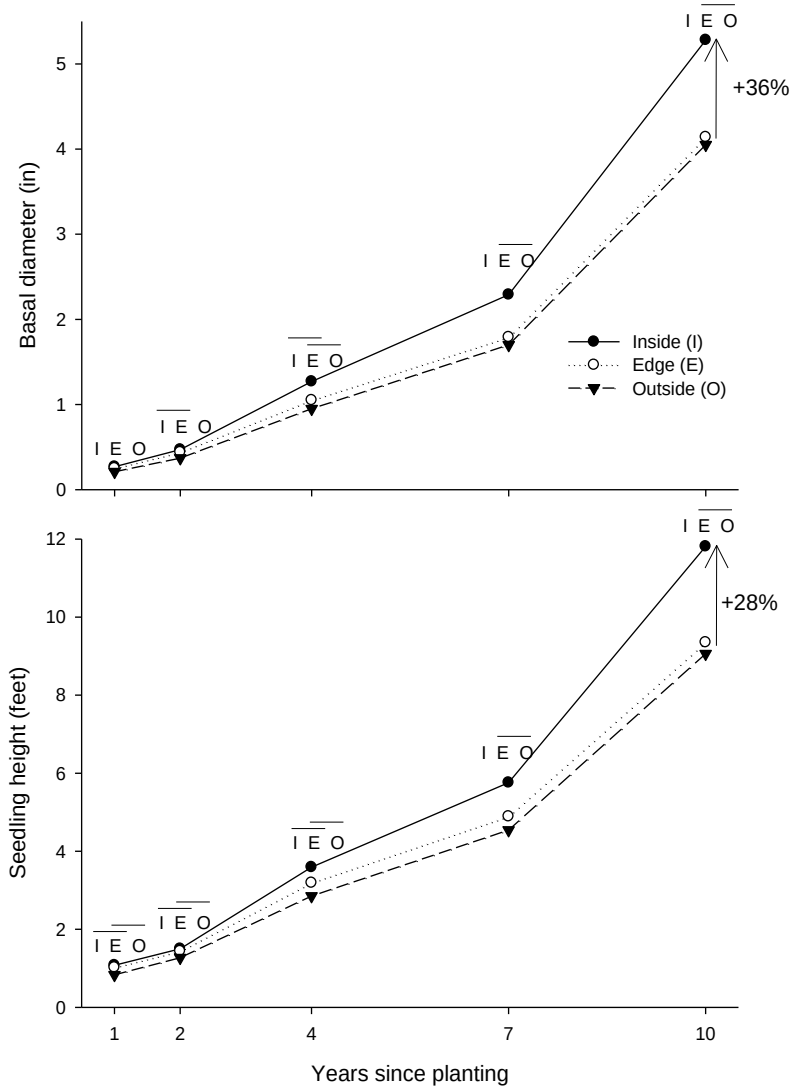


Figure 5. Giant sequoia growth trends of seedlings planted inside, on the edge of, and outside of ash substrates following the burning of debris piles in a Sierra Nevada mixed conifer forest. Horizontal lines connect treatment means that were not significantly different. Effect magnitude (%) is given for the 10th year after planting. From York et al. 2009.

Spatial and temporal analyses

The general facilitative role of fire in maintaining giant sequoia has long been understood. The recent studies described above confirm and expand the understanding of many of the details of the mechanism by which fire sustains native groves. They also document some of the patterns that have recently been observed following a range of fire severity and frequency. Given the importance of fire's past and future influence on the condition of giant sequoia, it follows that we focus our analysis on fire as the primary factor for assessing the condition of groves. Other data that we analyze here include measures of some of the other influences known to either directly influence the condition of giant sequoia or factors that are strong interactions with fire. These include grove elevation relative to snow-dominated zones, ozone concentration within groves, precipitation amount, minimum/maximum temperature, and climatic water deficit. We consider these non-fire factors to be important, but not suitable at this point as spatially explicit metrics for a condition assessment, given the lack of measured impact of these factors on giant sequoia. The objectives of this analysis are to 1) define the grove boundaries to create a single spatial later across both NPS and GSNM ownerships; 2) summarize measures of the factors listed above for each grove; 3) summarize the size structure of groves with the most recently available data from 4 of the agencies that manage groves; and 4) discuss the monitoring approaches so far taken by these 4 agencies.

Grove locations

Grove boundaries were merged from SEKI and GSNM GIS databases into a single layer (Map 1, Subappendix 2). The databases identified 70 different groves (some of these individual groves are often grouped into one grove when discussing biogeography of giant sequoia). 34 of these are managed all or partially by GSNM, and 36 are managed all or partially by NPS (Table 1 in Subappendix 2). Because there are stark differences from both ecological and management perspectives between large and small groves (some of which are formed by only a few trees), we separated groves into size categories for analysis. Numerically, the population of groves considered here is dominated by small groves, with 39 of the 70 groves being less than 44 hectares. In area, however, these smallest groves make up approximately only 4% of total grove area. 44 hectares appears to be a logical cutoff for distinguishing between "small" and "medium" groves in the distribution of grove sizes, as cumulative grove area increases substantially above 44 hectares. A second inflection point in the cumulative distribution occurs at 176 hectares, thus distinguishing another threshold (albeit an admittedly subjective one) in size between "medium" and "large" groves. 14 medium-sized groves make up approximately 12% of all grove area. The largest 17 groves make up the majority of grove area (84%) within SEKI and GSNM.

Fire Return Interval Departure – the primary metric of grove condition

Fire Return Interval Departure (FRID) is the primary metric we used in this case to assess grove condition. The FRID spatial layer codes the landscape by 30 x 30 m rasters according to the time since last fire occurrence (Caprio et al. 1997). Time since last fire is then expressed in terms of the number of average maximum fire-free intervals that have been surpassed, based on reconstructions of fire frequency prior to Euroamerican settlement. Average maximum intervals are determined using a randomization process of reconstructed fire intervals. This reduces the influence of a single long interval that may have been an outlier. Maximum values (as opposed to averages) for fire return intervals are used in this case to provide a conservative estimate of fire interval departure. FRID data as of the end of 2009 were available for both SEKI and

GSNM. We use the conventional coding of FRID, which can be somewhat confusing since low numerals indicate larger departures. When reading the tables and maps describing FRID in this assessment, it is important to keep this relationship in mind. FRID values include the following:

1 = Extreme (5 or more maximum return intervals surpassed)

2 = High (between 2 and 5 maximum intervals surpassed)

3 = Moderate (between 0 and 2 maximum intervals surpassed)

4 = Low (the last fire occurred within the maximum interval time period)

To generate FRID values for each grove, the fraction of each grove with 1, 2, 3, or 4 FRID values were first determined and used as weighting factors to derive the whole-grove FRID value. FRID values for groves were therefore between 1 (100% of grove covered by extreme FRID areas) and 4 (100% of grove covered by low FRID areas). Lower numerical values (more time since last fire) are considered to be an indication of poorer condition to the extent that the facilitating role of fire in regenerating and recruiting giant sequoia has not occurred for a longer period of time. Greater numerical values (less time since last fire) are considered to be an indication of improved condition. An important assumption in this case, however, is that the fires that did occur were of appropriate local severity and were then followed by local environmental conditions that were adequate for regeneration.

FRID values varied by grove between 1.0 and 3.9 (Map 2 and Table 2 in Subappendix 2). No grove was entirely within the low category, but many were entirely within the extreme category. The average for all groves was 1.5 (between high and extreme departure), and there was no discernable differences in FRID average or variability between grove size categories. For large groves, three of the 17 groves had values greater than 3.0 (moderate or low departure; Giant Forest, East Fork, Atwell). Castle Creek, Suwanee, Sequoia Creek, and Redwood Creek all had values greater than 3.0 for medium and small sized groves. All other groves had values of 2.9 or less. Again, the lower the numerical value, the poorer the condition because of the absence of fire's facilitative interaction with giant sequoia (Figures 1-5).

Snow-dominated precipitation

The objective of this analysis was to understand the proportion of areas within groves that are influenced by a snow-dominated precipitation environment (i.e. snow precipitation > rain precipitation). We do not use it as a metric for assessment, but instead document the conditions between groves as a reference that may be important in the future. 1600 m was used as the threshold between snow- and rain-dominated precipitation (Appendix 7). We note that 1600 m is not a universal threshold that applies in all groves. Groves on south versus north facing slopes, for example, are likely to have different timings of snow melt, which is at least as important as the amount of precipitation falling as snow with respect to giant sequoia regeneration. Another thorough analysis of snow-dominated precipitation within SEKI using data between ca. 1969 and 1984 concluded 2000 m to be the threshold (Stephenson 1988). An elevation of 2000 m may indeed be a more appropriate threshold for finer-scale analyses within groves. Here we use 1600 m to be consistent with the most recent analysis of snow-dominated precipitation (Appendix 7). The grove area layer described above was split into two categories using a 1600 m isoline in the GIS by deriving 100-m contour lines from a 10-m digital elevation model, acquired from the USGS Seamless Data Distribution site. Each portion of the grove was assigned an attribute value

of either “above” or “below” snowline. Groves were summarized by the area (ha) in each snowline class. Most groves have relatively little area beneath 1600 m (Map 3; Table 3 in Subappendix 2). Some of the smaller groves are entirely lower than 1600 m (Big Springs, Clough Cave, Putnam-Francis, Squirrel Creek, West Redwood Mountain, and Wishon). Of medium and large sized groves, only three (Belknap, Deer Creek, and Silver Creek) have more than 10% of grove area below 1600 m. Only 3% of total grove area is below 1600 m. The lower elevations of groves tend to be generally bounded by the snow-dominated elevation (Map 3 in Subappendix 2). A feasible outcome of climate change is a shifting of this elevation (most likely upward in elevation), which could affect giant sequoia regeneration disproportionately at the lower elevation boundaries of groves.

Ozone concentration

Among all groves, average monthly ozone concentration over the three year span from 2006 to 2008 ranged from 41 to 58 ppb (Map 4; Table 4 in Subappendix 2). 8-hour highs in concentration, estimated by multiplying monthly concentration by a factor of 1.75 (Subappendix 2) are between 71.7 to 101.5 ppb. These highs are far below the concentrations that have been observed to cause damage to giant sequoia seedlings. No trend between 2006 and 2008 within groves is apparent, although average ozone concentrations did differ between years as indicated by non-overlapping confidence intervals. 2008 had the highest average ozone concentration (95% confidence interval = 54.5-57.3), followed by 2006 (51.5-53.2) and 2007 (49.9-51.2).

Precipitation and maximum/minimum average temperature

Climate layers were derived from PRISM data. 800-m grids were clipped to the study areas and overlain with grove boundaries. The area-weighted average value of each climate metric for each grove was then calculated by weighting each variable value by the area within each grove with that value. 30-year average precipitation (1971-2000) ranged among groves from 69 to 115 cm (Map 5**,** Table 5 in Subappendix 2), but in general variation between groves was low (coefficient of variation among all groves is 7.3%). Among large groves, the Freeman grove was somewhat of an outlier with low average precipitation (69 cm). The Cunningham grove also had low precipitation (69 cm) among small groves. Variability in minimum and maximum temperatures was also low among groves (coefficient of variation = 60% for minimum and 11% for maximum temperature), and the range of minimum and maximum temperatures among groves each spanned 9 degrees Celsius. Some of the smaller groves (particularly Clough Cave, Putnam-Francis, and Wishon) have relatively high minimum and maximum temperatures.

Climatic water deficit

Climatic water deficit data (270-m resolution grids) averaged over the 30-year period from 1971 to 2000 (Appendix 1) were overlain with grove boundary data to derive deficit differences between groves (Map 6**,** Table 6 in Subappendix 2). Deficits ranged widely from 239 to 646 mm (higher number indicates more potential drought stress). No discernable differences were apparent between grove size categories. Among large groves, Big Stump (44% greater than average) and Redwood Mountain (+37%) had notably higher deficits. Among medium sized groves, Grant (+49%), Packsaddle (36%), and Long Meadow (32%) had relatively higher deficits. Small groves with deficits 30% greater than average included Wishon (44%), Big Springs (36%), Abbot (36%), Pine Ridge (35%), Deer Creek (34%), and Cunningham (33%). As will be discussed later, the water deficit results have limited use without corresponding information on giant sequoia physiology and soil properties within groves.

Size structures within groves

Change in forest structure is often described by collecting and assessing repeated measurements of tree diameter at breast height (e.g. Youngblood 2010). Although other measurements of tree size besides diameter at breast height may also be useful, especially when assessing whole tree volume in large trees (Sillett et al. 2010), diameter at breast height (dbh) remains an economical and widely-used method for quantitatively and visually representing forest structure. As demonstrated above, tree age is also helpful for assessing population change. Tree size is, however, strongly related to crown position which in turn is related to survival probability. This is especially relevant for giant sequoia trees, which have highly variable age-size relationships and are capable of releasing from competition as both young (York et al. 2006) and old trees (York et al. 2010).

As part of our spatial analysis of giant sequoia, we compiled most of the available dbh data that currently exists from within SEKI and from the agencies that manage surrounding groves in the southern Sierra Nevada. The analysis is spatially explicit to the extent that the locations of grove boundaries are approximately known. Databases that came from field surveys performed specifically for inventorying or monitoring giant sequoia structure were available from four agencies: SEKI, Giant Sequoia National Monument (GSNM), California Department of Forestry and Fire Protection (CDF), and UC Berkeley Center for Forestry (UCB). The latter two agencies manage a relatively small proportion of the groves within the Southern Sierra Nevada, but they are useful as examples of agencies that have begun long-term monitoring of giant sequoia structure. A brief description of each agency's inventory or monitoring method is given in Subappendix 2. First we present size structure differences between the four agencies- a large scale not defined by any biological reasoning, but useful as a way to compare survey methods and outcomes. To the extent possible given the data, we assess the structure of individual groves within SEKI and GSNM. Using data from UCB, we provide an example of measuring change in giant sequoia size structure. Finally, we demonstrate the utility of long-term monitoring.

Size structure by agency

For all size distributions, the bin width used is 15 cm dbh (i.e. 0 to 15 cm; 15-30 cm; etc.). Only giant sequoia trees are considered. Seedlings less than breast height were included in the 0 to 15 cm size class. For the groves that were sampled (those managed by GSNM, CDF, and UCB), each tree was multiplied by a weighting factor to convert to average trees per hectare. The weighting factor was calculated by dividing the tree's expansion factor (corresponding to plot size) by the number of plots, giving average density. For the SEKI groves, which were not sampled but instead had a 100% census, the weighting factor was simply the inverse of total grove area (i.e. 1 / 3318 hectares). The SEKI data are also unique in that measurement precision for larger trees was greater than the 15-cm bin widths used, so densities are given for every other size. To save graph space and to emphasize the structure of the smaller size classes, all trees greater than 285 cm breast height were combined in the last bin (also, precision of large tree diameter measurements declines considerably, diluting between-bin precision).

The size structures (Figure 6) show the general differences in grove structure between the agencies, as indicated by the databases. The structures cannot be used to quantitatively compare actual differences between agencies for several reasons. First, sampling intensity varies greatly from 100% in SEKI to less than 1% in GSNM. Second, the survey times vary greatly, from circa 1970 in SEKI to the 2009 survey at UCB's Whitaker's Forest. Third, sample areas vary greatly

from 129 ha at Whitaker's Forest to over 3000 hectares in SEKI. Finally, the density estimate depends to a large degree on how the grove boundaries are selected. While both SEKI and GSNM used the giant sequoia treelines of groves to define their sampling area, whether or not to lump several patches of giant sequoia together or to keep them separate is subjective. For example, several "complexes" within GSNM could have alternatively been split into separate groves (no standard exists for when to "clump versus split"). Splitting the complexes into groves would have increased average density since it would have excluded some habitat within the complex boundaries where giant sequoia do not exist. Despite the inability to measure differences in stem density between agencies, some general observations of size structures can be made.

The higher density of trees with diameters greater than 285 cm within SEKI compared to other agencies could be a reflection of past logging history. Most of the groves within SEKI did not experience large diameter giant sequoia logging, which did occur within some areas of the other agencies (Stephenson 1996). Whatever the reason, the higher density of large trees within SEKI compared to the other agencies is most likely a reality, but absolute differences (especially between SEKI and GSNM) are very uncertain because of differences in sampling intensity and grove boundary delineation. Besides a generally lower density across all size classes, the general structure of the compiled GSNM groves circa 2006 appear similar to SEKI groves circa 1970 (again, the difference in absolute density could be an artifact of differences in grove boundary delineation and sampling intensity). Most notable is the similarity in the high ratio of small to big trees. While the relatively high density of 0 – 15 cm trees would suggest a more sustainable structure, it is uncertain how dense smaller size classes must be in terms of replacing the larger trees. Assuming a generally positive, albeit highly variable, relationship between size and age, it is highly plausible that these relative densities of smaller trees are not nearly enough to replace larger trees given the compounding of mortality that occurs over the long lifespan of giant sequoia (see discussion in Subappendix 1**).**

The structures of Mt. Home in 2005 and Whitaker's Forest in 1999 do appear to be fundamentally different than the compiled grove structures of SEKI and GSNM. The densities of 0-15 cm diameter trees relative to larger trees are far lower. This comparison between agencies is again a qualitative one, but the Mt. Home and 1999 Whitaker's Forest structures do serve as examples of possibly unsustainable structures that may develop following periods of little regeneration. In the case of Whitaker's Forest, coring has determined that the 0-15 cm trees in 1999 belonged to the same cohort as the trees in the middle size classes, thus implying a lack of both small *and* young trees. A mechanical restoration treatment, followed by planting, was done between the 1999 and 2009 surveys at Whitaker's Forest. The treatment is what accounts for the reshaping of the size structure by 2009 to a structure that is similar to SEKI and GSNM, at least in the smaller size classes. The large number of trees in the 30-105 cm size classes at Whitaker's Forest is a result of a dense cohort that established following logging of large giant sequoia and pine species near the end of the 1800's. Despite some restoration treatments being done at Mt. Home (Stephens et al. 1999), there still appears to be a deficit of smaller sized trees. One of the possible reasons for the lack of regeneration following the Mt. Home treatments may be a "gap-capturing" process, where a high density of very large trees (higher than is present at Whitaker's) surrounding gaps occupied underground resources following gap creation, thus precluding giant sequoia establishment (York unpublished, York et al. 2010).

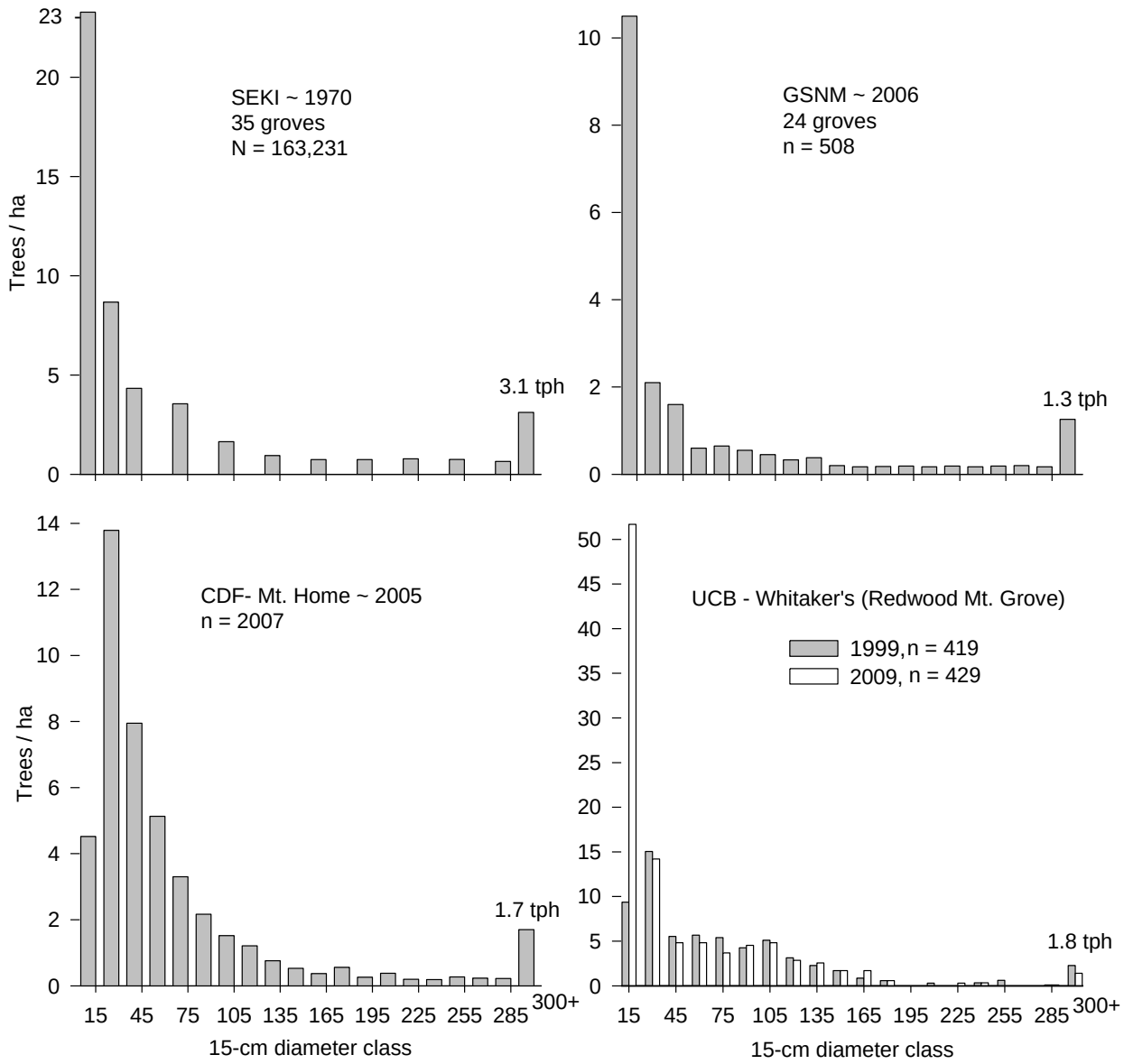


Figure 6. Size structure of giant sequoia by agency in the southern Sierra Nevada. The Y-axis is different between each graph because the size structures are meant to show only general differences between agencies. Also note that the gaps between larger size classes in the SEKI data are because diameters were measured to resolutions greater than the 15-cm bin widths.

SEKI and GSNM represent two opposing extremes of sampling intensity. In groves where giant sequoia is relatively rare, the GSNM surveys measured very few trees, which precluded describing the structure with precision (see Subappendix 2 and discussion below). The 100% inventory in SEKI, on the other hand, likely represents an unrealistic amount of effort with respect to monitoring. If individual trees from the Sequoia Tree Inventory (STI) within SEKI can be relocated, it represents a powerful opportunity to assess trends of large trees and to more accurately quantify mortality rates. Some individual trees from the STI have been resurveyed (Caprio, unpublished), and the potential for resurveying is recognized by NPS staff. The utility of long-term monitoring of large giant sequoia is exemplified by the surveys that have been done

at Whitaker's Forest, where trees greater than approximately 244 cm diameter have been monitored since 1915. Although there is some uncertainty in the accuracy of tree counts from individual years (especially those done in the 1980's), the downward trend in large trees is clearly evident (Figure 7). Note that the observed 0.18 % mortality rate per year at Whitaker's Forest is considerably higher than the 0.04% rate documented for large trees from the age structure analysis above (Figure 1).

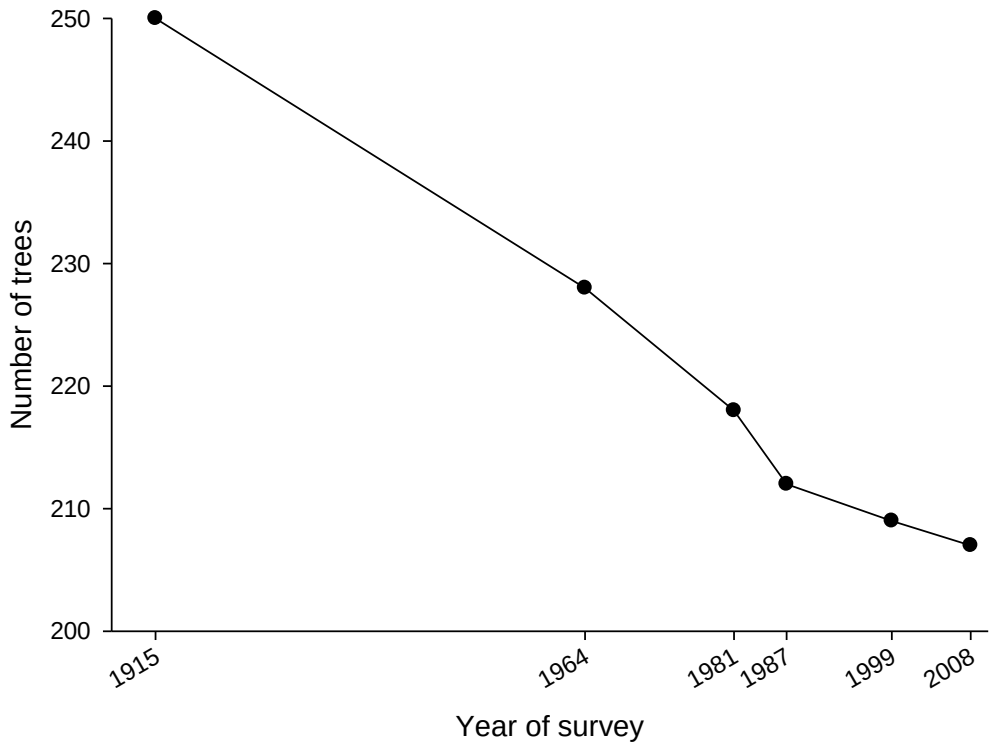


Figure 7. Trend in the number of giant sequoia greater than 244 cm dbh since 1915 at Whitaker's Forest. **Note that the Y-axis does not start at zero.**

It is unclear, however, whether the mortality rate at Whitaker's Forest is higher than the average for the larger population, because wide-spread and long-term repeat survey data are not available to compare it against. The STI within SEKI and the large tree survey at Mt. Home both represent good starting points for the development of databases that may eventually enable detecting changes in the mortality rate of large giant sequoia. Given the human propensity to count large trees, it is also possible that long-term surveys of large giant sequoia could be compiled from piecemeal surveys that have already been done across the population. Compiling these surveys could help detect any trends in large giant sequoia mortality. We recognize that detectable and meaningful trends will only come from decades and possibly centuries of monitoring, but the long-term nature of the trend at Whitaker's Forest is an example of the feasibility and value of such an effort. It is also feasible that mortality rates could increase (or decrease) relatively rapidly given novel forest environments, in which case even decade-level monitoring could detect changes.

Departure index shifts- An approach for detecting change in grove size structure

We have restricted our evaluation of size structures largely to visual comparisons between groves. Had repeat measures of size structure been available from monitoring efforts, a more quantitative approach could have been taken to document changes in size structure and to make inferences about whether trends were enhancing or diminishing the sustainability of giant sequoia. As an example of quantifying size structure changes over time and in particular evaluating treatments aiming to shift size structures to more desirable conditions, the Whitaker's monitoring data is used as an example since it includes repeat measurements. Visually, it appears that the mechanical treatment and subsequent planting that occurred between the 1999 and the 2009 surveys (Figure 6) was effective in moving the structure of giant sequoia to a more desirable condition (i.e. one with a higher density of smaller trees). To determine if this shift could be detected using a quantitative measure, we tested for a change in the size distribution using a departure index, M, that is similar to the Gini coefficient used by Stohlgren (1991) to evaluate SEKI grove structure using the STI database. Using M addresses two of Stohlgren's three critiques of the 1991 size distribution analysis of the STI database. Namely, it is relatively insensitive to sample size (i.e. the number of size classes) and it measures both the magnitude and direction of departure (Menning et al. 2007). The third critique- using models that are too simple to adequately describe giant sequoia size distributions, can be resolved with a model selection approach (Burnham and Anderson 2002) to choose a best alternative from a candidate set of models (*sensu* van Mantgem et al. In Press) that can include more complicated models such as a Weibull fit.

The departure index M for stem diameter size class distribution was calculated for the 2009 survey and then compared against M for the 1999 distribution. The effect of the treatment on size structure was evaluated by using a Wilcoxon rank sum test (one-way) to evaluate if the treatment was effective at shifting the distribution further to the left (i.e. increasing the relative number of small trees). The results indicated that the 1999 distribution was already heavily left shifted to begin with (this is apparent from the gray bar distribution from Whitaker's in Figure 6), which made it more difficult to detect a shift further to the left with a statistical test. Despite this, the departure in M was sufficiently large (-0.10) to detect a shift at $p = 0.07$. The leftward shift to more small trees represented a shift that was 45% of the maximum possible (i.e. 100% of trees within the smallest size class). The results demonstrate that this approach has good potential for use in evaluating future trends in giant sequoia structure, especially following treatments in areas where current structures are considered undesirable (e.g. the 1999 Whitaker's structure). Given the high densities of giant sequoia seedlings that are necessary to sustain populations (Figure 1), it may be necessary to consider using a higher p-value than the traditional 0.05 for a threshold of significance. In this case, a relatively low-power statistical test had to be used because of non-symmetrical distributions. This is expected, given that non-symmetrical size distributions are the norm for giant sequoia at the grove scale (Appendices 4 and 5).

Size structures of individual groves

The SEKI database is by far the most extensive in terms of the number of measurements, and it is also the oldest. Its age is very much a liability with respect to assessing current conditions for this assessment, but it is also a considerable asset with respect to serving as a baseline for assessing future trends. The database is derived from surveys conducted between 1964 and 1976 that attempted to perform a 100% census of giant sequoia trees within SEKI boundaries. Because the database was thoroughly analyzed previously (Stohlgren 1991), we do not re-analyze the data

here but instead present the data with descriptive statistics and graphs of grove structure (Subappendix 3). As Stohlgren (1991, Chapter 2) concluded, graphic representations of grove size structure are in many ways more useful than quantifications of structure. Additionally, there is no reference structure that represents an ideal or desired size structure for giant sequoia. The average structure of SEKI groves in the 1960's and 1970's may in fact be considered the least representative of a desirable structure because the negative effects of fire suppression would have been underway for several return intervals and prescribed burning programs had only just begun. Following future surveys, change in grove structure can be assessed quantitatively using a number of approaches such as the one demonstrated above.

The groves with a high priority for monitoring within SEKI include those which had relatively low small tree densities circa 1970. If prescribed fires have effectively initiated cohorts in these groves already, it should eventually be reflected in a change in the size structure. Those groves which Stohlgren (1991) noted as having a significant negative departure in the smallest size class include Big Stump, Board Camp, Cedar Flat, Coffeepot Canyon, Dennison, Devils Canyon, Eden, Homer's Nose, Little Redwood Meadow, Muir, Redwood Creek, Sequoia Creek, and Surprise. Of these groves, a subset had significantly negative departures in two or more of the smallest size classes: Dennison, Eden, Grant, Muir, and Sequoia Creek.

The size structures from surveys of groves within GSNM are given in Subappendix 4. Given the low frequency of giant sequoia within GSNM groves (78% of plots had no giant sequoia present), sampling intensity should be considered carefully. It is likely worthwhile to either sample with greater intensity, stratify sampling effort to focus on areas with giant sequoia, or use sampling schemes designed for rare communities. Inferences on size structure are limited until more data are available.

Analysis of Uncertainty

Uncertainties are described throughout this report whenever inferences are made. This section refers to the uncertainty in our spatial representation of grove boundaries, since between-grove inferences form the basis of our spatial analysis. We intentionally limited our inferences to the inter-grove level because of uncertainty in spatial data within groves. Many groves are very small, making within-grove analysis infeasible given current data sources. We consider the coarse level of inter-grove inference to be most suitable given available data and especially when considering groves simultaneously in both SEKI and GSNM. Within SEKI, grove boundaries were first derived from hand drawn maps made during field surveys**,** and then adjusted based on coordinates collected during the STI and from aerial imagery**.** The GSNM grove boundaries should have a fairly high degree of accuracy in terms of the spatial data locations matching what was intended from ground measurements. GSNM grove tree line boundaries were traversed by foot. Administrative buffers between 0 and 500 feet were then added onto grove tree lines. Global positioning devices were then used to measure administrative boundary location. For this analysis, groves were "de-buffered" to provide tree lines boundaries. Since modern global positioning devices were used to measure grove boundaries recently, accuracy of measurements should be within several meters. Precision in this case, however, is not necessarily as high as accuracy. Tree lines can be difficult to follow if irregular-shaped (e.g. cutting off individual trees or including bays of non-giant sequoia vegetation). There is no measure of precision, however, so it can not be quantified. It can be assumed that the core areas of groves are, in general, located with high precision. The grove boundaries, however, may not be. As noted earlier, subjectivity exists in the decision to either clump areas into one grove or to split into separate groves. GSNM staff in general followed the grove definitions of Rundle (1972a), so the degree of lumping or splitting is at least consistent to the degree that Rundle was consistent. Grove complexes (Belknap and Evans), in particular, have large areas within their boundaries that do not currently have giant sequoia habitat. Giant sequoia frequency in these complexes (Belknap = 22%; Evans = 17%), however, were not particularly lower than what occurred in the other groves.

Interactions with other focal resources

All of the focal resources interact with giant sequoia. Although there are very few known species that are unique to giant sequoia groves (besides the giant sequoias themselves), giant sequoias are not passive components of their ecological communities. They can dominate forest structure in basal area and canopy stature, if not in stem density. Interactions are further described below.

Stressors

Life histories of tree species are made up of competitive strategies for regenerating, recruiting, and persisting (Huston and Smith 1987). For giant sequoia, a stressor may interact differently with one life history phase compared to another. Drought in a single year, for example, may preclude germination (Stephenson 1994, York et al. 2011) but large trees still may be able to persist if they have access to deep water sources or to perennial surface water (Halpin 1995). Given its longevity and especially considering the sensitivity of the regeneration phase to

stressors, we consider these life phases as separate "resources." Of these life history phases, the regeneration phase is often the most critical as suggested from both demographic evidence (Stephenson 1994) and from the close physiological link between regeneration and fire (e.g. Harvey and Shellhammer 1991, Webster and Halpern 2010), as well as the link between regeneration and climate (e.g. Mutch and Swetnam 1995, Stephens et al. 1999, York et al. 2011). Below we address each stressor by first ranking the life history phase according to vulnerability. That is followed by listing additional stressors that, given what is currently known, have the greatest potential to interact with the given stressor. A brief discussion of the known impacts of the stressor and its interactions on giant sequoia follows.

Air quality

Life phase priority: 1) Regeneration, 2) Recruitment, 3) Persistence
Interactions: Altered fire regimes, Climate change

The review and management alternatives provided by Stephenson (1996) describes most of what is currently known about air pollution effects on giant sequoia. The relevant text from Stephenson (1996) is provided below:

Some of the worst air pollution in the United States is found periodically along the western flank of the southern Sierra Nevada, the home of the vast majority of sequoia groves (Peterson and Arbaugh 1992, Cahill et al. 1996). Mature giant sequoias seem to be resistant to present levels of ozone, the most damaging component of Sierran air pollution. One hundred twenty-year-old sequoias exposed to ozone for two months, some at concentrations up to three times ambient, showed no visible foliar injury or detectable changes in photosynthetic rates (Miller et al. 1994). In contrast, newly-emerged sequoia seedlings were more vulnerable. Seedlings exposed to ozone over an entire summer showed very slight foliar injury at ambient ozone levels; however, those exposed to 1.5 times ambient levels showed extensive foliar injury and lowered photosynthetic efficiency (Miller et al. 1994, Miller 1996).

If ozone concentrations in the Sierra Nevada remain relatively constant into the future (as they have over the last decade, due to increasing pollution control efforts in the face of rapid population growth; Cahill et al. 1996), air pollution may have some limited effects on the genetic composition of sequoia seedling populations, while significantly contributing to increased death rates and decreased recruitment of ponderosa pine and Jeffrey pine within sequoia groves (Miller 1996). If pollution were to increase beyond present levels, adult pines stressed by air pollution (compounded by crowding caused by fire suppression) may become more susceptible to fatal insect attacks, as they have in the Los Angeles basin to the south (Miller 1973, Ferrell 1996, Miller 1996). Additionally, sequoia seedling establishment, survival, and recruitment might eventually be reduced (assuming that conditions for establishment are otherwise favorable). Options for counteracting the effects of air pollution include (1) reducing production of air pollution, (2) reducing competition among trees by thinning (whether by fire or saws), and (3) identifying, breeding, and planting pollution-resistant varieties of selected tree species. In the latter case, genetic diversity within groves may diminish.

New information from two recent studies has relevance for this assessment of giant sequoia with respect to ozone:

1. Ozone concentrations have continued to remain stable in the last 14 years (Appendix 2).
2. Grulke et al. (1996) continued the physiology work mentioned above. This work emphasized again that susceptible individuals are likely to be selected against at a young age and that further steep *increases* in concentrations of ozone may interact with other physiologic stresses to affect some individual mature giant sequoias (~125 years old).

The studies suggest the importance of considering the different life phases of giant sequoia with respect to assessing air pollution stress. In the case of ozone, it is the young seedling phase that is most susceptible. Because ozone concentrations have continued to remain steady, ozone is likely of more concern in how it interacts with other stresses and not as an isolated stress. The stresses that are more likely to interact with ozone include those that alter water stress and gas exchange in individual trees (Grulke et al. 1996). Climate change (i.e. extended drought) and altered fire regimes (i.e. increased levels of inter-tree competition from fire suppression) are the two more obvious stresses, although others have potential to influence giant sequoia physiology to the point that ozone becomes more of a stress.

Land use/fragmentation

Life phase priority: 1) Regeneration, 2) Persistence, 3) Recruitment
Interactions: Climate change, Altered fire regime, Invasive species

Accessible giant sequoia groves are the more heavily-visited areas within SEKI. Impacts with relevance to giant sequoia include soil compaction, loss of topsoil, and reductions in soil organic matter (Demetry and Manley 2001). Other possible impacts include the *potential* for future increased rates of mortality of large giant sequoias in heavily used areas (although there is currently no evidence of this occurring), root-exposing erosion around the bases of large specimen trees, and severe compaction that inhibits giant sequoia regeneration. These impacts and possible management alternatives are described in greater detail by Stephenson (1996).

Although the potential for heavy-use impacts on large tree persistence warrants careful monitoring (e.g. Figure 7), the more relevant and immediate impact of concern is likely on giant sequoia regeneration because of the loss of adequate rooting substrates for seed germination on heavily compacted soils. A variety of treatments ranging from limiting foot traffic to actively reversing compaction with tilling or ripping could potentially address negative soil compaction effects. There is uncertainty, however, in which treatments can best restore compacted soils and, in turn, what the effects of treatment options are on giant sequoia regeneration, recruitment, and persistence. The restoration treatments performed in the Giant Forest grove provide a recent example of how active adaptive management can help resolve uncertainties while simultaneously implementing treatments that have some likelihood of meeting objectives.

The premise of the Giant Forest restoration project was to apply a gradient of restoration treatment intensities in order to restore soil properties and vegetation patterns found within fire-created canopy gaps (Demetry 1995). Treatments were conducted with an experimental approach

(i.e. randomization and replication) and were designed to be monitored over a long time period in order to improve future restoration efforts (details are provided in Demetry and Manley 2001). Cultivation of soils down to ~ 13 cm reduced compaction when organic matter was also added to the soil. The level of compaction in treated areas remained, however, far greater than in levels found in non-compacted reference sites (Fig. 8). Whether or not the degree of "de-compaction" from the treatments will influence the giant sequoia seedlings (whether planted or germinated from seed fall) within the restoration sites can only be evaluated with further monitoring. Such evaluations will be helpful for the design of future active adaptive management projects for restoring heavily used sites. For example, future restoration efforts may include a treatment option that is either more intense (e.g. deeper tilling) or less intense (not tilling at all) than those tried in this project. The continuation of monitoring following these projects and the feed-back of inferences into other similar projects is critical to the success of active adaptive management. The restoration treatments currently being planned in the heavily-visited Mariposa Grove in Yosemite should also be observed closely with an eye toward informing future treatment options in SEKI and GSNM.

The Long Term Soil Productivity project (Powers et al. 2005) is another study with relevance for how planted giant sequoia seedlings may be affected by compaction. 15 years following experimental compaction treatments, no negative effect of compaction has been detected on planted giant sequoia growth in loamy soils in the central Sierra Nevada range (Matt Busse, unpublished data). This suggests that the cultivation of soils as a restoration treatment may not be effective for promoting giant sequoia growth except in areas of extremely severe compaction or in clayey soils. Rather than broadcast tilling with equipment, another possible option is tilling small areas by hand, followed by planting. The restoration of heavily used areas is clearly an area where treatment options can be implemented with the intent of honing in on which treatments are most effective.

Severe fragmentation associated with land use (i.e. urbanization or highway construction) is not likely to occur within the giant sequoia population because the vast majority of the population is owned by federal or state agencies whose mission is to conserve giant sequoia. However, the population is already highly-fragmented. It is possible, therefore, that the interacting stressors described in this section may have especially large impacts. Already small and remote groves of giant sequoia have little room to contract without disappearing. Further, barriers such as shallow or rocky soils on the upper elevation edges of groves may preclude any natural expansion uphill as climates continue to warm. The existing rarity and fragmentation of giant sequoia make it important to consider the potentially profound effects that novel environmental stressors may have and the unique management responses that may be necessary.

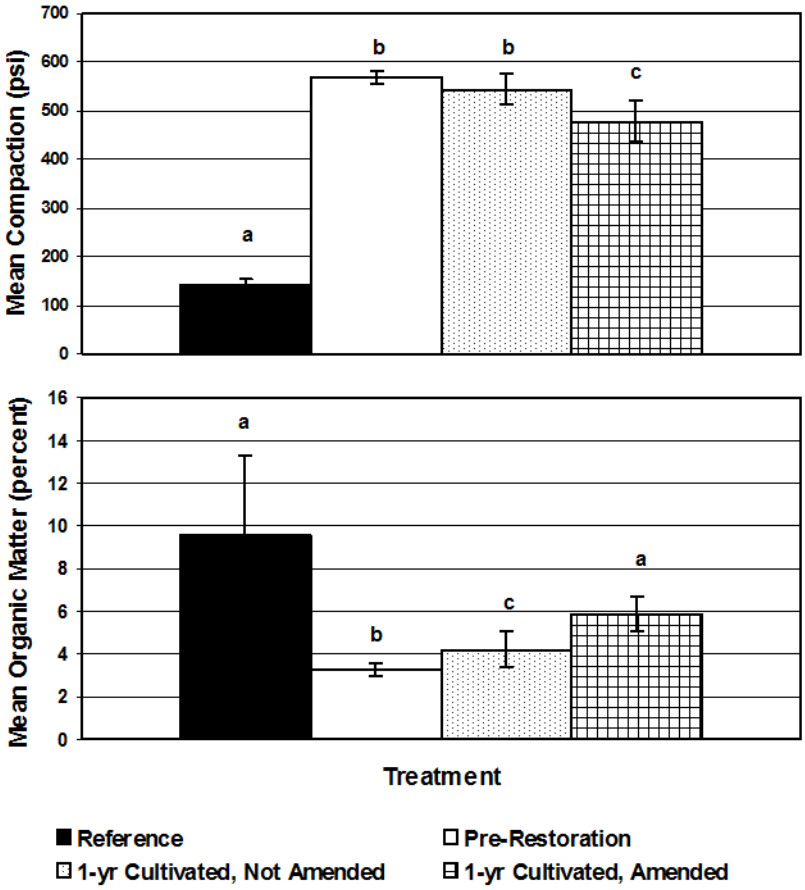


Figure 8. Mean surface soil compaction (top) and mean organic matter (bottom) in reference and restoration treatment areas within the Giant Forest grove. References areas are fire-created canopy gaps approximately ten years after fire. Cultivated but non-amended restoration treatments were measured one year after treatment. Cultivated and amended treatments were also measured one year after restoration. Error bars show ± one standard error of the mean. Significant differences resulting from Wilcoxon test for paired comparison of treatments are indicated by different letters. Adapted from a report by Demetry and Manley (2001).

Climate change

Life phase priority: 1) Regeneration, 2) Recruitment/Persistence
Interactions: Altered fire regime, Air quality, Land use, Invasive species, Emergent disease complexes

Anthropogenic climate change will almost certainly continue to affect giant sequoias. Precisely how they will interact with giant sequoia individuals and communities, however, is uncertain. Again, Stephenson (1996) provides the most relevant review of why climate changes are likely to influence giants sequoia and what future influences they may have:

Snow melt, a major source of soil-water recharge in sequoia groves (Rundel 1972b, Stephenson 1988), is likely to come earlier in the spring than at present, potentially prolonging the summer

drought characteristic of the Sierra's mediterranean-type climate. Depending on their magnitude, such climatic changes could have tremendous effects on giant sequoia ecosystems.

The paleoecological record is one of our best tools for understanding the possible magnitude of biotic changes resulting from climatic changes. Contrary to John Muir's glacial hypothesis (Muir 1876, Axelrod 1959), the fossil pollen record suggests that the present highly disjunct distribution of sequoias is due to the generally higher global summertime temperatures and prolonged summer drought in California of the early and middle Holocene (about 10,000 to 4500 years ago) (Anderson 1994, Anderson and Smith 1994). This explanation was earlier proposed by Rundel (1972b) and Axelrod (1986). During this period, sequoias were probably much rarer than today (at least in areas where they are presently found; Anderson 1994; Anderson and Smith 1994), existing only along creek and meadow edges where present groves exist. Pines were more abundant, firs less abundant. Only since cooling and shortening of summer droughts began about 4500 years ago has sequoia been able to spread out and create today's groves, over a period of only two or three sequoia lifespans (Anderson 1994; Anderson and Smith 1994).

This record of sequoia's response to past climatic changes offers an imperfect but instructive analog to the possible effects of future climatic changes. Projected increases in global temperature over the next several decades are of similar or greater magnitude than those that caused the dramatic increase in sequoia abundance during the last 4500 years, but they are in the opposite direction (Houghton et al. 1990). It therefore seems reasonable to conclude that, if model projections are correct, increasing temperature over the next several decades, by inducing earlier snowmelt and prolonging summer droughts, may cause a return to conditions unfavorable to sequoias. An immediate effect probably would be a widespread and continuing failure in sequoia reproduction, even in the presence of prescribed fires; this would be a consequence of the high vulnerability of sequoia seedlings to prolonged drought (Harvey et al. 1980, Mutch 1994). Death rates might increase among adult sequoias and associated species as drought stress makes them more vulnerable to insects, pathogens, and air pollution. Of course, there may be other species in the giant sequoia community that would be equally or more severely affected by climatic change than sequoias.

Several recent studies further support this emphasis on the interaction between climate change and snowmelt/summer drought in influencing giant sequoia. A consensus of models predict future warming trends along with associated earlier snowmelts (Barnett et al. 2005), and a trend toward earlier snowmelt over the last half-century in the western United States has been documented (Hidalgo et al. 2009). The high sensitivity of seedlings to soil moisture (Figure 9), even near the resource-rich centers of relatively large canopy gaps was documented by York et al. (2011). This supports the possibility that even following prescribed fires with adequate local severity, regeneration will likely be constrained by soil moisture and/or nutrients. Once established, seedlings appear to have some capacity to survive under moderate competition for soil moisture (York et al. 2011) by making physiological adjustments to drought (York 2006). Adaptations in root morphology also suggest a high degree of flexibility across different soil types (Hannah, unpublished). All phases will eventually be influenced by climate change, but it is the regeneration phase- dispersal, germination, and early establishment- where effects of climate change appear to have the greatest potential to be detectable in the near term.

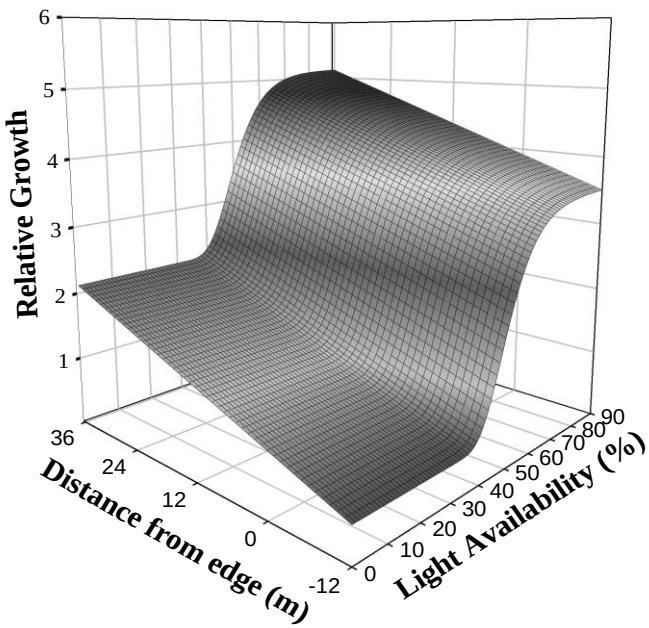


Figure 9. Predicted relative growth as a function of light availability and distance from gap edge (used as a soil resource availability index) at Whitaker's Forest Research Station, CA. The relationship suggests a co-limitation of seedling growth to light and underground resources, but also the sensitivity of seedling growth to changes in underground resources even under high resource availability conditions. Reproduced from York et al. 2011.

Over longer time periods, any climate change trends that alter surface and deep water hydrology will likely have impacts for both mature and regenerating giant sequoias (Halpin 1995). Recent tree-level physiology work supports previous suggestions (Rundel 1972b, Anderson et al. 1995) that large giant sequoias are accessing deep water sources (T. Dawson and A. Ambrose, unpublished data). Finally, York et al. (2010) found a correlation between mature tree diameter growth and the previous year's winter precipitation but no correlation with summer temperature. The most integrated measure of climatic stress for plants in the dry forests of the Sierra Nevada is climatic water deficit (Stephenson 1990). This may be especially important for giant sequoia, which limited data suggest already occurs across a relatively narrow range of water deficit (van Wagtendonk, 2007). While climatic water deficit can be calculated from available weather data, the importance of soil type and subsurface flow (Rundel 1972b, Halpin 1995) in predicting actual water stress for giant sequoia must be considered simultaneously with climatic water deficit. Detailed soil type maps, however, are not available for locations in and around giant sequoia groves in SEKI. Developing such maps should be a high priority for predicting the likely effects of climate change on giant sequoia.

Compared to consistent predictions of temperature increase and earlier snow melt in the Sierra Nevada, there is a higher degree of uncertainty in how precipitation will change (Lawler et al. 2010). Further, the general influence that changes in precipitation will have on vegetation are also uncertain. Compounding the uncertainty exponentially is the fact that the stressors we are considering here will interact with climate change to produce profoundly novel stressors. Predicting the complex effects of climate change on giant sequoia is largely beyond the scope of this assessment (and is probably impossible to do with widely-acceptable precision). Instead we

emphasize here the need for active adaptive management coupled with monitoring, as outlined by Walters and Holling (1990) and as put into a more recent context by Lawler et al. (2010). We revisit this topic below under recommendations for future study and research.

Invasive species

Life phase priority: 1) Regeneration, 2) Recruitment, 3) Persistence
Interactions: Climate change, Altered fire regime, Land use/fragmentation

The potential for exotic-invasive species to become stressors within giant sequoia groves is significant for at least two reasons. The first is that, like giant sequoia, many of the exotic-invasive species that have impacted ecosystems have pioneer life history strategies (Hobbs and Huenneke 1992). The resource-rich environments of recently created canopy gaps in the southern Sierra Nevada are associated with greater numbers of exotic species (Keeley et al. 2003). Local higher-severity disturbances that facilitate giant sequoia regeneration, therefore, also have potential to facilitate the invasion of exotic species. Competitive interactions with exotic species may negatively interact with giant sequoia by reducing seedling growth and survival, excluding associated native species, or by altering processes such as future fire regimes or nutrient cycling. The second, related reason is that exotic species in North American forests (including Sierra Nevada mixed conifer) have generally tended to increase in cover and richness following prescribed fires (Collins et al. 2007, Nelson et al. 2008, Sutherland and Nelson 2010). The primary treatment used to regenerate giant sequoia, therefore, also has potential to increase exotic species. The longest study of repeated fire effects on exotic species, however, was done in SEKI and found *no* increase in exotic species following repeat burning (Webster and Halpern 2010). It is noteworthy, however, that although giant sequoia regeneration in this study was only found in areas that had been burned, densities were too low to detect any significant association of giant sequoia regeneration with burning. Assuming other conditions (i.e. seed supply and soil moisture following the fires) were adequate for giant sequoia regeneration, it is likely that the prescribed fires in this case were not of high enough intensity to promote high densities of giant sequoia seedlings, and therefore possibly not of high enough intensity to promote exotic species. Slightly higher rates of exotic invasions may be an acceptable tradeoff for the benefit of increased giant sequoia establishment and growth following higher intensity disturbances (Mutch and Swetnam 1995, York et al. 2011), especially if exotics can be excluded/controlled, or if their presence is short-lived (Keeley et al. 2003, Collins et al. 2007).

While the regeneration phase is likely the most vulnerable to exotic invasive species, recruiting or persisting giant sequoia in dense-canopy forests are not necessarily immune to exotic invasions (Martin et al. 2009). This is especially relevant for groves that are visited often by humans, and therefore have a higher potential for human-vectored spread of exotic propagules. Perhaps more significant than this interaction with land use and fragmentation is the potential for interactions of invasive species with climate change and altered fire regimes. It is feasible, for example, that exotic annual grasses could eventually invade groves, feeding back into a fundamental alteration of the fire regime. The generally positive relationship between disturbance intensity and exotic species (Sutherland and Nelson 2010) suggests likely increases in exotic invasions as extensive wildfire severities increase within and surrounding giant sequoia groves.

Altered fire regimes

Life phase priority: 1) Regeneration, 2) Recruitment, 3) Persistence
Interactions: Climate change, Invasive species, Land use/fragmentation, Air quality

No stressor has had as discernable an impact on the mixed conifer forest as has the alteration of fire regimes. For giant sequoia, fires are stressors when both severity and frequency are too high, or when both severity and frequency are too low. While extensive high-severity fires did sometimes occur in the past, their frequency was very low (e.g. Caprio et al. 1994). The increasing trend in extensive high-severity fires (Westerling et al. 2006) has potential to stress all phases of giant sequoia life history, especially if dramatic changes in vegetation communities occur (as Goforth and Minnich (2007) have suggested has occurred following the Cedar Fire in the Penninsular Range to the south of the Sierra Nevada). On the opposite extreme, low-severity fires may not be hot enough to initiate cohorts of giant sequoia (assuming other conditions for germination and establishment are adequate). While many prescribed fires have resulted in net increases in giant sequoia relative to other species (see above; Caprio, unpublished data), other fires have resulted in only small increases (e.g. Webster and Halpern 2010) relative to what appears necessary for sustaining the population over long time periods (Fig. 1).

Despite these challenges, SEKI has set an example for managers trying to reverse the negative consequences of fire suppression. As Pyne et al. (1996) noted:

> Sequoia-Kings Canyon have fashioned a robust program that has, in a pragmatic way, brought fire back, debated what that restoration means and how it can be measured, and are well suited to adapt to the unexpected developments that the future can be expected to throw their way.

Observations of vegetation responses to the reintroduction and repetition of fire within SEKI have indeed provided much of what is now understood about how fire interacts with giant sequoia. The challenge within SEKI now turns from understanding and defining restoration targets (Stephenson 1999) into how fire regimes should be managed in the face of interacting and novel stressors. These challenges will surely test Pyne et al's prediction of a robust and adaptable fire program. The continuation or expansion of SEKI's fire program, the monitoring efforts associated with it (e.g. the Fire Effects Monitoring – Caprio *unpublished*), and the reporting of results to the broader management and scientific community are critical for facilitating the positive evolution of the fire program.

The fire program also represents an opportunity to practice active adaptive management. Increasing fire frequency to match the high frequency found during hot and dry periods in the past (Swetnam et al. 2009), for example, may prove beneficial for protecting large giant sequoia from extremely severe and extensive fires during drought years. But a possible tradeoff of consistent low-severity burns is inadequate regeneration. A fire program that continues to aim for variation in fire severity, frequency, and seasonality can continue to identify such tradeoffs and inform future giant sequoia management.

Emergent disease complexes[1]

Life phase priority: 1) Persistence, 2) Recruitment/Regeneration
Interactions: Climate change, Altered Fire Regime

While numerous insect and pathogen[2] species interact with giant sequoia, it is likely that only a small fraction of the existing associated species have even been identified. For those that have been identified, their significance in contributing to giant sequoia mortality remains poorly understood (Piirto 1992). Although widespread mortality episodes related to diseases have not been commonly observed in the past, emergent disease complexes have significant potential to become stressors in the future. This is especially important considering the unknown interactions between existing diseases, climate change, and altered fire regimes. As we have observed in other ecosystems, climate change in particular has potential to expand disease ranges and/or modify disease behavior, resulting in episodic mortality of hosts. A recent example comes from western Canada, where mountain pine beetle (*Dendroctonus ponderosae)* outbreaks on unprecedented scales were facilitated by climate change (Logan and Powell 2001, Kurz et al. 2008). The probability of a similar outbreak impacting giant sequoia is unknown. But it is unlikely that reliance upon giant sequoia itself to maintain its over-emphasized inherent resistance to disease will provide protection against emergent disease complexes. The relatively low genetic variability (compared to its associated tree species) of giant sequoia (Libby 1986) may also make it vulnerable to emergent diseases. A relevant example of the effects of past genetic bottlenecking interacting with emergent diseases comes from red spruce (*Picea rubens*) in northeastern forests. Red spruce is a long-lived species that had a population contraction within the lifespan of its oldest individuals. The past reduction of genetic diversity interacted with novel air pollution stressors to lower its physiological resistance to cold (Eagar 1992, DeHayes et al. 1999), leading to widespread decline. We use this example to point out that the genetic makeup of the giant sequoia population will influence interactions with all stressors, not just emergent disease complexes.

The disease most commonly mentioned that is currently observed interacting with giant sequoia is annosus root rot (*Heterobasidion annosum*). Stephenson (1996) succinctly summarized the interaction and discussed one of the management alternatives:

> Annosus root rot (*Heterobasidion annosum*), a native fungus, may be killing more sequoias now than in pre-Euroamerican times. Fire suppression has allowed white fir to grow more densely in sequoia groves than it did in the past, meaning that there are more opportunities for root rot to spread from infection centers and to be transmitted to sequoias through root contact (Piirto 1977, Piirto et al. 1984). Sequoias weakened by root rot are more susceptible to falling than those free of infection. Restoration of groves to their more open pre-Euroamerican conditions probably will reduce the occurrence of

---

[1] We prefer the term "complex" over "paradigm," which may be used in other parts of this NRCA and refers to an example serving as a model or pattern, which implies a past condition.

[2] Here we consider both insects and pathogens as forms of "disease"

annosus root rot; the direct effects of fire on the pathogen are less certain (Piirto et al. 1992).

Reducing inter-tree competition by lowering density can increase vigor (to the extent that vigor is indicated by radial growth), even in very large giant sequoias (York et al. 2010). Improving the understanding of the interaction between fire, tree vigor, and disease represents yet another opportunity that can come from SEKI's fire program. Host management of non-giant sequoia species will also indirectly influence giant sequoia disease interactions. As mentioned above, increases in white fir density may be increasing the occurrence of Annosus root rot infections. Alternatively, the opposite may occur if a non-giant sequoia species becomes a preferred host and reduces infection of giant sequoia by nature of the preferred host being present. Armillarea root disease (*Armillaria mellea*), for example, may interact with giant sequoia based more upon the occurrence of black oak (*Quercus kelloggii)* than giant sequoia in lower elevation portions of groves. The complexities of host-environment interactions are extreme, even for a species thought to have relatively few disease interactions.

A final example of the complexity of existing disease paradigms, let alone new ones, comes from a current study at Whitaker's Forest that is exploring giant sequoia- mycorrhizal interactions beneath canopy gaps (C. Fahey[1] and R. York, manuscript in review). Arbuscular mycorrhizae (AM) colonize giant sequoia seedlings and play a potentially important role in the establishment and recruitment of new giant sequoia cohorts. In addition to supplying nutrients to giant sequoia roots, AM were found to be negatively correlated with other non-AM fungal species, indicating a potential resistance-building function of AM in protecting giant sequoia seedlings against pathogens. The study further suggests that low light availability limits the colonization of giant sequoia seedlings by AM, further defining the mechanism by which distinct canopy gaps facilitate giant sequoia regeneration and recruitment.

[1] Catherine Fahey, Cornell University, Department of Natural Resources

Assessment

Giant sequoia in a novel environment

Facing a looming novel environment, giant sequoia would seem to have several characteristics in its favor for being resistant or resilient to impending stressors:

- It has persisted through large climatic fluctuations in the past, indicating that it might also persist through wide fluctuations in the future.
- Despite being heavily visited by vectoring humans, no known exotic pest or pathogen has yet to negatively influence it.
- It has survived through at least one modern stressor (ozone) with only minor direct effects.
- It has already been planted widely outside of native groves, which offers some bio-geographical hedging against regional and global stressors.
- It is both long-lived and highly variable in its growth rate, offering some resilience for recovering from negative effects that have already occurred (i.e. fire exclusion).
- Its life history suggests that it may actually increase following extensive high-severity fires, which have been increasing in the recent past.
- Finally, it is a charismatic species that will undoubtedly receive a great deal of attention and assistance when stressors begin to affect it in catastrophic ways.

For each of these characteristics, however, there are counter-traits which also suggest a high level of vulnerability to novel stressors:

- Past contractions of the population from climate change may have decreased genetic variability to a point that is relatively low compared to other times during its evolution.
- The climatic fluctuations that the species has persisted through occurred more slowly than what is likely to occur in the future.
- It is already a rare species with narrow geographic range; native groves cover only 14,000 hectares in fragmented and sometimes isolated populations.
- Negative effects of fire suppression may have already predisposed the population to further impacts from continued alterations of the fire regime.
- Tree species that have declined because of exotic pests or pathogens were not known to have a vulnerability to exotic species prior to its impact.
- While plantings beyond grove boundaries are widespread, the genetic makeup of these plantings is limited, with most seed coming from two groves (Redwood Mountain and Mt. Home).
- Despite its competitive nature of rapid growth and persistence, it has an Achilles heel in the narrow range of conditions under which regeneration can occur. Local high-severity fires are necessary but not sufficient; they must be coupled with adequate soil moisture for regeneration to occur.

- Individuals are susceptible to drought, which is a plausible outcome of climate change
- Large individuals may be susceptible to changes in underground hydrology, which is also a plausible outcome of climate change.
- Extensive high-severity wildfires may cause direct mortality of large giant sequoias, which would likely be of great social concern; they may also result in fundamental changes in vegetation type that further limit giant sequoia regeneration and persistence.
- Charisma is not necessarily an inherent buffer against climate change (e.g. polar bears).

Inter-grove assessment

As with our data analysis, inferences for assessment are made at the between-grove scale. Of the data that were analyzed spatially, only fire suppression (FRID) and ozone impacts on giant sequoia have been measured to the degree necessary for conducting a data-based assessment of condition. Size structure is an appropriate measure of condition, and it has been measured very thoroughly especially in SEKI, but data are not current. For the other data measured (snow-dominance of precipitation, total precipitation, min/max temperature, and water deficit), we consider these to be important influences on giant sequoia condition, but either impacts on giant sequoia need to be measured or other data are needed for interpretation. These other data are therefore considered to be important integrity metrics, even if their current impact on condition is unknown (Table 2). Integrating the data and studies considered above, four categories of groves that have a higher likelihood of being under more stress or which have a higher likelihood of becoming stressed are apparent:

Groves at elevation extremes

Groves at elevation extremes, either low or high, may be more vulnerable. Lower elevation groves may experience extended summer droughts, affecting giant sequoia either directly via moisture stress or indirectly from extensive high-severity wildfires. The elevation that the population spans is not large, but there is some variability between groves. In SEKI, for example, three groves (Clough Cave, Putnam Francis, and Big Spring) have mid-ranges in elevation that are more than 20% lower than average for all SEKI groves. Wishon in GSNM also stands out as a low elevation grove. As the lower elevation of snow-dominated zones within groves continues to rise in elevation, the conditions for seedling establishment may become more limited in the lower elevation portions within groves. At higher elevations, the minimum temperatures that may limit the upper range of giant sequoia are not likely to decrease, but other stressors could potentially interact with the cold tolerance of giant sequoia. Further, as Stephenson (1996) has noted, soils tend to be less well developed at the upper elevation ranges thus presenting a possible barrier to uphill migration. With the exception of Eden in SEKI and perhaps Maggie Mountain in GSNM, however, there do not appear to be any groves which have the majority of their area in extreme upper elevation ranges compared to all other groves.

Small groves

Groves that are especially small in size and number of individuals may also be more vulnerable. Although among-grove genetic variation has not been observed to be large (Fins and Libby 1994), the genetic makeup of many small groves has not been explored. Two of the smaller groves that have been studied (Placer and Deer Creek) have expressed signs of genetic inbreeding (these groves are also near the latitudinal extremes of the range). By simple

probabilistic nature of their small size, they are also more susceptible to catastrophic loss from extensive high-severity fires as they become more common, and especially if repeat high-severity fires occur prior to a new cohort reaching maturity. Groves with large portions of their area on exposed south-facing slopes (e.g. Case Mountain and Black Mountain) are also likely to be more vulnerable to catastrophic loss from extensive high-severity fires.

Groves with extreme fire return interval departures

This categorization assumes that fire is the desired disturbance for regenerating giant sequoia. However, as we have documented above, fire occurrence is not a guarantee of giant sequoia regeneration. Fires must include localized patches of sufficiently high severity and be coupled with subsequent soil conditions that are adequate. Groves without large fire return interval departures, therefore, are not necessarily in a "good" condition with respect to giant sequoia regeneration. They may or may not have sustainable age/size structures. Groves and surrounding forests that have had long fire-free periods, however, are well-documented as having gone through fundamental changes in structure and species composition. Because most groves are currently experiencing long fire-free periods, the overall condition assessment with respect to fire return interval departure is considered poor (Table 2).

Groves with persistent and large climatic water deficit

Perhaps as important as changing fire regimes in terms of potential impact on giant sequoia is the trend in drought stress, measurable by climatic water deficit. Rapid changes in water deficit could have profound impacts on forest composition, with species responding individualistically (Lutz et al. 2010). Information about the relationship between deficit patterns and giant sequoia physiological tolerance will therefore be important for assessing grove conditions. Currently, however, impacts are unknown (Table 2).

Table 2. Integrity metrics and condition assessments

Metric	Integrity Measure	Current Condition	Summary Comments and Potential Impact
Fire Return Interval Departure	Higher degrees of departure = poorer integrity. Values are between 1.0 (extreme departure) and 4.0 (no departure)	POOR	In some high-profile groves repeated burns are maintaining low departures, but on the whole departures remain high. Most groves are currently surpassing several maximum return intervals. The potential impact is high because of the risk of extensive high-severity fire following extended fire-free periods and because of inadequate regeneration correlated with disturbance-free periods.
Ozone	Ozone concentration within groves (ppb). Damage not expected unless 8-hr highs > 200 ppb	GOOD	Current levels are lower than those observed to be necessary for damaging individuals. Levels have not increased, although some seedlings may be affected at current levels. The potential impact is low at current levels.
Size structure	Number of giant sequoias in small size classes, particularly relative to the number in large classes. Poor integrity = number of small trees < number of large trees.	UNKNOWN-Monitoring data are currently insufficient. However, given isolated studies and prescribed burning rates being lower than targeted, it is plausible that many structures are not currently sustainable.	In general, there is a positive relationship between local disturbance severity and density of giant sequoia regeneration. Those areas that have not experienced local patches of high severity disturbances are expected to be in poorer condition with respect to size structure. The capacity of giant sequoia to be resilient to temporary alterations of size structure, however, is high, thus buffering the potential impact.
Elevation of snow-dominated precipitation	Either elevation of snow-dominance or timing of spring snow melt	UNKNOWN	Snow melt has been trending toward earlier times of the year, potentially reducing seedling establishment success. The potential impact is high.
Drought stress	Climatic water deficit (mm of water)	UNKNOWN- Water balance range for giant sequoia is uncertain	Information on water balance for giant sequoia, as well as spatial information on soil properties within and around groves is needed for interpretation. The potential impact is high, given giant sequoia's sensitivity to drought stress during the regeneration phase. Deep water access of large trees could buffer drought effects, but its importance is unknown.

Level of confidence in assessment

The cumulative efforts of giant sequoia research during the past 50 years gives relatively high confidence that the processes and factors that influence giant sequoia (most notably fire) have changed and that these changes have had profound impacts on the current giant sequoia population. We know with very high certainty that a lack of an appropriate disturbance regime in the recent past has led to a decrease in giant sequoia density relative to other tree species. The confidence in the degree to which giant sequoia will be impacted in the future, however, is somewhat moderated because of the scarcity of widespread monitoring of responses to these factors as they continue to change. Given the already novel conditions of giant sequoia groves, marginal changes in factors that influence giant sequoia could lead to disproportionately large impacts. That fire regimes have changed fundamentally, for example, is unequivocal. Further, negative effects of altered fire regimes on giant sequoia age and size structure have been adequately documented. But the long-lived and variable nature of giant sequoia makes it difficult to put these relatively short-term and sometimes isolated observations into an assessment that applies generally. Another example is with the effect of climate on seedling establishment. There is relatively high confidence that long, dry summers following seed dispersal can limit successful seedling establishment. Because temperatures have increased and snow melt has begun earlier, there is enough reason to suspect that there may be an ongoing decline in regeneration success because of a trend toward poorer conditions for seedling establishment and survival. But confidence that this is actually occurring or that perhaps a threshold has been crossed is restricted by a lack of widespread monitoring data to verify it. Despite these uncertainties, there is adequate confidence to suggest that management efforts turn to addressing the reality that the factors that influence giant sequoia have changed fundamentally.

Gaps in understanding

The primary limitation in making an assessment is the lack of data tracking growth and mortality rates of giant sequoia. A very extensive and intensive inventory was done in the 1960's and 1970's, but its utility is limited by its age and by the fact that repeat measures have not been extensively done. While vegetation monitoring plots occur throughout SEKI, a monitoring effort designed specifically for giant sequoia is necessary because of its unique spatial variability, rarity, and long life-span. A monitoring plan is being developed (N. Stephenson, unpublished), but details of the plan are not yet available. Subappendix 2 provides examples of monitoring efforts of other agencies managing giant sequoia groves. For the assessment of groves within GSNM, data were collected from a protocol designed specifically for giant sequoia groves, but sampling intensity was often too low given the low frequency of giant sequoia occurrence within groves. Further, several data gaps existed in the database, thus several groves were not considered. The GSNM database was only recently compiled, and further database management should serve to fill in some of these gaps. Future monitoring, especially on the designated permanent plots, may be improved by increasing sampling intensity, stratifying sampling efforts or modifying sampling schemes to increase efficiency in gathering repeat measurements of giant sequoia individuals.

Early in the resource assessment process, it was recognized by SEKI staff that a significant limitation in assessing giant sequoia's response to drought is the lack of soils data across SEKI. This remains a considerable information gap, considering the important role of soil moisture in giant sequoia regeneration.

When assessing how conifer tree species in the Sierra Nevada may respond to climate change and other stressors, giant sequoia is sometimes conspicuously left out. This may be because it is either rare compared to other conifers species or because not enough relevant data exists for making assessments. While there has been great public interest in giant sequoia and therefore a lot written about it, much of the literature is "gray literature" or natural history writing that has importance but may be of limited value with respect to understanding how giant sequoia may respond to future stressors. Many gaps in understanding can therefore be filled by incorporating giant sequoia into studies that broadly attempt to understand the nature of all Sierra Nevada mixed conifer species. For example, giant sequoia can be incorporated into the resurgence of common-garden experiments used to evaluate the potential for species to respond to climate change. Similar experimental work designed to understand basic tree species ecology can be done (or re-done) within the specific context of novel environmental stressors.

Recommendations for future study/research

With the caveat that giant sequoia are a small component of complex communities and that its associated species also need further study, we suggest areas for furthering the understanding of giant sequoia from monitoring and inventory, basic research, and active adaptive management.

Monitoring and Inventory

- Long-term monitoring designed specifically for giant sequoia should be initiated. Standardized monitoring protocols, especially between SEKI and GSNM, will greatly assist future assessment efforts.
- Soil maps within and surrounding groves should be developed.
- High resolution remote sensing techniques (i.e. LiDAR), as well as objective approaches for defining grove boundaries can be used to define modern grove boundaries and to track structural changes in gap fraction and perhaps for individual large tree monitoring. The methods should be repeatable so that future grove boundary delineations can be used to detect change in total grove area.
- When extensive high-severity fires do occur within groves, they should be monitored for indications of long-term habitat change (sensu Goforth and Minnich 2007) and to find out dispersal patterns of giant sequoia following extensive high-severity disturbance.
- A range of past disturbances that have varied in both quality (i.e. fire, logging, and single-tree mortality) and severity create a disturbance gradient over which measurements can help further refine the understanding of the giant sequoia-disturbance relationship.

Basic research

- The influence of nitrogen and perhaps phosphorous availability on giant sequoia growth could improve the understanding of how giant sequoia may respond to climate change. The competitive response of giant sequoia to changes in light and water that come from either altered fire regimes and/or climate change will likely be influenced by nutrient availability.
- The potential reliance of large giant sequoias on deep water for persisting in dry locations and possibly for persisting through extended drought periods could be confirmed with physiology studies. Studies using isotope analysis for tracing water source may be able to parse the use of surface versus deep water within groves and along their margins. This has relevance for understanding how giant sequoias may respond to periods of severe drought, which is a plausible future scenario. Similarly, the rooting behavior of seedlings during the process of establishment may also reveal how smaller trees may respond to periods of drought. Specifically, tracking the progression of root growth into deep water zones would be helpful. Also similarly, the horizontal spread of roots is not well understood. Estimates vary from 30 to 60 meters, but only in one case appear to be based on an actual measurement.
- Basic information related to water balance in natural populations of giant sequoia is not available (Lutz et al. 2010). This information will be necessary for modeling responses of giant sequoia to future climate scenarios.

- The experimental work of Stark (1968b, 1968a), which still provides useful information on giant sequoia germination, should be redone within the context of climate change. Specifically, germination responses to gradients in soil moisture, nutrients, and temperature could shed light on how or where giant sequoia may grow in a changing environment. Some experimental work is underway (T. Dawson, personal communication), but this could be expanded to include gradients of soil type as a treatment. Also important is further study understanding the ecological context of in situ seedling establishment and survival during the initial years following germination. Again, this could be done within the context of a changing climate.
- Following the spatial identification of soil types mentioned above, existing work on soil moisture patterns (e.g. Halpin 1995) can help identify possible refugia or higher elevation areas that might become suitable for giant sequoia.

Active adaptive management experiments

- Encourage fire regime variability by designating groves or grove areas that will be burned using a wide range of frequencies. This will be an important source for judging the success of prescribed burning methods and for altering future burns to facilitate desired regeneration and recruitment (or at least to avoid an absence of regeneration). Diversity in burn severity is also an important treatment of management experiments. Implicit with an active adaptive management approach is long-term monitoring following treatments. Such experimental management and monitoring will help to eventually validate the appropriateness of the assessment we have done here.
- Treatments that aim to build resilience within high-use groves, as was done in the Giant Forest grove, should refine treatments based on observations of past successes, while continuing to take an experimental approach to exploring treatment options. Conducting intensive restorative treatments (such as irrigation or planting) can provide guidance for options for future more wide-spread treatments when interacting stressors create catastrophic impacts.
- Treatment options following extensive high-severity fires within groves are best articulated prior to the fires occurring.
- Fuel reduction treatments throughout the southern Sierra Nevada (both mechanical and fire) can be done with an experimental approach, a primary objective being to assess the outcome of several diverse treatment options for short-term modification of fire behavior, while designing treatments to also assess mid- and long-term impacts on giant sequoia regeneration, recruitment, and persistence.

Literature Cited

Ambrose, A. R., S. C. Sillett, and T. E. Dawson. 2009. Effects of tree height on branch hydraulics, leaf structure and gas exchange in California redwoods. *Plant, Cell, and Environment* 32:743-757.

Anderson, M. A., R. C. Graham, G. J. Alyanakian, and D. Z. Martynn. 1995. Late summer water status of soils and weathered bedrock in a giant sequoia grove. *Soil Science* 160:415-422.

Anderson, R. S. 1994. Paleohistory of a giant sequoia grove: the record from Log Meadow, Sequoia National Park. Pages 49-55 *in* P. S. Aune, editor. Proceedings of the Symposium on Giant Sequoias: Their place in the ecosystem and society. General Technical Report PSW-GTR-151. US Forest Service.

Anderson, R. S., and S. J. Smith. 1994. Paleoclimatic interpretations of meadow sediment and pollen stratigraphies from California. *Geology* 22:723-726.

Aune, P. S., technical coordinator. 1994. Proceedings of the Symposium on Giant Sequoias: Their place in the ecosystem and society. General Technical Report PSW-GTR-151, US Forest Service, Albany, CA..

Axelrod, D. I. 1959. Late Cenozoic evolution of the Sierran bigtree forest. *Evolution* 13:9-23.

Axelrod, D. I. 1986. The sierra redwood (Sequoiadendron) forest: end of a dynasty. *Geophytology* 16:25-36.

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438:303-309.

Biswell, H., H. Buchanan, and R. P. Gibbens. 1966. Ecology of the vegetation of a second-growth sequoia forest. *Ecology* 46:630-634.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: A practical information-theoretic approach, 2nd edition. Springer-Verlag, New York.

Cahill, T. A., J. J. Carroll, D. Campbell, and T. E. Gill. 1996. Air quality. *in* Sierra Nevada Ecosystem Project: final report to Congress, volume II. Assessments and scientific basis for management options. Centers for Water and Wildland Resources, University of California, Davis, California, USA.

Caprio, A. C., L. S. Mutch, T. W. Swetnam, and C. H. Baisan. 1994. Temporal and spatial patterns of giant sequoia radial growth response to a high severity fire in A.D. 1297. Contract report to the California Department of Forestry and Fire Protection, Mountain Home State Forest.

Caprio, A., C. Conover, M. Keifer, and P. Lineback. 1997. Fire management and GIS: a framework for identifying and prioritizing fire planning needs. *in* Proceedings: Fire in California Ecosystems: Integrating Ecology, Prevention, and Management. San Diego, CA.

Certini, G. 2005. Effects of fire on properties of forest soils: a review. *Oecologica* 143:1-10.

Collins, B. M., J. J. Moghaddas, and S. L. Stephens. 2007. Initial changes in a forest structure and understory plant communities following fuel reduction activities in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management* 239:102-111.

DeHayes, D. H., P. G. Schaberg, G. J. Hawley, and G. R. Strimbeck. 1999. Acid rain impacts on calcium nutrition and forest health. *Bioscience* 49:789-800.

Demetry, A. 1995. Regeneration patterns within canopy gaps in a giant-sequoia-mixed conifer forest: Implications for forest restoration. Thesis. Northern Arizona University, Flagstaff, Arizona.

Demetry, A. 1998. A Natural Disturbance Model for the Restoration of Giant Forest Village, Sequoia National Park. Pages No. 13. 142-159 *in* W. R. Keammerer and E. F. Redente, editors. High Altitiude Revegetation Workshop, Fort Colllins, Colorado Water Resources Research Institute.

Demetry, A., W. W. Covington, and D. M. Duriscoe. 1995. Regeneration patterns within canopy gaps in a giant sequoia-mixed conifer forest: Implications for forest restoration. *Bulletin of the Ecological Society of America* 76:62-63.

Demetry, A., and J. Manley. 2001. Ecological Restoration in a Giant Sequoia Grove. *in* D. Harmon, editor. Crossing Boundaries in Park Management: Proceedings of the 11th Conference on Research and Resource Management in Parks and on Public Lands. The George Wright Society, Hancock, Michigan.

Eagar, C., and M. B. Adams, editors. 1992. Ecology and decline of red spruce in the Eastern United States. Springer Verlag, New York, New York.

Ferrell, G. T. 1996. The influence of insect pests and pathogens on Sierra forests. *in* Sierra Nevada Ecosystem Project: final report to Congress, volume II. Assessments and scientific basis for management options. Centers for Water and Wildland Resources, University of California, Davis, California, USA

Fins, L., and W. J. Libby. 1994. Genetics of giant sequoia. Pages 65-68 *in* P. S. Aune, editor. Proceedings of the Symposium on Giant Sequoias: Their place in the ecosystem and society. General Technical Report PSW-GTR-151, U.S. Forest Service. Albany, CA

Ghent, A. W. 1955. A guide for the re-alignment of off-center increment borings. *Forestry Chrnoicle* 31:353-355.

Goforth, B. R., and R. A. Minnich. 2007. Densification, stand-replacement wildfire, and extirpation of mixed conifer forest in Cuyamaca Rancho State Park, southern California. *Forest Ecology & Management* 256:36-45.

Grulke, N. E., P. R. Miller, and D. Scioli. 1996. Response of giant sequoia canopy foliage to elevated concentrations of atmospheric ozone. *Tree Physiology* 16:575-581.

Halpin, P. N. 1995. A cross-scale analysis of environmental gradients and forest pattern in the giant sequoia - mixed conifer forest of the Sierra Nevada. PhD Dissertation. University of Virginia.

Harvey, H. T., H. S. Shellhammer, and R. E. Stecker. 1980. Giant Sequoia Ecology. U.S. Department of the Interior, National Park Service, Washington, DC., USA.

Harvey, T. H., and H. S. Shellhammer. 1991. Survivorship and growth of giant sequoia (*Sequoidendron giganteum* (Lindl.)Buchh.) seedlings after fire. *Madrono* 38:14-20.

Hidalgo, H. G., T. Das, M. D. Dettinger, D. R. Cayan, D. W. Pierce, T. P. Barnett, G. Bala, A. Mirin, A. W. Wood, C. Bonfils, B. D. Santer, and T. Nozawa. 2009. Detection and Attribution of Streamflow Timing Changes to Climate Change in the Western United States. *Journal of Climate* 22:3838–3855.

Hobbs, R. J., and L. F. Huenneke. 1992. Disturbance, diversity, and invasion: Implications for conservation. *Conservation Biology* 6:324-337.

Houghton, J. T., G. J. Jenkins, and J. J. Ephraums. 1990. Climate change: The IPCC assessment. Cambridge University Press, New York.

Huston, M., and T. Smith. 1987. Plant succession: Life history and competition. *The American Naturalist* 130:168-198.

Keeley, J. E., D. Lubin, and C. J. Fotheringham. 2003. Fire and grazing impacts on plant diversity and invasives in the southern Sierra Nevada. *Ecological Applications* 13:1355-1374.

Kilgore, B. M., and D. Taylor. 1979. Fire history of a sequoia-mixed conifer forest. *Ecology* 60:129-142.

Kurz, W. A., C. C. Dymond, G. Stinson, G. J. Rampley, E. T. Neilson1, A. L. Carroll, T. Ebata, and L. Safranyik. 2008. Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452:987-990.

Lambert, S., and T. J. Stohlgren. 1988. Giant Sequoia Mortality in Burned and Unburned Stands Does Prescribed Burning Significantly Affect Mortality Rates. *Journal of Forestry* 86:44-46.

Lawler, J. J., T. H. Tear, C. Pyke, M. R. Shaw, P. Gonzalez, P. Kareiva, L. Hansen, L. Hannah, K. Klausmeyer, A. Aldous, C. Bienz, and S. Pearsall. 2010. Resource management in a changing and uncertain climate. *Frontiers in Ecology and the Environment* 8:35-43.

Libby, W. J. 1986. Genetic variation and early performance of giant sequoia in plantations. Pages 17-18 *in* C. P. Weatherspoon, Y. R. Iwamoto, and D.D. Piirto, technical Coordinators. Proceedings of the workshop on management of giant sequoia. General Technical Report PSW-GTR-95. US Forest Service, Albany, CA

Logan, J. A., and J. A. Powell. 2001. Ghost forests, global warming, and the mountain pine beetle (Coleoptera: Scolytidae). *American Entomologist* 47:160-173.

Lutz, J. A., J. W. van Wagtendonk, and J. F. Franklin. 2010. Climatic water deficit, tree species ranges, and climate change in Yosemite National Park. *Journal of Biogeography* 37:936-950.

Martin, P. H., C. D. Canham, and P. L. Marks. 2009. Why forests appear resistant to exotic plant invasions: intentional introductions, stand dynamics, and the role of shade tolerance. *Frontiers in Ecology* 7:142-149.

Menning, K. M., J. J. Battles, and T. L. Benning. 2007. Quantifying change in distributions: a new departure index that detects, measures and describes change in distributions from population structures, size-classes and other ordered data. *Oecologica* 154:75-84.

Miller, P. R. 1973. Oxidant-induced community change in a mixed conifer forest. Pages 101-117 *in* J. A. Neagle, editor. Air pollution damage to vegetation. American Chemical Society, Washington, D.C.

Miller, P. R. 1996. Biological effects of air pollution in the Sierra Nevada. *in* Sierra Nevada Ecosystem Project: final report to Congress, volume II. Assessments and scientific basis for management options. Centers for Water and Wildland Resources Report no. 37, University of California, Davis, California, USA.

Miller, P. R., N. E. Grulke, and K. W. Stolte. 1994. Air pollution effects on giant sequoia ecosystems. Pages 90-98 *in* P. S. Aune, editor. Proceedings of the symposium on giant sequoias: Their place in the ecosystem and society. General Technical Report PSW-GTR-151, US Forest Service. Albany, CA.

Muir, J. 1876. On the post-glacial history of Sequoia gigantea. *in* Proceedings of the American Association for the Advancement of Science 25:242-253.

Mutch, L. S. 1994. Growth responses of giant sequoia to fire and climate in Sequoia and Kings Canyon National Parks, California. Thesis. University of Arizona, Tucson, Arizona.

Mutch, L. S., and T. W. Swetnam. 1995. Effects of Fire Severity and Climate on Ring-Width Growth of Giant Sequoia After Fire. Pages 6 *in* J. K. M. Brown, Robert W.; Spoon, Charles W.; Wakimoto, and t. C. Ronald H., editors. Symposium on Fire in Wilderness and Park Management: Past Lessons and Future Opportunities, March 30-April 1, 1993. U.S. Department of Agriculture, Forest Service, Intermountain Research Station., Missoula, Montana.

Nelson, C. R., C. B. Halpern, and J. K. Agee. 2008. Thinning and burning result in low-level invasion by nonnative plants but neutral effects on natives. *Ecological Applications* 18:762-770.

Peterson, D. L., and M. J. Arbaugh. 1992. Mixed conifer forests of the Sierra Nevada. Pages 443-459 *in* R.K. Olson, D. Binkley, and M. Bohn, editors. The response of western forests to air pollution. Ecological Studies 97. Springer-Verlag, New York.

Piirto, D. D. 1977. Factors associated with tree failure of giant sequoia. Dissertation. University of California, Berkeley.

Piirto, D. D. 1992. Giant sequoia insect, disease, and ecosystem interactions. Pages 82-89 *in* P. Aune, editor. Giant sequoias: Their place in the ecosystem and society, Visalia, California. General Technical Report PSW-GTR-151. US Forest Service. Albany, CA.

Piirto, D. D., K. L. Piper, and J. R. Parmeter. 1992. Biological and management implications of fire/pathogen interactions in the giant sequoia ecosystem: Part I -- Fire scar/pathogen studies. Final report, National Park Service Cooperative Agreement No. 8000-8-0005.

Piirto, D. D., W. W. Wilcox, J. R. Parmeter, and D. L. Wood. 1984. Causes of uprooting and breakage of specimen giant sequoia trees. University of California, Berkeley, Division of Agriculture and Natural Resources Bulletin 1909.

Powers, R. F., A. D. Scott, F. G. Sanchez, R. A. Voldseth, D. Page-Dumroese, J. D. Elioff, and D. M. Stone. 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. *Forest Ecology and Management* 220:31-50.

Pyne, S. J., P. L. Andrews, and R. D. Laven. 1996. Introduction to Wildland Fire, 2nd edition. John Wiley & Sons, New York.

Rundel, P. W. 1971. Community Structure and Stability in the Giant Sequoia-G Groves of the Sierra-Nevada California. *American Midland Naturalist* 85:478-492.

Rundel, P. W. 1972a. An Annotated Checklist of the Groves of Sequoiadendron Giganteum in the Sierra Nevada, California. *Madrono* 21:319-328.

Rundel, P. W. 1972b. Habitat restriction in Giant Sequoia: the environmental control of grove boundaries. *American Midland Naturalist* 87:81-99.

Shellhammer, H. S., and T. H. Shellhammer. 2006. Giant sequoia (Sequoiadendron giganteum Taxodiaceae) seedling survival and growth in the first four decades following managed fires. *Madrono* 53:342-350.

Sillett, S. C., R. Van Pelt, G. W. Koch, A. R. Ambrose, A. L. Carroll, M. E. Antoine, and B. M. Mifsud. 2010. Increasing wood production through old age in tall trees. *Forest Ecology and Management* 259:976-994.

Stark, N. 1968a. The environmental tolerance of the seedling stage of sequoiadendron giganteum. *The American Midland Naturalist* 80:84-95.

Stark, N. 1968b. Seed Ecology of Sequoiadendron-Giganteum-G. *Madrono* 19:267-277.

Stephens, S. L., D. J. Dulitz, and R. E. Martin. 1999. Giant sequoia regeneration in group selection openings in the southern Sierra Nevada. *Forest Ecology and Management* 120:89-95.

Stephenson, N. L. 1988. Climatic control of vegetation distribution: The role of the water balance with examples from North America and Sequoia National Park, California. Dissertation, Cornell University, Ithica, New York.

Stephenson, N. L. 1990. Climatic Control of Vegetation Distribution: The Role of the Water Balance. *The American Naturalist* 135:649-670.

Stephenson, N. L. 1994. Long-term dynamics of giant sequoia populations: Implications for managing a pioneer species. General Technical Report PSW-GTR-151:56-63.

Stephenson, N. L. 1996. Ecology and management of giant sequoia groves. *in* Sierra Nevada Ecosystem Project: final report to Congress, volume II. Assessments and scientific basis for management options. Centers for Water and Wildland Resources Report no. 37, University of California, Davis, California, USA

Stephenson, N. L. 1999. Reference conditions for giant sequoia forest restoration: Structure, process, and precision. *Ecological Applications* 9:1253-1265.

Stephenson, N. L., and A. Demetry. 1995. Estimating ages of giant sequoias. *Canadian Journal of Forest Research* 25:223-233.

Stohlgren, T. J. 1991. Size distributions and spatial patterns of giant sequoia (Sequoiadendron giganteum) in Sequoia and Kings Canyon National Parks, California. National Park Service Technical Report No. 43. Cooperative National Park Resources Studies Unit, University of California, Davis.

Stohlgren, T. J. 1992. Resilience of a heavily logged grove of giant sequoia (Sequoiadendron giganteum) in Kings Canyon National Park, California. *Forest Ecology and Management* 54:115-140.

Sutherland, S., and C. R. Nelson. 2010. Nonnative Plant Response to Silvicultural Treatments: A Model Based on Disturbance, Propagule Pressure, and Competitive Abilities. *Western Journal of Applied Forestry* 25:27-33.

Swetnam, T. W. 1993. Fire history and climate change in giant sequoia groves. *Science* (Washington D C) 262:885-889.

Swetnam, T. W., C. H. Baisan, A. Caprio, P. M. Brown, R. Touchan, R. S. Anderson, and D. J. Hallett. 2009. Multi-millennial fire history of the Giant Forest, Sequoia National Park, California, USA. *Fire Ecology* 5:120-150.

van Mantgem, P. J., N. L. Stephenson, E. Knapp, J. J. Battles, and J. E. Keeley. In Press. Long-term effects of prescribed fire on mixed conifer forest structure in the Sierra Nevada, California. *Forest Ecology and Management.*

van Wagtendonk, J. W., J.A. Lutz, and J.F. Franklin. 2007. Fire regime attributes of wildland fires in Yosemite National Park, USA. *Fire Ecology* 3:34-52

Walters, C. J., and C. S. Holling. 1990. Large scale management experiments and learning by doing. *Ecology* 71:2060-2068.

Webster, K. M., and C. B. Halpern. 2010. Long-term vegetation responses to reintroduction and repeated use of fire in mixed-conifer forests of the Sierra Nevada. *Ecosphere* 1:1-27.

Westerling, A. L., H. G. Hidalgo, D. R. Craven, and T. W. Swetnam. 2006. Warming and earlier spring increase Western U.S. forest wildfire activity. *Science* 313:940-943.

Willard, D. 2000. A Guide to the Sequoia Groves of California. Yosemite Association.

York, R. A. 2006. Experimental insights into gap phase succession of mixed conifer tree species of the Sierra Nevada, California. Dissertation. UC Berkeley, CA.

York, R. A., J. J. Battles, A. E. Eschtruth, and F. G. Schurr. 2011. Giant sequoia (Sequoiadendron giganteum) regeneration in experimental canopy gaps. *Restoration Ecology* 19:14-23.

York, R. A., J. J. Battles, and R. C. Heald. 2003. Edge effects in mixed conifer group selection openings: Tree height response to resource gradients. *Forest Ecology and Management* 179:107-121.

York, R. A., J. J. Battles, and R. C. Heald. 2006. Release potential of giant sequoia following heavy suppression: 20-year results. *Forest Ecology and Management* 234:136-142.

York, R. A., D. Fuchs, J. J. Battles, and S. L. Stephens. 2010. Radial growth responses to gap creation in large, old Sequoiadendron giganteum. *Applied Vegetation Science* 13:498-509.

York, R. A., Z. Thomas, and J. Restaino. 2009. Influence of Ash Substrate Proximity on Growth and Survival of Planted Mixed-Conifer Seedlings. *Western Journal of Applied Forestry* 24:117-123.

Youngblood, A. 2010. Thinning and Burning in Dry Coniferous Forests of the Western United States: Effectiveness in Altering Diameter Distributions. *Forest Science* 56:46-59.

Subappendix 1: Methods for the developing the hypothetical stationary age distribution for giant sequoia[1]

Since human life spans are far too short to observe a single sequoia cohort from birth to death, the only reasonable way to understand sequoia population dynamics is to use quantitative demographic models to determine the relative balance between birth rates and death rates compounded over centuries and millennia. Here we present the results of the first such demographic model for giant sequoia. Further, we compare the stationary age distribution with actual measurements of age structure in areas that had been burned with prescribed fire, along with areas that had not been burned within the last century. The utility of the model is demonstrated by evaluating the relative degree to which burning (and not burning) promoted the basic shape of a sustainable age structure.

General approach

We compared actual sequoia population age structures, determined in plots with different recent fire histories, with hypothetical age structures derived from simple models driven by meaningful assumptions. Under ideal conditions we would model sequoia population age structures using dynamic matrix models incorporating age- or stage- specific natality and survival rates. Relatively reliable age- and stage-specific survival data were available from the literature for sequoias both in the presence and absence of fire (Lambert and Stohlgren 1988, Harvey and Shellhammer 1991). However, the available data related to sequoia natality (seed production by tree age or stage; seed release relative to tree age, stage, and fire intensity; and seed survival until germination) were too limited to be used realistically in models. We therefore made a very simple assumption about natality: namely, that the overall population rate of seedling establishment was either zero (without fire) or a constant (with fire). However simplistic this assumption, it allowed us to derive two useful hypothetical sequoia population age structures: (1) the age structure expected in 1990 assuming that fire had never been suppressed and that sequoia population natality rates and age-specific survival rates were constant over the last three millennia (i.e. a stationary age distribution); and (2) the age structure expected in 1990 if the conditions described in (1) were maintained until natality dropped to zero and age-specific survival rates changed to new constant values, appropriate to sequoias not subjected to periodic fire, following 1870 (the approximate date of the last major fires in the sequoia groves examined here; (Swetnam 1993)). These hypothetical age structures would serve as yardsticks for interpreting the actual age structures of sequoia populations in 1990, which we determined by increment boring. We chose a temporal model resolution of one decade -- roughly of the same order as average pre-Euroamerican fire return intervals (Kilgore and Taylor 1979, Swetnam 1993), and short enough to capture rapid changes in age-specific survival rates of sequoia seedlings. We note here that the first assumption (constant natality and survival rates over the past three millennia) is certainly false for giant sequoia as well as any other tree species. The utility of the assumption is in providing a reference for identifying age classes that have large-scale departures from a stationary population. Ostensibly, potential reasons for departures can then be identified.

---

[1] Adapted from a draft manuscript by Nathan L. Stephenson

Estimating age-specific survival rate

We used published data to estimate age-specific survival rates for sequoias in the presence and absence of fire. Survival rates for each of the first two (fire-free) decades of life were calculated from data presented by Harvey and Shellhammer (1991). For 20 years Harvey and Shellhammer monitored the germination and survival of more than 7,000 individual sequoia seedlings following prescribed surface fires conducted in 1965 and 1966. We calculated survival rates relative to established (one-year-old) seedlings, thereby excluding the massive mortality that seedlings suffer during their first summer following germination. The second decade's survival rates were calculated by linearly extrapolating one to three years, depending on replicate, beyond Harvey and Shellhammer's (1991) published annual survival values. After excluding Harvey and Shellhammer's unburned ("scarified") treatments, we averaged survival rates from all remaining replicates of their other three treatments (burn piles, surface burns, and surface burns with soil scarification) to arrive at a single summary survival rate for each of the first two decades of seedling life.

These survival rates were assigned both to seedlings in environments subject to periodic fire and those in environments protected from fire. The assumption that similar survival rates apply to both populations is reasonable; our personal observations of prescribed fires in sequoia groves suggest that the sites of future sequoia recruitment -- canopy gaps created by an earlier fire -- usually require more than one or two decades to develop surface fuels with enough continuity to carry a fire throughout most of the gap.

nlike the seedling survival rates just described, age-specific survival rates for mature sequoias had to be calculated from size-specific rates. From 1964 to 1986 Lambert and Stohlgren (1988) recorded the survival of 1,135 mature sequoias in four size classes: <0.305 m (< 1 ft), 0.305 to 1.981 m (1 to 6.5 ft), 1.981 to 3.810 m (6.5 to 12.5 ft), and >3.810 m (> 12.5 ft). To convert from size-specific to age-specific survival rates, we first determined the median tree age in 1975 (the mid-point of the 1964 to 1986 period) for each of Lambert and Stohlgren's size classes, using age and size data from 409 sequoias we had cored for age determination in our two Giant Forest plots (described below; this is the same sequoia grove in which Lambert and Stohlgren's survival rates were determined). The overall survival rate within each size class over the period of Lambert and Stohlgren's study (standardized to decadal survival rate) was then assigned to its respective median decadal age class. During the 22-yr study period about one-half of the trees in all size classes experienced a prescribed surface fire; survival rates were calculated separately for these treatments. Unlike whole groves, which experienced shorter fire return intervals, 22 years probably falls within the normal range of pre-Euroamerican fire return intervals for individual trees (Caprio, personal observation).

The combined seedling and mature tree data thus provided survival rates for six decade-long age classes, both in the presence and absence of fire. With two exceptions, survival rates for all other age classes were estimated by linear interpolation between these values (or by linear extrapolation, for age classes greater than 1690 to 1700 yrs -- the median age of Lambert and Stohlgren's largest size class). The first exception was for survival rates interpolated between the 100 - 110 year age class (corresponding to the median age of the <0.305 m dbh size class) and the 230 - 240 year age class (corresponding to the median age of the 0.305 - 1.981 m size class). Between these ages survival rates began to approach 1 asymptotically; we therefore interpolated

survival rates using a simple asymptotic equation of the form $y = 1 - b\,(e^{-cx})$, where y = probability of surviving the next decade and x = decade.

The second exception was for interpolating survival rates within the 1.981 to 3.810 m dbh size class. Both in the presence and absence of fire, survival rates reached their maximum in this size class. If we were to assign the size class' overall survival rate only to its median decade-long age class, then linearly interpolate to the median ages of the adjacent size classes, we would underestimate survival rates for the 1.981 to 3.810 m size class as a whole. Instead, we assigned the size class' overall survival rate to all decade-long age classes within the size class. This required that we use the age and size data from our two Giant Forest plots to determine the sequoia ages best corresponding to the endpoints of the 1.981 to 3.810 m dbh size class: 440 and 1240 years.

Calculating hypothetical age structures

The stationary age distribution in presence of fire was calculated as

$$[1] \qquad n_a = c \prod_{d=1}^{a} p_d$$

where n_a is the number of sequoias in decadal age class a, p_d is the probability of a sequoia surviving from decade d to decade $d + 1$ in the presence of fire (calculated as described the previous subsection), and c is a constant chosen as will be discussed below.

Decadal age classes were converted to calendar decades, with the most recent ending in AD 1990. For clarity of presentation and comparison with actual age structures determined by increment boring, numbers of individuals were then lumped by calendar century.

The following line of reasoning motivated our selection of constants b and c. If we were to sample the age structure of a natural population of sequoias whose dynamics we could model precisely, we would still expect the measured age distribution to deviate from the modeled age distribution. These deviations might result from small sample sizes, errors in age determinations, or both. For about half of all age classes we therefore would expect the measured numbers of individuals to be greater than the modeled numbers of individuals; the reverse would hold for the remaining age classes. Assuming that the direction of measurement error did not vary systematically with age class, there should be no distinct pattern as to which measured age classes have more or fewer individuals than the modeled age classes. Thus, to use our modeled age distributions (equation 1) as yardsticks for judging our measured age distributions (see below), we chose values of b and c that scaled the modeled age distributions in such a way that equal numbers of measured age classes contain more or fewer individuals than the modeled age classes.

Selection of the age determination plots

Four criteria were used to select locations for sequoia age determination plots: (1) availability of detailed, millennial-length fire histories from the immediate areas (Swetnam 1993), (2) minimal human-induced changes in stand structure other than those resulting from changing fire regimes, (3) geographic dispersion of the plots, and (4) both recently burned and unburned plots needed to be represented. Four plots were selected: two in Giant Forest (Sequoia National Park), and one each in Atwell Grove (Sequoia National Park) and Mariposa Grove (Yosemite National Park). Plots were rectangular, oriented toward the cardinal directions, and of variable size (6 to 18 ha; Table 1); plot sizes were increased until 150 to 200 living sequoias were encountered and cored in each. The Central Giant Forest plot, earmarked for detailed spatial analysis in the future, was expanded until 250 sequoias were included.

In all plots, sequoias were a numerically minor component of mixed conifer forest dominated by *Abies concolor*, with lesser amounts of *Pinus lambertiana*. The Central Giant Forest plot also contained *A. magnifica* as a codominant with *A. concolor*.

Table 1. Sources of cores used to determine giant sequoia ages

Plot	Location (UTM zone 11)	Size (ha)	Number of sequoias cored	Elevation (m)	Average slope steepness	Dominant aspect	Year of last known fire
Mariposa		6.0	178	2250	8°	S	1970's (prescribed)
Central Giant Forest	4048 N 343 E	8.7	250	2110	4°	--	1982 (prescribed)
Peripheral Giant Forest	4047 N 345 E	17.9	159	2160	12°	SW	1863*
Atwell	4037 N 350 E	7.5	155	2100	27°	SE	1875

Determining sequoia ages

Different methods were used to determine the ages of (1) young seedling sequoias, (2) non-seedling sequoias <~2 m dbh, (3) sequoias >~2 m dbh, and (4) sequoias that presented special problems. Two of the four study plots had recently been prescribed burned (Table 1; Mariposa in the early 1970s; central Giant Forest in 1982) and therefore had sequoia seedlings too small to be cored for age determination. These post-burn sequoia seedlings, which had slender, flexible main stems, were very easy to distinguish from pre-burn sequoias, which had thick, woody main stems. Reference to a complete pre-burn map of sequoias confirmed that we were able to distinguish precisely between post-burn seedlings and sequoias that were present before the prescribed burns. We assumed that all seedlings germinated within one to three years of the prescribed burns in each of the two plots; this assumption is supported by our personal observations of patterns of seedling germination following fire and by our ring counts on a subsample of seedlings of widely differing sizes, cut near ground level in the central Giant Forest plot. All of the seedlings in each of the two burned plots were counted systematically.

Approximately seventy-two percent of the sequoias that we cored for age determination had small enough bole diameters (~2 m or less) to be cored all the way to the pith region, providing an accurate age estimate from ring counts. All core surfaces were prepared with 400-grit sandpaper and rings were counted under a dissecting microscope. If a core bypassed the pith, the number of years missed to the pith was estimated by first estimating the distance to the pith (Ghent 1955) then dividing by the average ring width of the innermost 10 rings. Whenever possible, cores were taken at ground level. For cores taken from above ground level, the number of years missed to the height of the core was estimated by multiplying the height of the core above ground level (in m) by $178x^{-0.957}$, where x is the cumulative width (in mm) of the innermost 10 rings of the core. This empirical factor, which scales height growth to radial growth, was derived from ring measurements of 41 sequoias which were cored to the pith region both near ground level and near breast height.

Our increment borers were too short to reach the pith region of 28% of the sequoias we cored (those >~2m in diameter). We estimated the ages of these sequoias by first taking two long cores from opposite sides of each tree. We then determined the tree's radial growth rate from the cores and applied Stephenson and Demetry's (1995) age estimation equations. Tests of these equations on 231 sequoia stumps of known ages have demonstrated that for stumps up to 3200 years old and 6.5 m in diameter, actual ages ranged from -7% to +9% of estimated ages half of the time, and from -24% to +20% of estimated ages 95% of the time (Stephenson and Demetry 1995). The age estimates for very large sequoias we report here might be somewhat less precise than those reported by Stephenson and Demetry, for reasons that they discussed.

Fifteen non-seedling sequoias had boles that were so narrow at ground level (<4 cm diameter) that extracting cores might have damaged them. We conservatively assumed that these sequoias germinated in the 1900s, though we have found even smaller sequoias that clearly (by microscopic ring count) germinated in the 1800s. Ten large sequoias in the Atwell plot had been cut in the early 1900s. Survival rates of large sequoias (see above) suggest that 8 or 9 of these trees probably would have lived to the present, had they not been cut. We therefore determined the ages of the 8 stumps that were in good enough condition to provide accurate ring counts, and included them in our sample of living sequoias.

Subappendix 2: – Spatial analysis data and maps

Tables

Table 1. Groves that were spatially identified and analyzed. Grove designations were derived from the GIS databases provided by SEKI and GSNM.

Grove	Agency	ha	% of grove area	Size group[1]
Abbot	GSNM	3	0.00%	S
Agnew	GSNM	16	0.10%	S
Alder Creek	GSNM	317	2.10%	L
Atwell	NPS	542	3.50%	L
Bearskin	GSNM	34	0.20%	S
Belknap Complex	GSNM	996	6.50%	L
Big Baldy South	GSNM	15	0.10%	S
Big Springs	NPS	1	0.00%	S
Big Stump	NPS	212	1.40%	L
Black Mountain	GSNM	866	5.70%	L
Board Camp	NPS	40	0.30%	S
Burro Creek	GSNM	121	0.80%	M
Cahoon	NPS	13	0.10%	S
Castle Creek	NPS	170	1.10%	M
Cedar Flat	NPS	13	0.10%	S
Cherry Gap	GSNM	41	0.30%	S
Clough Cave	NPS	1	0.00%	S
Coffeepot Canyon	NPS	10	0.10%	S
Converse Basin	GSNM	1498	9.80%	L
Cunningham	GSNM	3	0.00%	S
Deer Creek	GSNM	21	0.10%	S
Deer Meadow	GSNM	68	0.40%	M
Dennison	NPS	8	0.10%	S
Devils Canyon	NPS	6	0.00%	S
Dillonwood	NPS/GSNM	683	4.50%	L
Douglass	NPS	1	0.00%	S
East Fork	NPS	397	2.60%	L
Eden Creek	NPS	290	1.90%	L
Evans Complex	GSNM	1375	9.00%	L
Forgotten	NPS	2	0.00%	S
Freeman	GSNM	580	3.80%	L

1S = Small grove (0-44 ha), M = Medium grove (44-146 ha), L = Large grove (176+ ha)

Table 1. Groves that were spatially identified and analyzed. Grove designations were derived from the GIS databases provided by SEKI and GSNM (continued).

Grove	Agency	ha	% of grove area	Size group[1]
Garfield	NPS	624	4.10%	L
Giant Forest	NPS	935	6.10%	L
Granite Creek	NPS	1	0.00%	S
Grant	NPS	163	1.10%	M
Homers Nose	NPS	94	0.60%	M
Horse Creek	NPS	44	0.30%	S
Indian Basin	GSNM	87	0.60%	M
Landslide	GSNM	42	0.30%	S
Little Redwood Meadow	NPS	19	0.10%	S
Long Meadow	GSNM	138	0.90%	M
Lost	NPS	21	0.10%	S
Lower Horse Creek	NPS	3	0.00%	S
Maggie Mountain	GSNM	29	0.20%	S
Middle Tule	GSNM	256	1.70%	L
Monarch	GSNM	28	0.20%	S
Mt. Home	GSNM/CDF	1624	10.60%	L
Muir	NPS	154	1.00%	M
New Oriole Lake	NPS	15	0.10%	S
Oriole Lake	NPS	99	0.70%	M
Packsaddle	GSNM	137	0.90%	M
Peyrone	GSNM	176	1.20%	M
Pine Ridge	NPS	29	0.20%	S
Putnam-Francis	NPS	< 1	0.00%	S
Red Hill	GSNM	219	1.40%	L
Redwood Creek	NPS	42	0.30%	S
Redwood Meadow	NPS	147	1.00%	M
Redwood Mountain	NPS/GSNM	1466	9.60%	L
Sequoia Creek	NPS	14	0.10%	S
Silver Creek	GSNM	78	0.50%	M
Skagway	NPS	35	0.20%	S
South Fork	NPS	167	1.10%	M
South Peyrone	GSNM	19	0.10%	S
Squirrel Creek	NPS	< 1	0.00%	S
Starvation Complex	GSNM	15	0.10%	S

1S = Small grove (0-44 ha), M = Medium grove (44-146 ha), L = Large grove (176+ ha)

Table 1. Groves that were spatially identified and analyzed. Grove designations were derived from the GIS databases provided by SEKI and GSNM (continued).

Surprise	NPS	15	0.10%	S
Suwanee	NPS	42	0.30%	S
Upper Tule	GSNM	9	0.10%	S
West Redwood Mountain	GSNM	1	0.00%	S
Wishon	GSNM	< 1	0.00%	S

[1]S = Small grove (0-44 ha), M = Medium grove (44-146 ha), L = Large grove (176+ ha)

Table 2. Ranked FRID index for groves by size class. **Lower FRID values indicate a longer time since fire occurrence.** 1 = Extreme departure (greater than 5 maximum return intervals missed), 2 = High departure (between 2 and 5 intervals missed), 3 = Moderate departure (between 0 and 2 intervals missed), 4 = low departure (less than 0 intervals missed). **Bold text** indicates an integrity condition of "good"; *italics text* indicates an integrity condition of "moderate"; normal text indicates an integrity condition of "poor."

Large groves		**Medium groves**		**Small groves**	
Grove	**FRID index**	**Grove**	**FRID index**	**Grove**	**FRID index**
Freeman	1.0	Burro Creek	1.0	Abbot	1.0
Red Hill	1.1	Oriole Lake	1.0	Bearskin	1.0
Dillonwood	1.1	Homers Nose	1.1	Cunningham	1.0
Middle Tule	1.1	Packsaddle	1.1	Deer Creek	1.0
Mt. Home	1.1	Deer Meadow	1.2	Douglass	1.0
Alder Creek	1.1	Indian Basin	1.2	Forgotten	1.0
Belknap Complex	1.2	Silver Creek	1.2	Monarch	1.0
Eden Creek	1.2	Long Meadow	1.3	Squirrel Creek	1.0
Evans Complex	1.2	Peyrone	1.4	Wishon	1.0
Big Stump	1.3	Muir	1.5	Upper Tule	1.0
Black Mountain	1.6	South Fork	1.6	Lower Horse Creek	1.0
Garfield	2.0	Redwood Meadow	1.7	Board Camp	1.0
Converse Basin	2.0	Grant	2.2	Big Baldy South	1.0
Redwood Mountain	2.2	Castle Creek	3.1	Landslide	1.0
Giant Forest	3.0			Coffeepot Canyon	1.1
East Fork	3.1			South Peyrone	1.1
Atwell	3.9			Granite Creek	1.1
				Cahoon	1.1
				Little Redwood Meadow	1.1
				Starvation Complex	1.2

Table 2. Ranked FRID index for groves by size class. **Lower FRID values indicate a longer time since fire occurrence.** 1 = Extreme departure (greater than 5 maximum return intervals missed), 2 = High departure (between 2 and 5 intervals missed), 3 = Moderate departure (between 0 and 2 intervals missed), 4 = low departure (less than 0 intervals missed). **Bold text** indicates an integrity condition of "good"; *italics text* indicates an integrity condition of "moderate"; normal text indicates an integrity condition of "poor " (continued).

Large groves		**Medium groves**		**Small groves**	
Grove	**FRID index**	**Grove**	**FRID index**	**Grove**	**FRID index**
				Agnew	1.2
				Dennison	1.2
				West Redwood Mountain	1.2
				Devils Canyon	1.2
				Maggie Mountain	1.3
				Lost	1.4
				Cedar Flat	1.4
				Surprise	1.6
				Cherry Gap	1.7
				New Oriole Lake	1.9
				Horse Creek	2.0
				Pine Ridge	2.0
				Putnam-Francis	2.0
				Skagway	2.2
				Big Springs	2.3
				Clough Cave	2.4
				Suwanee	3.0
				Sequoia Creek	3.7
				Redwood Creek	3.9

Table 3. Groves ranked by the portion of grove area below 1600 m, which is a broad generalization of the snow-dominated elevation threshold (Appendix 7).

Large groves		**Medium groves**		**Small groves**	
Grove	**Portion below 1600 m**	**Grove**	**Portion below 1600 m**	**Grove**	**Portion below 1600 m**
Belknap Complex	12%	Silver Creek	19%	Big Springs	100%
Redwood Mountain	9%	South Fork	7%	Clough Cave	100%
Dillonwood	7%	Castle Creek	6%	Putnam-Francis	100%
Garfield	4%	Peyrone	1%	Squirrel Creek	100%

Table 3. Groves ranked by the portion of grove area below 1600 m, which is a broad generalization of the snow-dominated elevation threshold (Appendix 7) (continued).

Large groves		Medium groves		Small groves	
Grove	**Portion below 1600 m**	**Grove**	**Portion below 1600 m**	**Grove**	**Portion below 1600 m**
Black Mountain	3%	Burro Creek	0%	West Redwood Mountain	100%
Mt. Home	2%	Deer Meadow	0%	Wishon	100%
Alder Creek	1%	Grant	0%	Pine Ridge	66%
Atwell	0%	Homers Nose	0%	Cedar Flat	45%
Big Stump	0%	Indian Basin	0%	Starvation Complex	35%
Converse Basin	0%	Long Meadow	0%	Deer Creek	14%
East Fork	0%	Muir	0%	Monarch	10%
Eden Creek	0%	Oriole Lake	0%	Lower Horse Creek	9%
Evans Complex	0%	Packsaddle	0%	Abbot	0%
Freeman	0%	Redwood Meadow	0%	Agnew	0%
Giant Forest	0%			Bearskin	0%
Middle Tule	0%			Big Baldy South	0%
Red Hill	0%			Board Camp	0%
				Cahoon	0%
				Cherry Gap	0%
				Coffeepot Canyon	0%
				Cunningham	0%
				Dennison	0%
				Devils Canyon	0%
				Douglass	0%
				Forgotten	0%
				Granite Creek	0%
				Horse Creek	0%
				Landslide	0%
				Little Redwood Meadow	0%
				Lost	0%
				Maggie Mountain	0%
				New Oriole Lake	0%
				Redwood Creek	0%
				Sequoia Creek	0%
				Skagway	0%
				South Peyrone	0%

Table 3. Groves ranked by the portion of grove area below 1600 m, which is a broad generalization of the snow-dominated elevation threshold (Appendix 7) (continued).

Large groves		Medium groves		Small groves	
Grove	**Portion below 1600 m**	**Grove**	**Portion below 1600 m**	**Grove**	**Portion below 1600 m**
				Surprise	0%
				Suwanee	0%
				Upper Tule	0%

Table 4. Groves ranked by interpolated ozone concentration (monthly averages) for the years 2006-2008. See Appendix 2 for details about the source of the data.

Large groves		Medium groves		Small groves	
Grove	**Ozone concentration (ppb)**	**Grove**	**Ozone concentration (ppb)**	**Grove**	**Ozone concentration (ppb)**
Converse Basin	56	Peyrone	56	Dennison	58
Mt. Home	55	Grant	54	Devils Canyon	58
Garfield	54	Long Meadow	54	Forgotten	58
Redwood Mountain	54	Packsaddle	54	South Peyrone	58
Big Stump	53	Burro Creek	53	Cedar Flat	56
Dillonwood	53	Indian Basin	53	Coffeepot Canyon	56
Eden Creek	53	Muir	53	Cherry Gap	55
Black Mountain	52	South Fork	53	Clough Cave	55
Alder Creek	51	Castle Creek	52	Putnam-Francis	55
Giant Forest	51	Oriole Lake	51	Skagway	55
Middle Tule	51	Silver Creek	51	Suwanee	55
Red Hill	51	Homers Nose	49	Cahoon	54
Evans Complex	50	Deer Meadow	47	Horse Creek	54
Freeman	49	Redwood Meadow	45	Landslide	54
Belknap Complex	48			Lower Horse Creek	54
Atwell	46			Pine Ridge	54
East Fork	44			Abbot	53
				Sequoia Creek	53
				West Redwood Mountain	53
				Big Baldy South	52

Table 4. Groves ranked by interpolated ozone concentration (monthly averages) for the years 2006-2008. See Appendix 2 for details about the source of the data (continued).

Large groves		Medium groves		Small groves	
Grove	**Ozone concentration (ppb)**	**Grove**	**Ozone concentration (ppb)**	**Grove**	**Ozone concentration (ppb)**
				Big Springs	52
				Board Camp	52
				Deer Creek	52
				Starvation Complex	52
				Bearskin	51
				Cunningham	51
				Douglass	51
				Upper Tule	51
				Wishon	51
				Maggie Mountain	50
				Squirrel Creek	50
				Lost	49
				New Oriole Lake	49
				Surprise	49
				Agnew	48
				Granite Creek	48
				Monarch	48
				Redwood Creek	47
				Little Redwood Meadow	41

Table 5. Groves ranked by average interpolated precipitation for the years 1971-2000, as indicated by PRISM data.

Large groves		Medium groves		Small groves	
Grove	**Mean ppt (cm)**	**Grove**	**Mean ppt (cm)**	**Grove**	**Mean ppt (cm)**
Freeman	84	Packsaddle	92	Cunningham	69
Converse Basin	101	Long Meadow	94	Deer Creek	89
Big Stump	102	Peyrone	99	Starvation Complex	90
East Fork	103	Grant	100	Clough Cave	92
Evans Complex	103	Indian Basin	101	Putnam-Francis	93
Black Mountain	104	Silver Creek	106	South Peyrone	97
Red Hill	104	South Fork	106	Wishon	98

Table 5. Groves ranked by average interpolated precipitation for the years 1971-2000, as indicated by PRISM data (continued).

Large groves		Medium groves		Small groves	
Grove	**Mean ppt (cm)**	**Grove**	**Mean ppt (cm)**	**Grove**	**Mean ppt (cm)**
Redwood Mountain	104	Redwood Meadow	108	Monarch	99
Mt. Home	105	Homers Nose	109	Sequoia Creek	101
Belknap Complex	106	Castle Creek	110	Abbot	102
Alder Creek	109	Deer Meadow	110	Big Springs	102
Eden Creek	109	Muir	110	Cedar Flat	102
Atwell	110	Oriole Lake	110	West Redwood Mountain	102
Dillonwood	110	Burro Creek	112	Big Baldy South	103
Garfield	111			New Oriole Lake	103
Middle Tule	112			Squirrel Creek	103
Giant Forest	114			Devils Canyon	104
				Forgotten	104
				Horse Creek	104
				Pine Ridge	104
				Cahoon	105
				Cherry Gap	105
				Little Redwood Meadow	105
				Lower Horse Creek	105
				Bearskin	106
				Surprise	106
				Board Camp	107
				Dennison	107
				Agnew	108
				Coffeepot Canyon	108
				Granite Creek	108
				Redwood Creek	109
				Skagway	109
				Suwanee	110
				Lost	112
				Landslide	113
				Maggie Mountain	113
				Upper Tule	113
				Douglass	115

Table 6. Interpolated minimum and maximum temperature by grove (ranked by highest maximum) for the years 1971 through 2000, as indicated by PRISM data.

Large groves			Medium groves			Small groves		
Grove	**Min**	**max**	**Grove**	**Min**	**Max**	**Grove**	**Min**	**Max**
Belknap Complex	3	17	Silver Creek	3	17	Clough Cave	8	21
Freeman	1	17	Castle Creek	4	16	Putnam-Francis	6	19
Black Mountain	5	16	Peyrone	3	16	Wishon	6	19
Big Stump	2	15	Redwood Meadow	3	16	Big Springs	5	18
Dillonwood	3	15	Grant	2	15	Cunningham	4	18
Mt. Home	4	15	Indian Basin	4	15	Lower Horse Creek	4	18
Red Hill	3	15	Long Meadow	3	15	West Redwood Mountain	5	18
Redwood Mountain	2	15	Packsaddle	3	15	Cedar Flat	4	17
Alder Creek	3	14	South Fork	1	15	Squirrel Creek	4	17
Atwell	2	14	Burro Creek	2	14	Granite Creek	2	16
Converse Basin	5	14	Homers Nose	3	14	Pine Ridge	4	16
East Fork	0	14	Muir	1	14	Starvation Complex	4	16
Eden Creek	3	14	Oriole Lake	4	14	Abbot	3	15
Evans Complex	2	14	Deer Meadow	0	13	Big Baldy South	3	15
Garfield	2	14				Coffeepot Canyon	4	15
Middle Tule	2	14				Deer Creek	3	15
Giant Forest	3	13				Monarch	2	15
						New Oriole Lake	3	15
						Redwood Creek	2	15
						Sequoia Creek	2	15
						South Peyrone	3	15
						Bearskin	0	14
						Board Camp	0	14
						Cahoon	1	14
						Cherry Gap	4	14
						Dennison	4	14
						Devils Canyon	4	14
						Forgotten	4	14
						Horse Creek	0	14
						Maggie Mountain	1	14
						Surprise	4	14

Table 6. Interpolated minimum and maximum temperature by grove (ranked by highest maximum) for the years 1971 through 2000, as indicated by PRISM data (continued).

Large groves			Medium groves			Small groves		
Grove	**Min**	**max**	**Grove**	**Min**	**Max**	**Grove**	**Min**	**Max**
						Suwanee	2	14
						Agnew	1	13
						Landslide	0	13
						Little Redwood Meadow	-1	13
						Lost	0	13
						Skagway	2	13
						Upper Tule	2	13
						Douglass	3	12

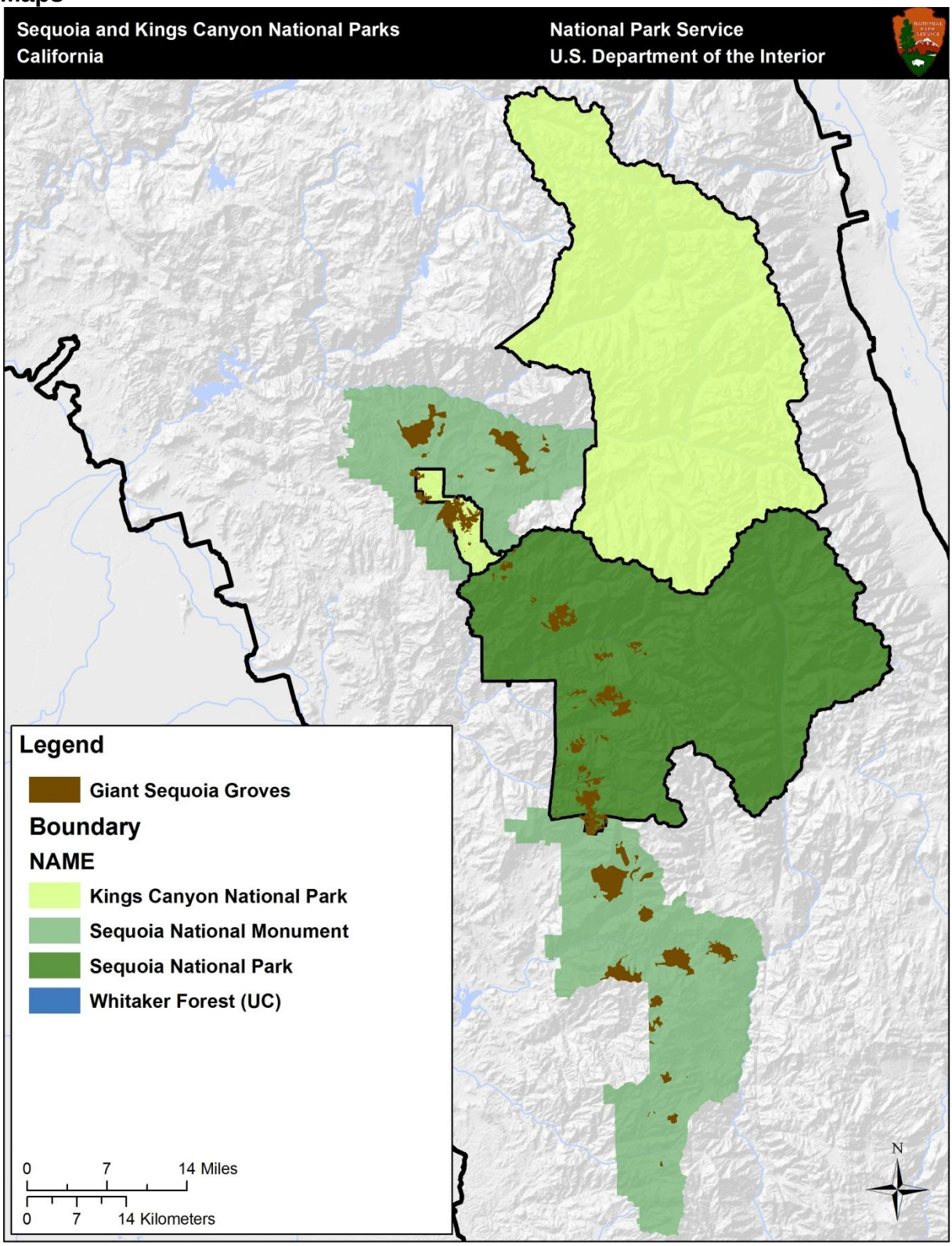
Table 7. Groves ranked by estimated water deficit for the years 1971 through 2000. Note that inferences of climatic water deficit with respect to giant sequoia impacts are limited until more information describing soils, underground hydrology, and giant sequoia physiology is available.

Large groves		Medium groves		Small groves	
Grove	**Mean ppt (cm)**	**Grove**	**Mean ppt (cm)**	**Grove**	**Mean ppt (cm)**
Big Stump	509	Grant	630	Wishon	646
Redwood Mountain	484	Packsaddle	576	Big Springs	613
Belknap Complex	416	Long Meadow	561	Abbot	611
Middle Tule	414	Silver Creek	486	Pine Ridge	607
Red Hill	401	Burro Creek	426	Deer Creek	603
Garfield	385	Homers Nose	422	Cunningham	598
Giant Forest	369	Muir	422	Starvation Complex	567
Evans Complex	364	Peyrone	419	Bearskin	548
Converse Basin	360	South Fork	413	Putnam-Francis	542
Dillonwood	355	Castle Creek	366	Clough Cave	538
Eden Creek	338	Indian Basin	363	Cherry Gap	534
East Fork	329	Deer Meadow	288	Cedar Flat	500
Mt. Home	284	Redwood Meadow	288	Skagway	488
Black Mountain	280	Oriole Lake	267	Suwanee	486
Freeman	263			West Redwood Mountain	479
Alder Creek	238			Lost	478
Atwell	232			Lower Horse Creek	470
				Big Baldy South	462

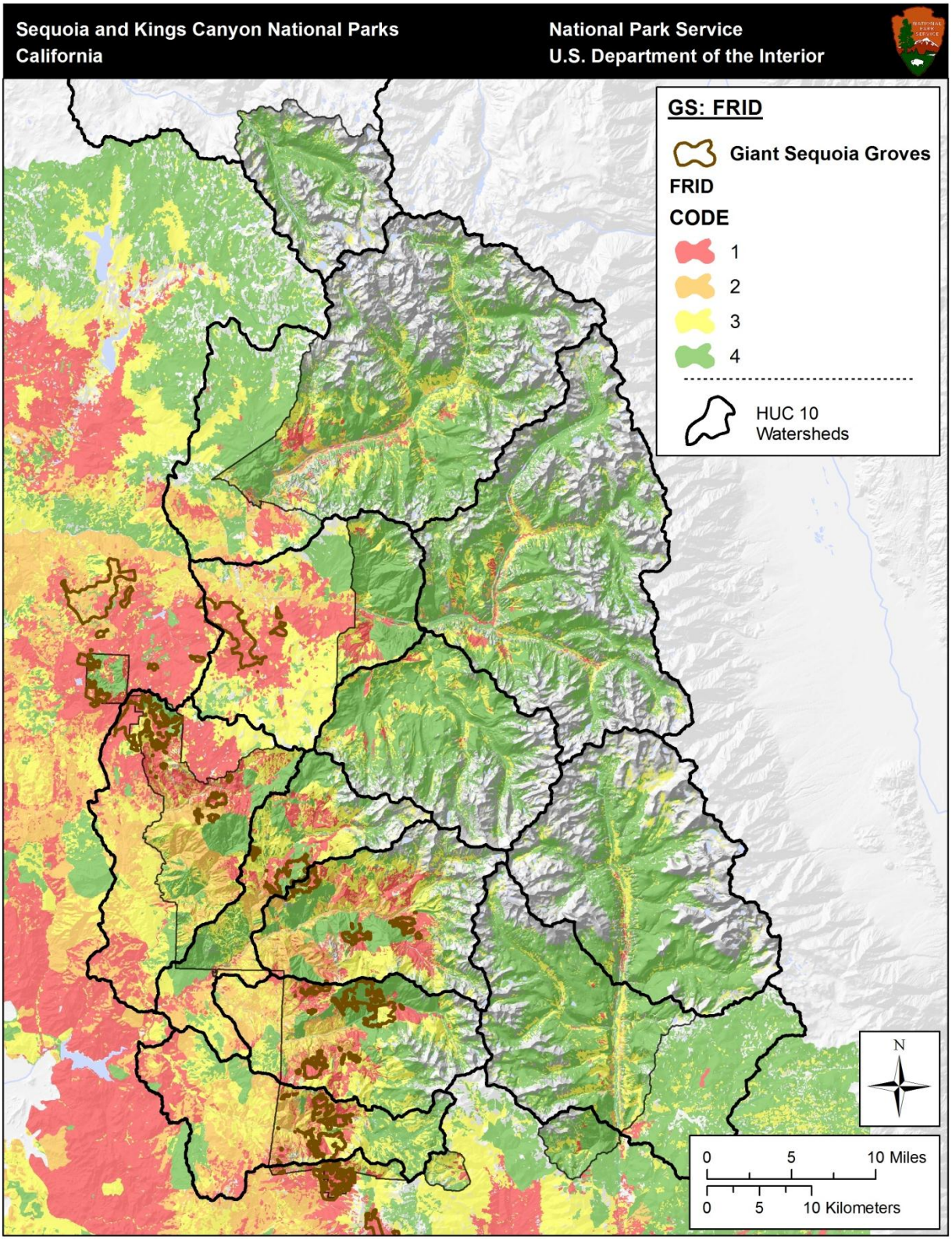
Table 7. Groves ranked by estimated water deficit for the years 1971 through 2000. Note that inferences of climatic water deficit with respect to giant sequoia impacts are limited until more information describing soils, underground hydrology, and giant sequoia physiology is available.

Large groves		**Medium groves**		**Small groves**	
Grove	**Mean ppt (cm)**	**Grove**	**Mean ppt (cm)**	**Grove**	**Mean ppt (cm)**
				New Oriole Lake	461
				Coffeepot Canyon	455
				South Peyrone	446
				Surprise	436
				Board Camp	434
				Landslide	432
				Dennison	423
				Devils Canyon	415
				Maggie Mountain	413
				Sequoia Creek	405
				Cahoon	389
				Squirrel Creek	387
				Horse Creek	372
				Redwood Creek	366
				Granite Creek	314
				Upper Tule	309
				Forgotten	293
				Douglass	278
				Little Redwood Meadow	264
				Monarch	239
				Agnew	224

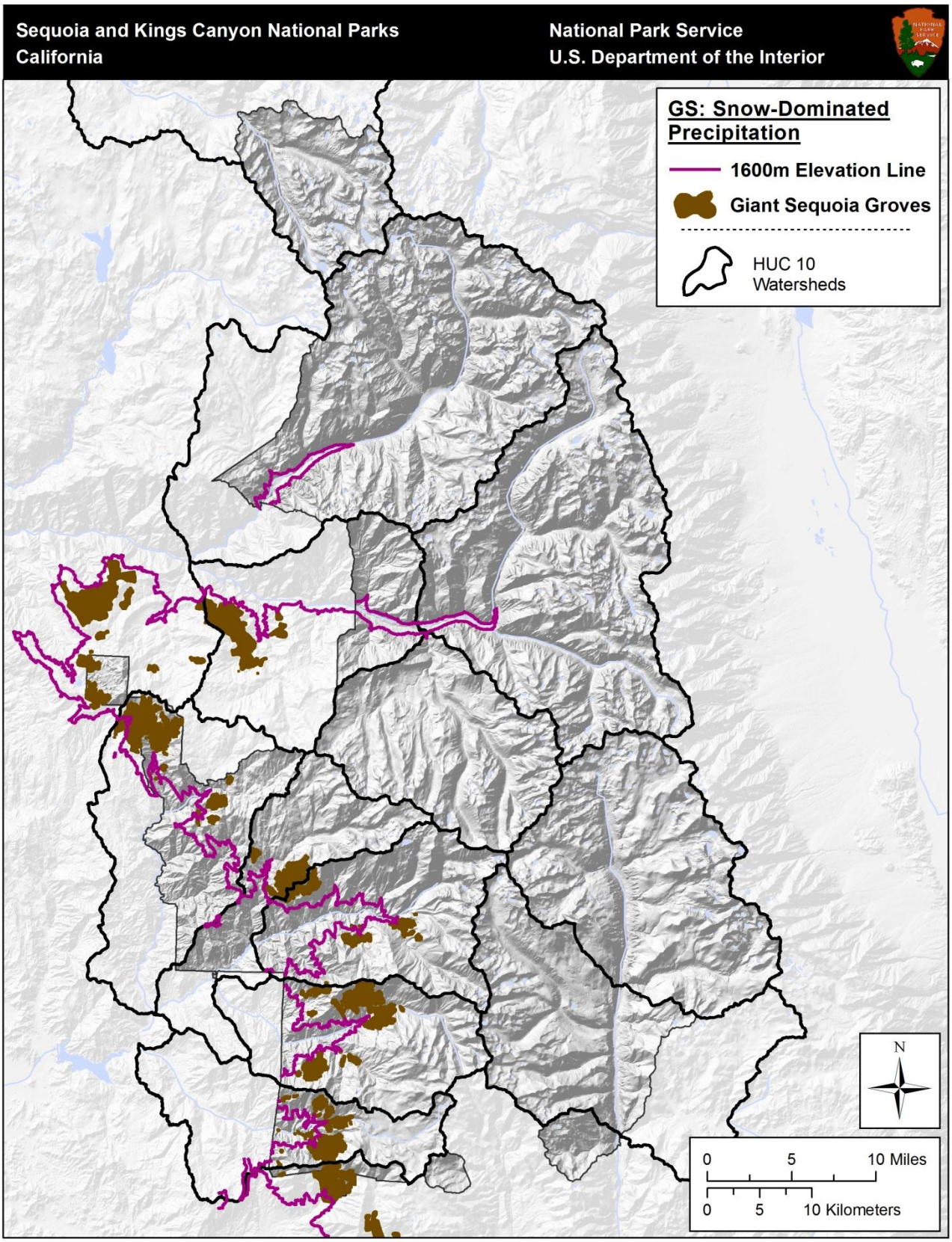
Maps



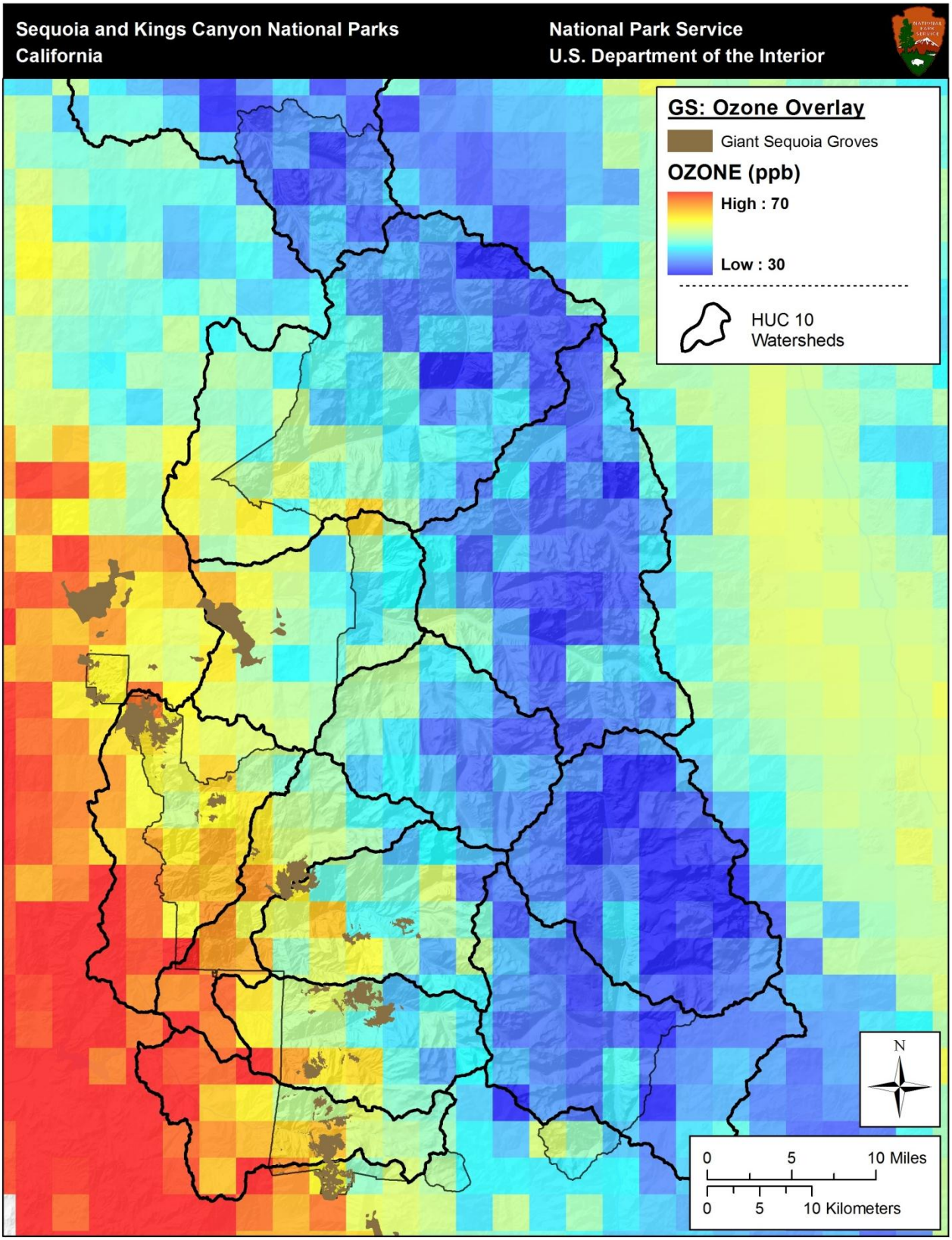
Map 1. Groves locations from SEKI and GSNM considered in this assessment



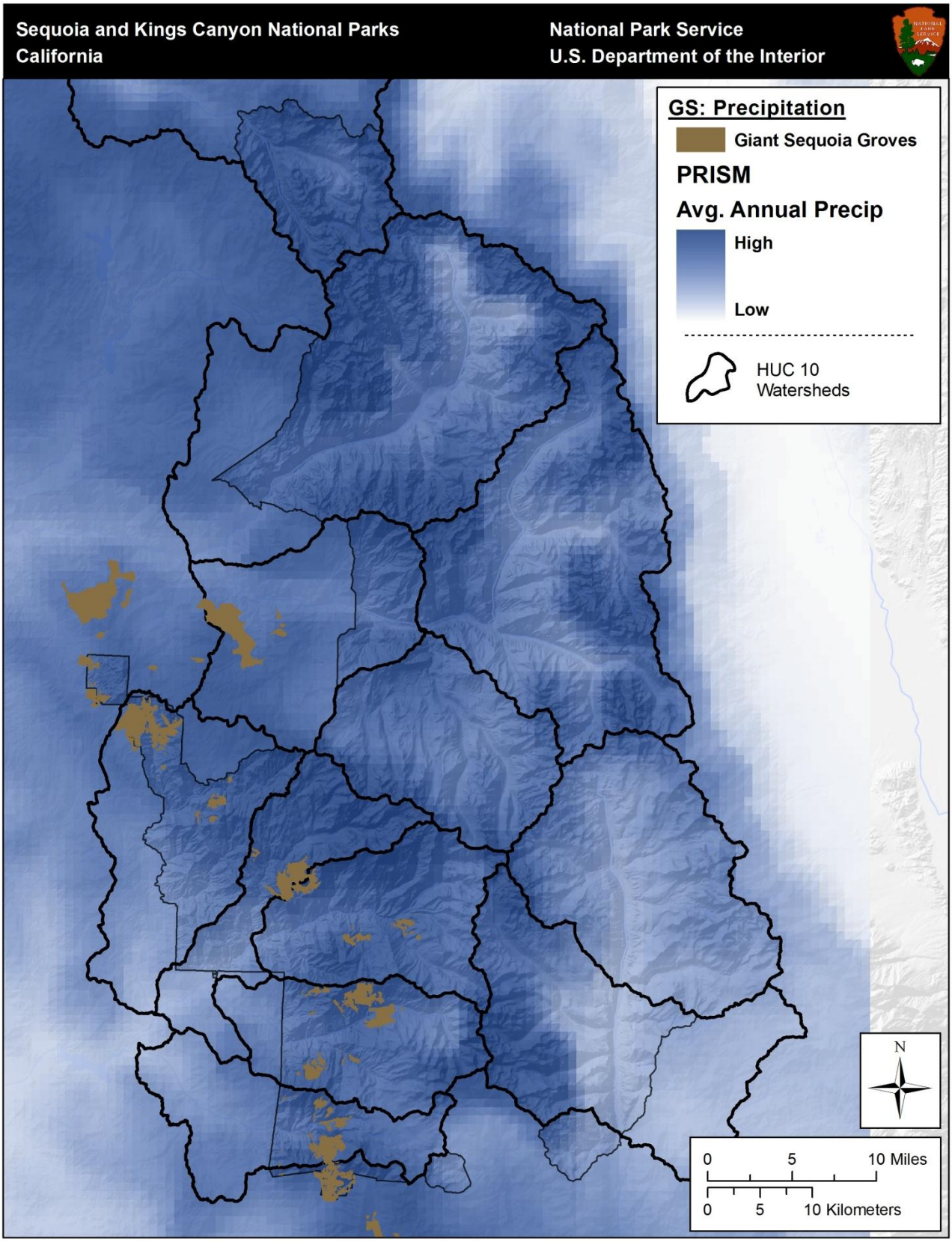
Map 2. FRID classifications, giant sequoia grove boundaries, and HUC watersheds within SEKI. A FRID value of 1 = extreme departure (5 or more maximum return intervals missed), 2 = high departure (2 – 5 intervals missed), 3 = moderate (0-2 intervals missed), 4 = low (time since last fire < max return interval).



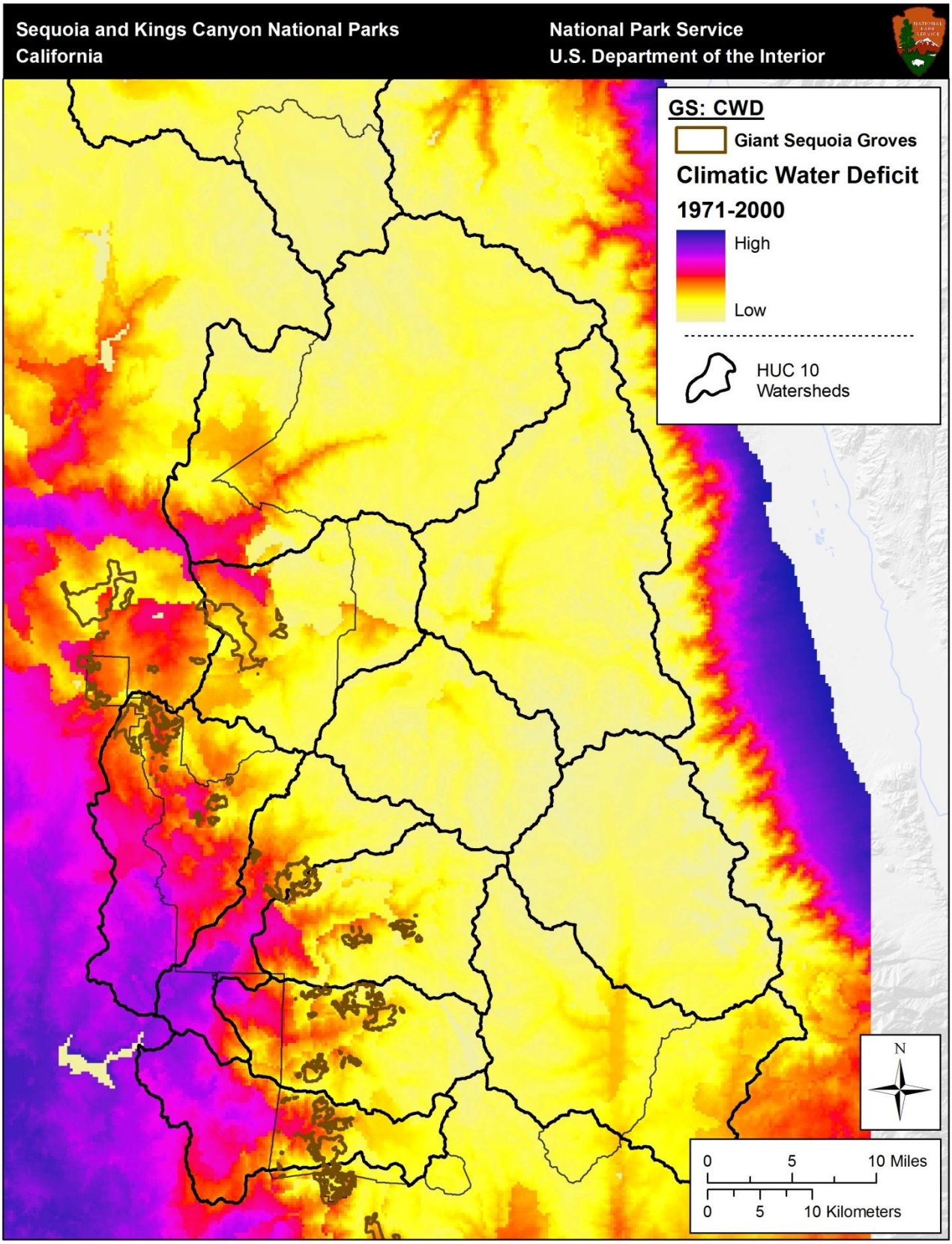
Map 3. 1600-m elevation contour in relation to giant sequoia grove location within SEKI.



Map 4. Ozone concentration and giant sequoia grove locations within SEKI. Ozone concentrations are from monthly averages between 2006 and 2008 (inclusive).



Map 5. Average annual precipitation (1971 – 2000) and giant sequoia grove locations within SEKI.



Map 6. Climatic water deficit (averaged from 1971 to 2000) and giant sequoia grove location within SEKI.

Subappendix 3: Inventory and monitoring methods of agencies managing giant sequoia groves

Table 1. Sampling methods of 4 agencies managing giant sequoia groves in the southern Sierra Nevada

Agency	Sampling type	Smallest size class monitored	Installation period	Remeasure frequency	Sample intensity
NPS-SEKI	100% census	Seedlings <1.3m tall	1964 -1976	None besides an isolated resurvey	100%*
USFS-GSNM	Combination of fixed and variable radius plots; subset of plots designated as permanent	Seedlings <1.3m tall on nested plots	1999-2009	None yet, but permanent plots are designed for re-measure	0.96% for all plots; 0.30% for permanent plots
CDF- Mt. Home Demonstration Forest	Combination of permanent and temporary variable radius plots; 100% census of "old growth" trees	Seedlings <1.3m tall on nested plots	1970, re-measured in '75, '80, '85, '90, '95, '00, and '05**	5 years	BAF 4.6 and 9.2 m^2/ha on 100 x 200m grid, 100% for "old growth" trees***
UCB- Whitaker's Forest	Permanent fixed-radius plots and 100% census of "old growth" trees	Seedlings <1.3m tall on nested plots	1999, re-measured in 2004 and 2009	5 years	2.7% for permanent plots; 100% for "old growth" trees****

* There is no information available on how well this survey achieved the 100% intensity, although personal field observations indicate that the inventory was remarkably close to 100%.

** Digital data from surveys prior to 1990 were not available as of the writing of this report.

*** "Old growth" trees are defined by morphological traits; survey not complete as of the writing of this report.

**** "Old growth" trees are defined as those with dbh greater than 244 cm.

National Park Service – Sequoia Kings Canyon

A monitoring plan is being developed**,** but there has been no systematic monitoring specifically designed to track giant sequoia within SEKI. The ambitious Sequoia Tree Inventory (STI) that took place between 1964 and 1976 and measured over 160,000 trees has recently been transferred to an accessible database, and has been used to profile size structure of giant sequoia within the parks (Stohlgren 1991). While it is likely infeasible to resurvey giant sequoia with the same intensity as the initial STI, some areas of specific interest have been re-surveyed (Lambert and Stohlgren 1988). The STI database provides a useful foundation for future monitoring designs and for evaluating on a large scale the effectiveness of burn treatments in initiating giant sequoia cohorts.

U.S. Forest Service – Giant Sequoia National Monument

Like in SEKI, giant sequoia has been inventoried, but not monitored with repeated measures. Surveys designed to acquire information (especially for regeneration and larger trees) were conducted in all groves between 1999 and 2009. The resulting database includes approximately

550 giant sequoia trees. The database allows for a coarse analysis of size structure when all groves are combined, but analyses for individual groves are limited because of the lack of data. Many groves, either because they are very small in size or because giant sequoia is relatively rare, have very few trees available for analysis or for monitoring. The number of giant sequoia trees measured per grove ranges from 1 (Abbot, Agnew, Red Hill, and Wishon) to 80 (Belknap and Evans Groves), and half have fewer than 13 trees available for analysis. While some plots are designated as permanent sampling points, more will be needed to eventually develop a database capable of assessing grove-wide trends in giant sequoia. Forest Inventory and Analysis plots will provide additional monitoring data, but given the spatially clumped location of giant sequoia and in some cases their rarity, a monitoring plan designed specifically for giant sequoia would be appropriate. A monitoring effort coordinated by both monument and park staff is desirable given the large majority of grove area under the two agencies' management.

During the 2009 surveys on monument lands, 6 of the groves (Abbot, Cunningham, Evans, Freeman, South Peyrone, and Belknap) included surveys beyond the treelines of groves in order to look for possible evidence of giant sequoia expansion. No giant sequoia regeneration was detected from 57 0.008 ha plots. Although evidence so far suggests relatively stable grove boundaries (Rundel 1971), continued surveys such as the one conducted by GSNM with perhaps higher sampling intensities could be valuable for detecting any future evidence of gap expansion. Considering the only expansions previously observed followed heavy logging surrounding groves (Stohlgren 1992), future expansions may be most likely to occur following fuel treatments or high-severity wildfires in areas surrounding grove boundaries.

California Department of Forestry and Fire Protection - Mt. Home Demonstration Forest

Although limited to only one grove (Mt. Home), CDF's monitoring has been relatively intensive, frequent, and now extends back several decades to 1970. The monitoring is not designed specifically for giant sequoia (although see description of 100% census below), but instead aims to capture structure and composition variability of the forest resource in general, especially with respect to gathering information for the ongoing timber management program. Monitoring consists of three components:

1. Intensive Forest Inventory (IFI)- IFI data were collected between 2003 and 2007 from 768 plots established on a grid across the approximately 1,900 hectares. IFI plots are temporary, located systematically between the CFI plots described below. Variable radius plots are used to measure plot-level density and basal area. Each tree is measured for diameter while a subset is measured for height. Prisms with 9.2 m2/hectare basal area factors are used to sample old growth giant sequoia, while 4.6 m2/hectare factor prisms are used for other trees. Nested 0.004 ha fixed-radius plots are used to sample trees less than 15 cm dbh.
2. Continual Forest Inventory (CFI)- CFI data have been collected periodically from 120 permanent plots established on a grid in 1970 and remeasured on a 5-year frequency. Measurements are the same as with the IFI plots described above, except trees are tagged for long-term tracking and there are no nested plots for measuring trees with dbh less than 15 cm. The current database does not yet include data prior to 1990.

3. Big tree census ("S trees")- Trees defined as old growth (using characteristics such as fire scars, rounded tops, and absent lower branches) are being systematically located and tagged for long-term tracking. Initiated in 2001, the survey is on-going and has yet to tag the estimated 4000+ large giant sequoia trees, nor are the data in an accessible digital format.

Combining the most recent CFI survey along with the IFI survey yields a database of 2007 giant sequoia trees- large enough for a basic assessment of size structure within the portion of Mt. Home managed by CDF. The strength of the database is in the potential to track long-term trends in giant sequoia size structure, especially within Mt. Home's relatively unique context of conducting mechanical fuel and harvesting treatments. The lack of regeneration measurements in the CFI plots, however, results in missing data for a critical phase of giant sequoia.

UC Berkeley - Whitaker's Forest (within Redwood Mountain grove)

Although very small (129 ha) relative to other agencies managing groves, Whitaker's Forest (WF) is noteworthy because of its history of research (e.g. Biswell et al. 1966, Harvey et al. 1980) and recent giant sequoia physiology and restoration studies (Ambrose et al. 2009, York et al. 2011). Monitoring is done on fixed-radius permanent plots (0.04 ha) with relatively high sampling intensity (2.7%). Regeneration is measured on 0.004 ha nested plots. Plots were established in 1999 and are measured with a 5 to 10 year frequency. Complete censuses of large trees (greater than 2.4m dbh) have been conducted periodically since 1915. Because of its small size, the complete census at WF has limited value for providing information about large tree trends beyond the boundary of WF. The power of long-term tracking, however, is demonstrated by observing the trend in the large tree population that has existed at WF since 1915 (Fig. 5 in report).

Subappendix 4: Size structures of groves within SEKI as of ~1970

The 30 largest groves are displayed in order from largest to smallest in terms of grove area. The five smallest groves (Big Springs, Clough Cave, Granite Creek, Putnam-Francis, and Squirrel Creek) are not displayed. Data include diameter at breast height measurements from the 100% census that occurred between 1964 and 1976, as described in Subappendix 2. The Y-axes are the same for each panel on a given page (scaled to match the grove with the highest density in any size class), but they are different on individual pages. Bin-widths are 15 cm, starting at 0-15 cm. For size classes greater than 45 cm, alternate bins have no data because larger trees were measured to the nearest 1 foot (greater than the 15-cm bin width). 15-cm bin widths were used in order to distinguish the structure of smaller size classes. The final bar on each graph is for all trees greater than 285 cm dbh. The grove areas described in Stohlgren (1991) were used to calculate density.

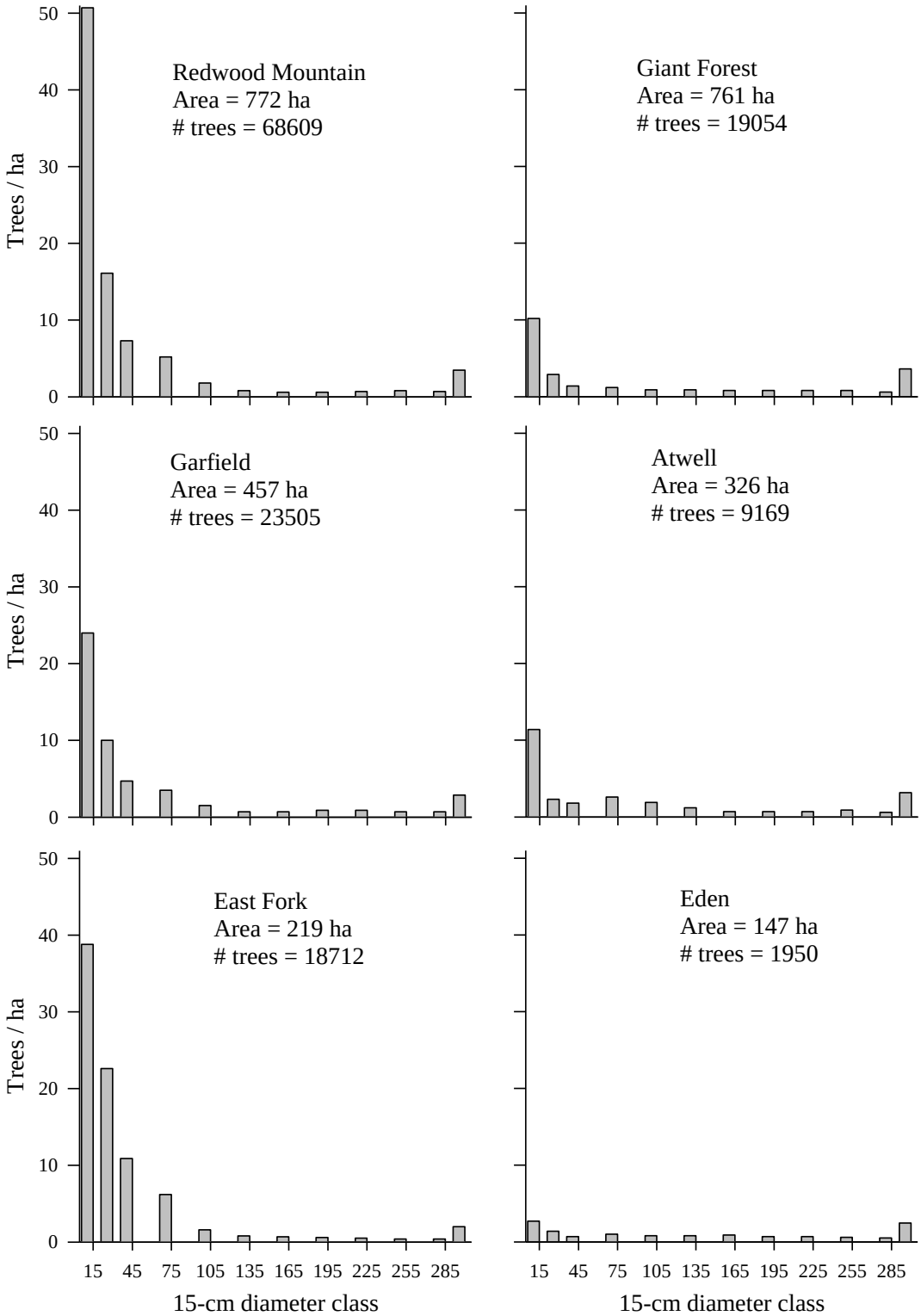


Figure 1. Giant sequoia size structure within the largest groves in SEKI as of ~1970.

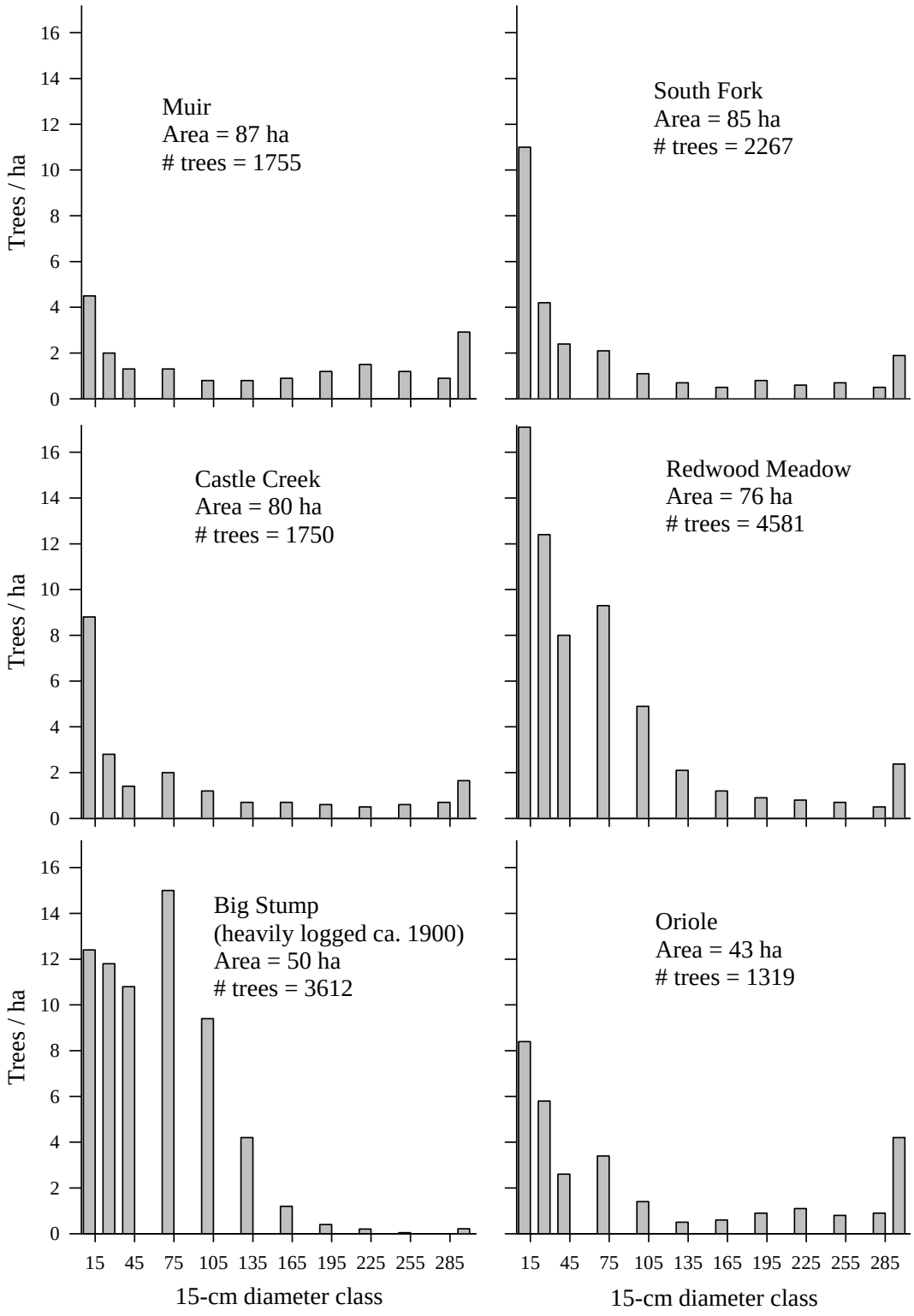


Figure 2. Giant sequoia size structure within groves in SEKI as of ~1970.

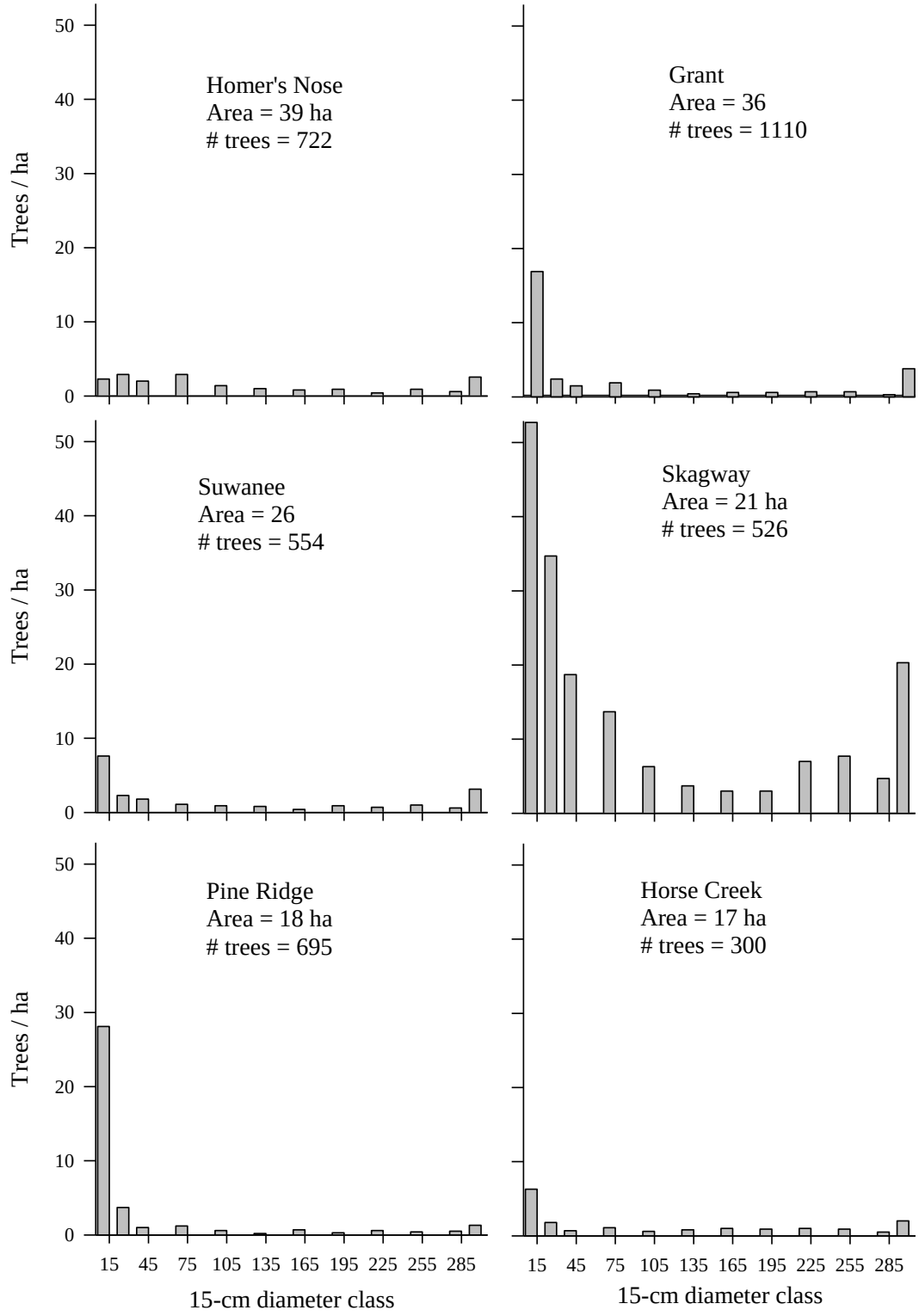


Figure 3. Giant sequoia size structure within groves in SEKI as of ~1970.

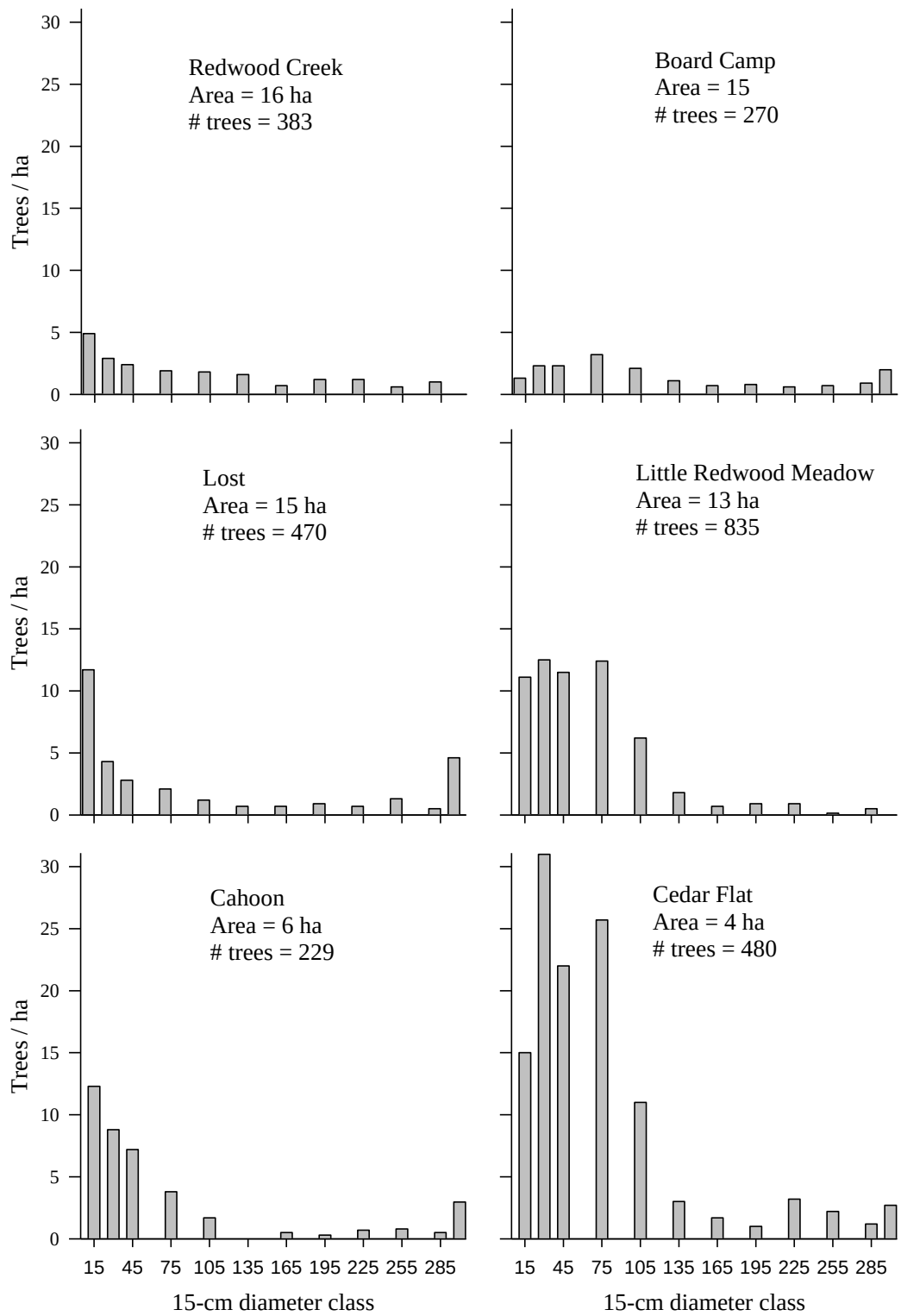


Figure 4. Giant sequoia size structure within groves in SEKI as of ~1970.

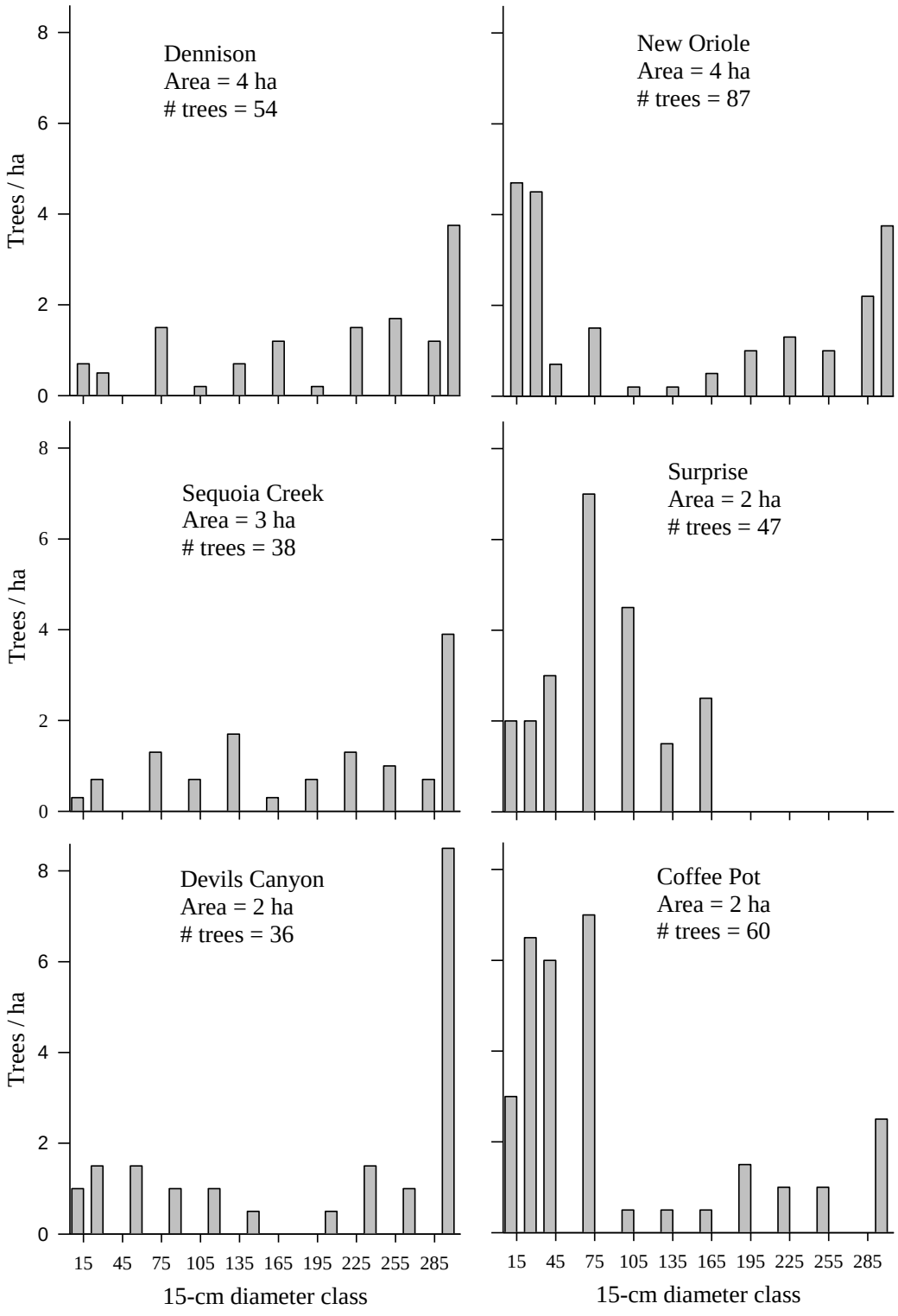


Figure 5. Giant sequoia size structure within groves in SEKI as of ~1970.

Subappendix 5: Size structures of groves within GSNM as of ~2005

Sampling methods are described in Subappendix 2. Surveys were done between 1999 and 2009. 24 groves are displayed in order from largest to smallest. Data include diameter at breast height measurements from surveys conducted between 1999 and 2009, as described in Subappendix 2

The Y-axes are the same for each panel on a given page (scaled to match the grove with the highest density in any size class), except for two outlier groves (Long Meadow and Bearskin), which had exceptionally high small tree densities. Bin-widths are 15 cm, starting at 0-15 cm. The final bar is for all trees greater than 285 cm dbh. Frequencies were calculated as the percent of plots measured that had at least one giant sequoia present. Several groves were not included (Black Mountain, Redwood Mountain, Red Hill, Indian Basin, Big Stump, Grant, Landslide, and Cherry Gap) because only regeneration survey data were available. Treeline grove areas, measured from either field surveys or helicopter surveys, were used to calculate densities.

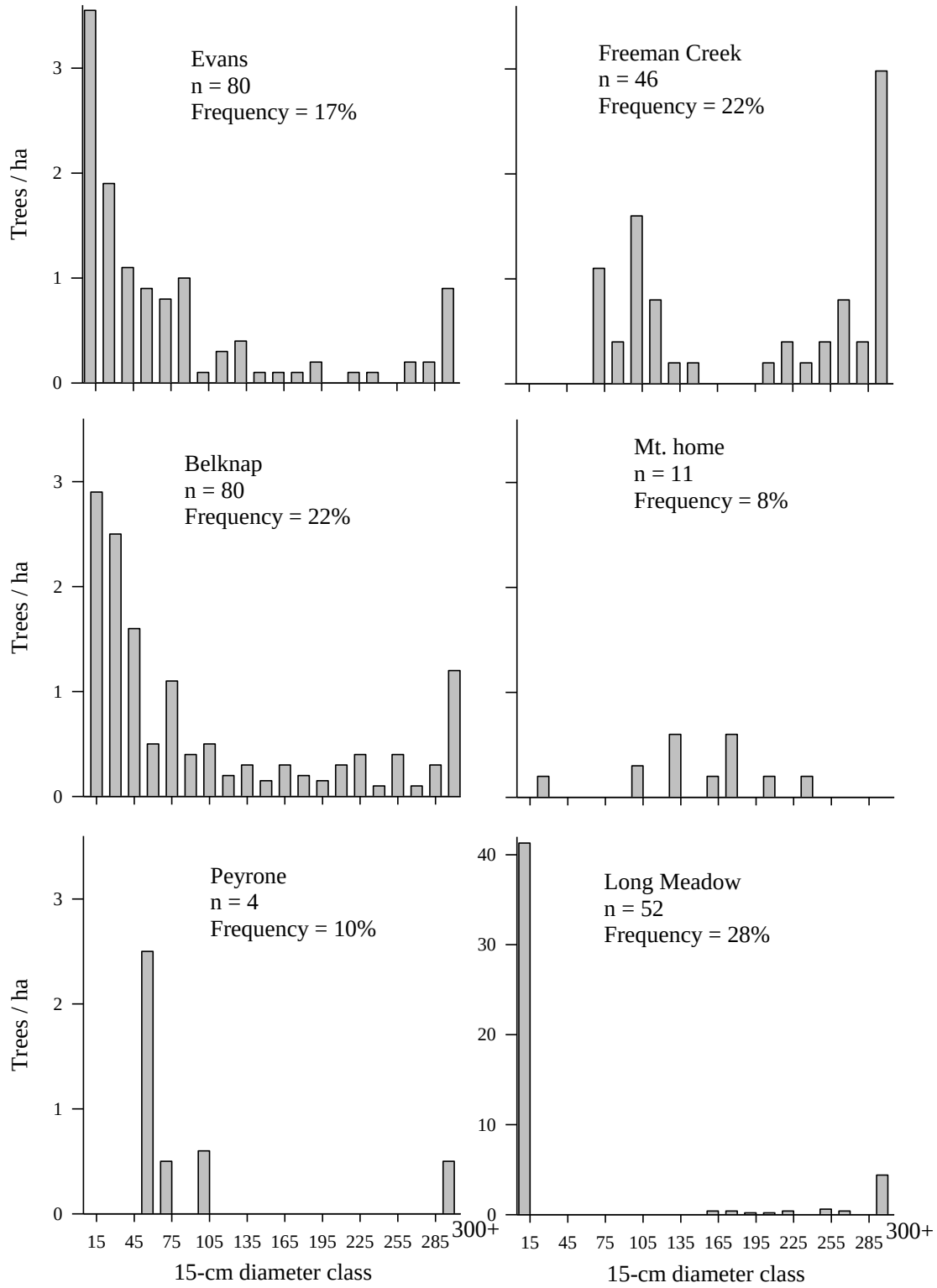


Figure 1. Giant sequoia size structure of 6 of the larger groves within GSNM, as indicated by the most recent surveys.

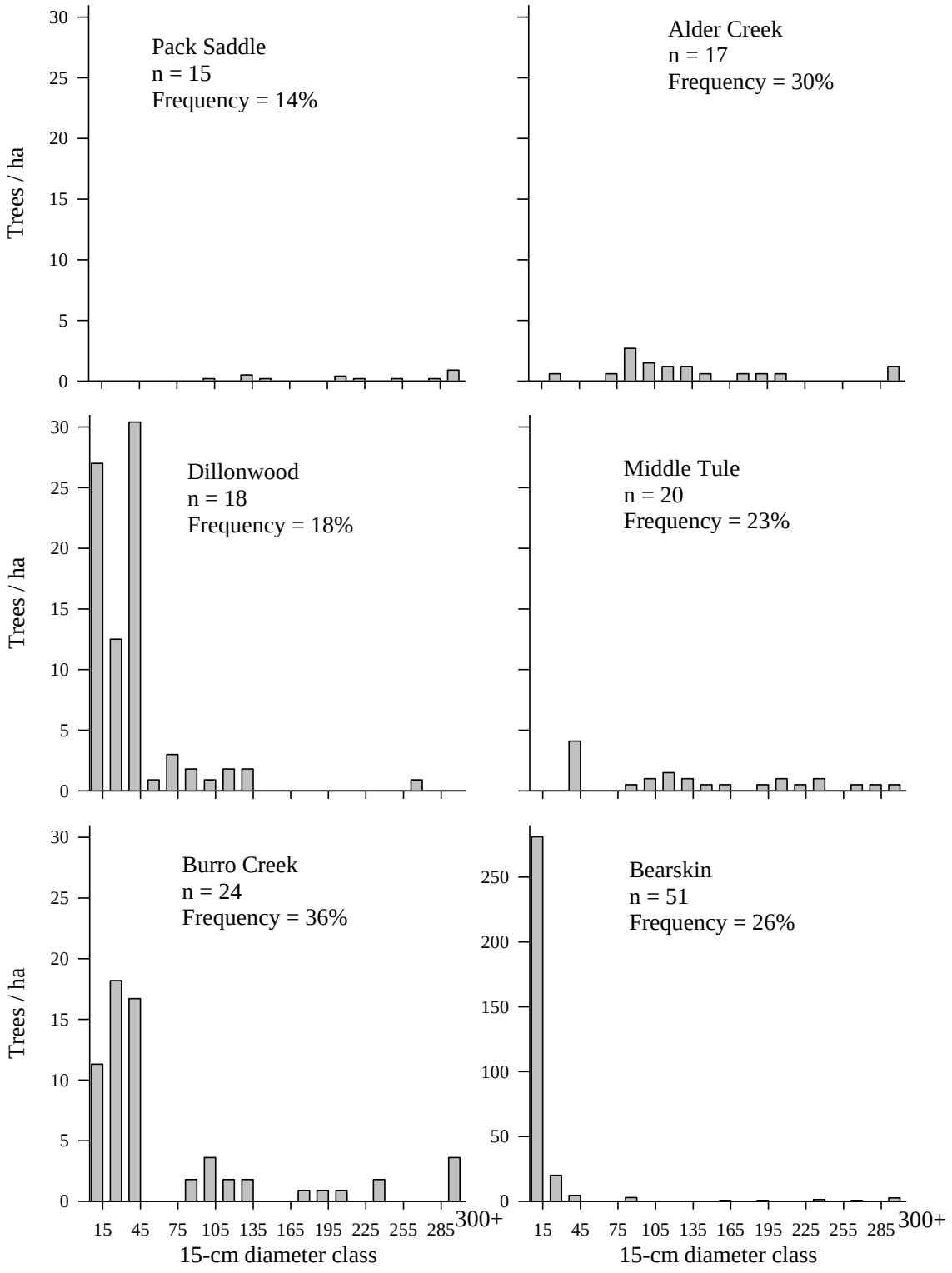


Figure 2. Giant sequoia size structure of 6 groves within GSNM, as indicated by the most recent surveys.

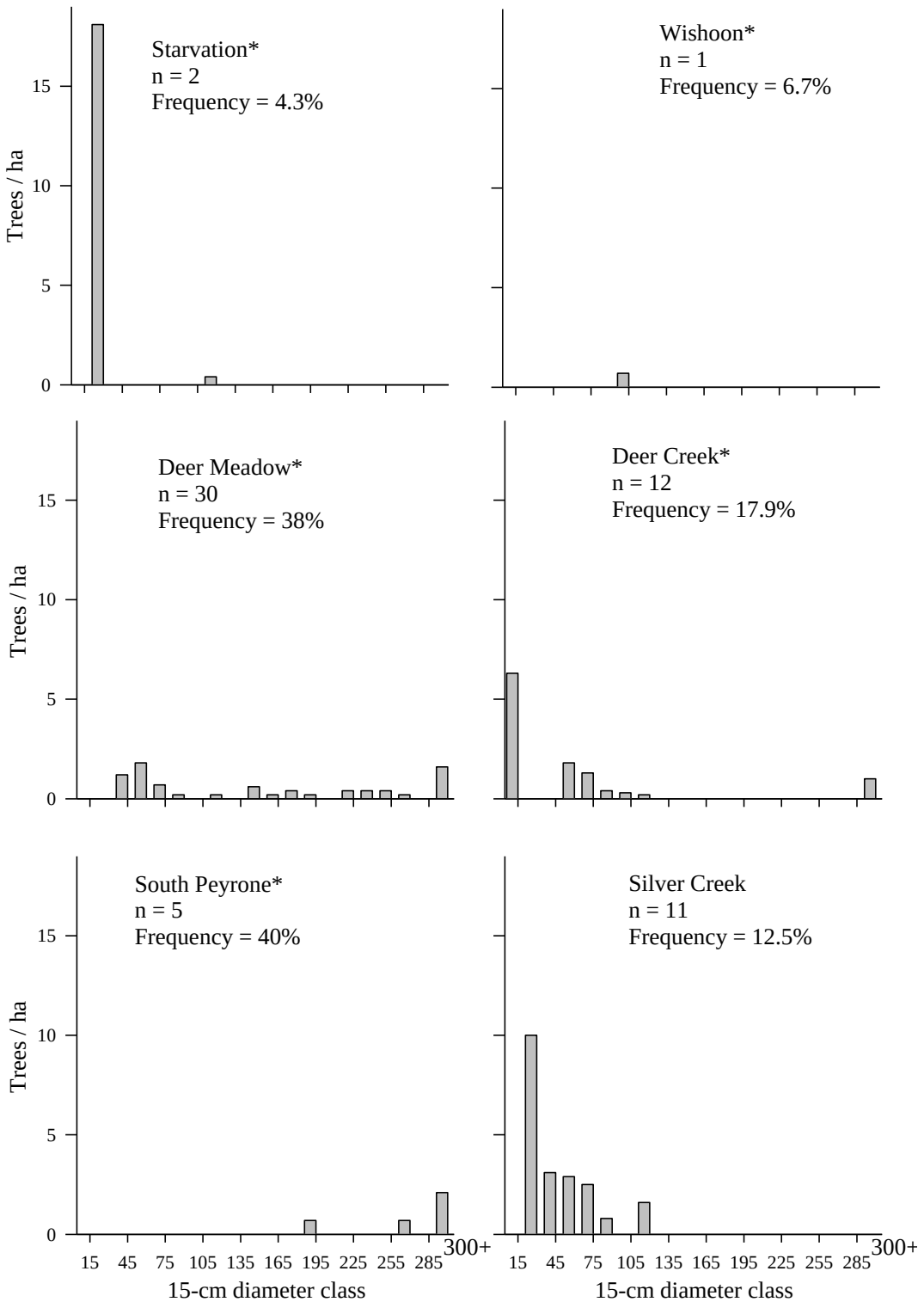


Figure 3. *Data from extra regeneration plots were not available. Power of detection for trees in the 0-15 cm diameter class is lower than for groves that did have extra regeneration plot data available. Starvation grove has different bar heights and only 2 trees sampled because the smaller diameter tree is from a nested plot. Its expansion factor to convert to trees / ha is therefore greater.

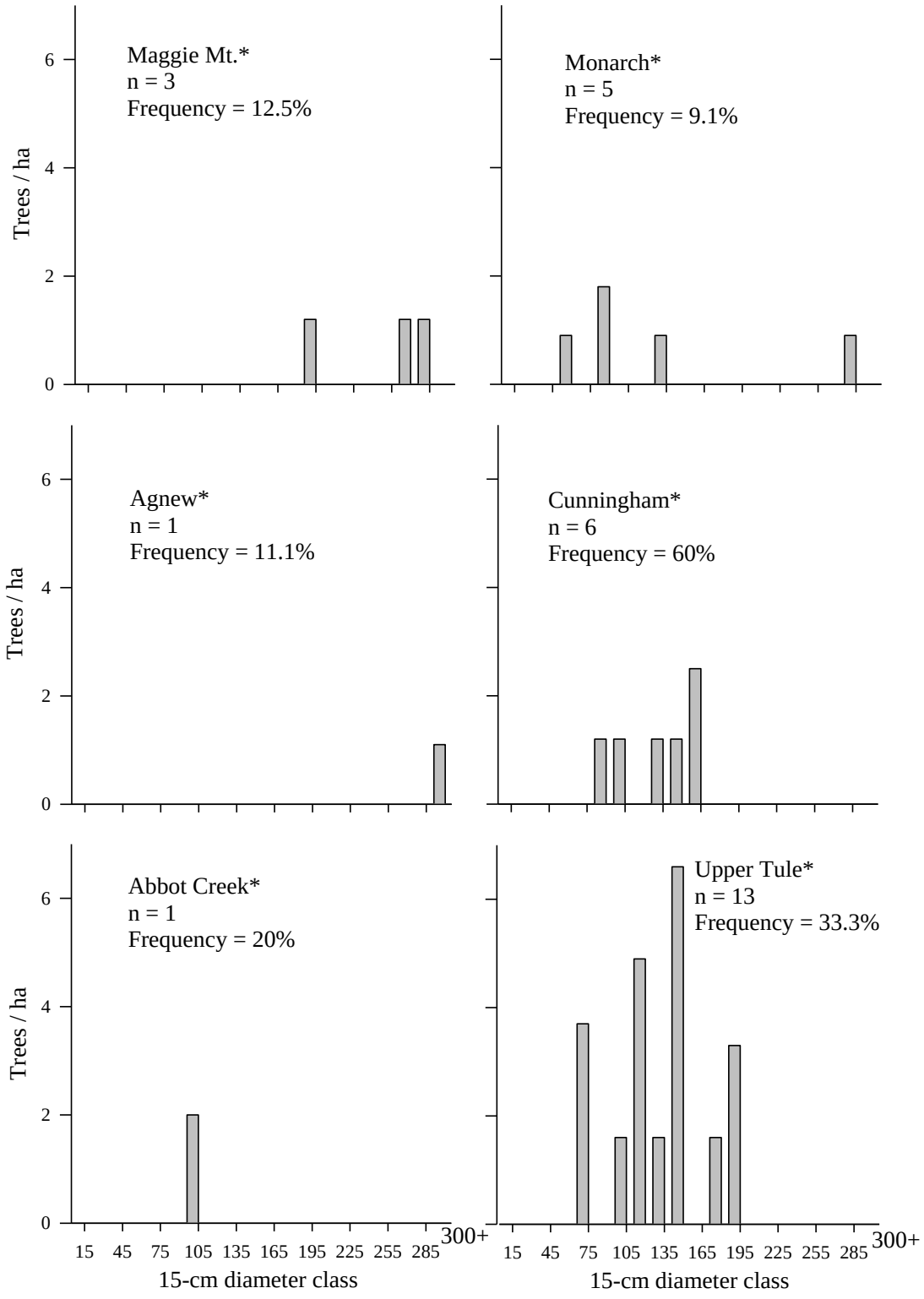


**Figure 4. ***Data from extra regeneration plots were not available. Power of detection for trees in the 0-15 cm diameter class is lower than for groves that did have extra regeneration plot data available.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 102/121034, June 2013

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov