National Park Service
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Natural Resource Stewardship and Science

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

Appendix 11b - Giant Sequoia Literature Review

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

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

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Executive Summary

Giant Sequoias 2011: State of Knowledge, Current Status, and Management Concerns

Giant sequoia is an iconic plant species native to California's Sierra Nevada, and is perhaps one of the most culturally important non-commercial species in the United States – and perhaps the world. It is one of only a few species – plant or animal – that have the distinction of contributing greatly to the evolution of how humanity views its relationship to the natural world (Tweed 1994; Engbeck 1973). This paper reviews and summarizes the giant sequoia literature, the range of management methods used by various agencies responsible for giant sequoia groves, the current status of the species in general, and ecological threats that the species may be facing.

Natural History of Giant Sequoia

Paleohistory

- The past million years have been climatologically dynamic. Within several years to a few decades, temperatures had risen or fallen from 3-15° C, marking either the end of a glacial epoch or the end of an interglacial period (Millar 2003).
- Sequoias moved westward during the mid to late Tertiary Period in conjunction with the Sierra Nevada uplift (Axelrod 1959, 1962). Giant sequoia were well established on the western slope of the Sierra Nevada by the beginning of the Quaternary Epoch, when the elevation at the Sierran crest would have prevented any opportunity for further western migration.
- Groves are a relatively recent phenomenon, prior to about 4500 BP, giant sequoias were a more widespread, but infrequent, part of the early Holocene Sierra Nevada forest.
- Given the longevity of the species, the studies of Anderson and others show that the current groves in the southern Sierra Nevada may perhaps only two to three sequoian generations old, which in turn raises some doubt as to how stable the groves are, and what their current distribution actually represents. It now seems more likely that the groves represent a reaction to transient ecological conditions specific to the past few thousands of years.
- Fossil giant sequoia pollen deposits indicate the trees may have been widespread and common during the early Holocene.

Current Distribution

- There are approximately 77 groves of giant sequoia covering 14,600-17,500 hectares (Stephenson 1996, USDA Forest Service 2010a). Approximately 94% of the land is managed by government agencies and 6% is in private ownership.
- Current distribution reflects climatic patterns of the past several thousand years, while the size and species distribution of sequoias within groves over the last few hundred years may represent even more fine-scale variations in climate, and most likely do not represent the potential suitable habitat for sequoias in the future.

- Groves are arranged in a North-South distribution along the western slope of the Sierra Nevada generally from 1400m to 2150m. In general, the groves display a predictable and general rise in elevation with decreasing longitude.

Giant Sequoia Ecology

- The forest of the western, mid-elevation slope of the Sierra Nevada could have developed much as it is today if giant sequoia had not arrived.
- Sequoias are best described as a pioneer species (albeit a persistent one), colonizing an area only after some major gap-producing disturbance occurs that removes potential competitors for sunlight.
- There are a number of factors that may explain why giant sequoia groves exist where they do. Giant sequoias prefer sandy soils with a low clay content. Some research suggests that soils in giant sequoia groves are more mesic, higher in pH, higher in calcium and lower in nitrogen than the soils associated with other neighboring conifers, although this may represent centuries of plant-soil chemistry interaction, rather than a site preference.
- On a small scale, the movement of water over the surface of the ground – before it reaches even ephemeral streams – does have an influence on creating suitable habitat. At the patch level, the determining factor is the result of interactions between giant sequoias and their environment.
- At least in terms of soil nutrients and soil hydrology, it is reasonable to assume that other sites within the Sierra Nevada have comparable qualities, but these have not been colonized by giant sequoia. Either the species did not occur in the vicinity to begin with, or other as yet undetermined environmental factors prevented establishment. As the climate changes, grove structure, at least as we know it, may no longer be a viable option for the species.
- Giant sequoias produce seeds with low caloric value, and are therefore not a preferred target for herbivory by birds, mammals, and insects. On the other hand the cones bearing those seeds do have nutritional value, and are an important food source for the larval stage of at least two insects, and these insects help disperse the seeds.
- Approximately 300,000 seeds are dispersed per year, per tree but few will actually germinate and survive. Some are cached or fall close to the parent bole, but seeds that do fall from the canopy tend to sail, and can be carried distances of up to 400 meters from the source tree.
- Fire is the most important mechanism for stimulating seed release from cones. It removes the organic overload from mineral soil, sterilizes the soil of seedling pathogens, opens up the forest canopy to allow sufficient and it may establish beneficial chemical characteristics, such as soil nutrients and acidity.
- Giant sequoias display more rapid growth towards the center of canopy gaps. The minimum initial size of highly productive gaps seems to be about 0.1 ha (0.24a), although York et al. (2009) found that seedling survival and growth in gaps as small as 0.05 hectares (0.12 acres) were still more successful recruitment sites than under a full canopy.

- The likelihood of a surface fire evolving into an active crown fire is unlikely except in forests with a vertically continuous canopy, high surface fuel loads, and/or a significant understory of shrubs or trees.
- Even though they are resilient sequoias are susceptible to various pests and pathogens, and are especially sensitive at the seedling and small tree stages of life. There is still little more than anecdotal evidence of direct or indirect severe impacts to giant sequoias from pests or pathogens. The most commonly cited pathogens to giant sequoia in its natural range are annosus root rot *(Heterobasidion annosu)* and Armillaria root disease (*Armillaria mellea).* There are also a number of pathogens that effect plantings outside the native range. The most common pest is is the carpenter ant (*Camponotus modoc*), which form galleries in the wood and bark of the tree.

Genetics of Giant Sequoia

- A low to moderate degree of genetic variability between groves, with some degree of variation from southern to northern populations. There is no clear indication, however, that this North-South variation is associated with fitness based on latitude.
- On the other hand, within grove variation does seem to display some degree of topographic stratification, with a tendency for families in a grove located at higher elevations performing better in cold-related tests (Melchior and Herrmann (1987); Guinon et al 1982).
- Heterozygosity displayed a significant correlation with latitude, with the northern groves being less variable than the southern populations. Given the relative isolation and generally smaller sizes of the northern groves, this result is not surprising (Fins and Libby 1982).
- Concern has been raised over the threat to genetic integrity presented by the presence of non-native sequoia plantings near existing groves.

Giant Sequoia Management

National Park System

- The National Park System (NPS) from 1916 to 1963 focused on protecting giant sequoias from the public and from wildfire. As early at the 1920s some managers thought controlled burns would benefit the species, but the common practice was fire suppression.
- In 1963 the Leopold Report and the Robbins Report started to change the NPS' management philosophy. Both documents are significant to the history of giant sequoia management by introducing the concept of ecosystem-based management and by stimulating some of the most important research conducted on the species.
- The Leopold Report claimed that the NPS had based its management on the care of charismatic objects (e.g., elk in Yellowstone, giant sequoias in the Sierra Nevada parks), without caring for the overall ecosystems within which these 'objects' occur. It was also instrumental in the agency's adoption of prescribed fire as a management technique.

- The Robbins Report suggested that NPS reorganize to better integrate science into its management structure, creating a "permanent, independent, and identifiable research unit," and that important actions and decisions taken by NPS would be based on sound research.
- Currently NPS is pursuing a management philosophy that emphasizes ecological restoration of management groves through fire regime but they are limited by concerns that burning reduces on air quality.

Forest Service

- The Forest Service was established with the goals of managing the nation's federally owned forest lands to sustain and improve both timber production and water generation. As a result, the resources contained within the forests – including giant sequoias – were viewed as commodities to be utilized in a sustainable manner.
- The Forest Service implemented a strict policy of fire suppression, and the use of prescribed fire as a tool in giant sequoia forests was not integrated into management practices until the late 1970s, and even then only on a limited basis.
- Since 1988 The Forest Service has ceased the use of prescribed burning in groves until a number of conditions had been met, the creation of an ecological database for the groves, the implementation of ecologically based management, and the development of a new management plan (Elliott-Fisk et al. 1996; Piirto 1992; USDA Forest Service 2010a).
- The Forest Service was required by law to prepare a management plan for the Giant Sequoia National Monument. The current iteration of the plan focuses on fire risk reduction, while there is also a section on sequoia regeneration.
- CALIFORNIA DEPARTMENT OF FORESTRY AND FIRE PROTECTION
- The Mountain Home State Demonstration Forest (MHSDF), conducts research into the growth and harvest of forest products. Since 1946 the MHSDF has protected old growth sequoias, and generally limited the harvested of young ones.
- MHSDF has also conducted non-commercial investigations into giant sequoia ecology and silviculture, and has encouraged the use of their forest for research by others.
- The California Department of Forestry and Protection has established new generations of sequoia primarily by the mechanical creation of forest gaps within groves during harvests of other species, although some limited use of prescribed fire occurs. Recognizing that interest is increasing in the commercial use of giant sequoia lumber, a current focus of their research is on the growth, yield, and utilization of the species.

California department of Parks and Recreation

- Since 1853 the North Calaveras Grove has been managed for tourism, but the South Calaveras Grove has always remained much less accessible.
- In 1975 fire was initiated as a management tool in the South Grove and when conditions did not support the use of prescribed fire crews thinned the forest using manual thinning.

- The smaller North Grove has been more challenging for resource specialists to manage as a natural system due to its heavy use, proximity to a highway, and nearby communities, as well as the very mesic nature of the site. Some burning has been completed in the past.
- Beginning in 2000 the California Department of Parks and Recreation has primarily reduced ladder fuels in vertically continuous fuel beds in the South Grove. Prescribed burns are planned for the North Grove in the future, but the problems of smoke generation will mean that these burns will be small and infrequent.

University of California

- Whitaker's Forest has the oldest continuously monitored forest plots in the Sierra Nevada and one of the earliest sites to have prescribed fire trials in a sequoia grove. The area was harvested extensively prior to 1900, and harvesting continued through much of the 20^{th} Century.
- The University of California's Whitaker Forest does not have a management plan, although it is anticipated that research into giant sequoia ecology will play an important part of any future activities.

Managing Giant Sequoia with Fire

- Early efforts to re-introduce fire into sequoia groves were often ecologically insignificant, due to a desire to limit fire intensity. reduce the risk of fire escape, and convince skeptical stakeholders of the agency's ability to manage prescribed burns. As a result, initial burns were not always successful at stimulating sequoia recruitment and significantly alter undesirable stand density and species composition.
- Fire can be an effective restoration tool when used with an appropriate return interval and sufficient severity to alter forest structure in the short-term, and remain within a desired range of variability in the long-term.
- A mosaic of forest structure is essential to creating and maintaining a healthy Sierran forest, and this can be created by properly applied fires, through the creation of canopy gaps Increasing fire intensity and severity can be achieved by allowing fires to burn in different directions relative to slope and wind, and by shifting prescription values towards drier fuels.
- Fires aimed at forest restoration (whether prescribed or managed unplanned ignitions) can only be effective if they can create canopy gaps, and achieving that requires local areas of very high intensity.
- Constraints on the ability of grove managing agencies to use effectively use fire are making it difficult to achieve desired diverse fire behavior and fire frequency. These constraints include, but are not limited to, funding, agency policies, availability of trained personnel, environmental regulation, competing land use, and grove accessibility (Caprio and Graber 2000).
- Some constraints can be minimized if other management tools are used, such as manual or mechanical thinning used in conjunction with fire (Miller and Urban 2000b; Stephens and Moghaddas 2005).

Reconstructing Giant Sequoia Groves

- There is a debate as to what restoration goals should be. Two philosophical approaches have been presented: the direct restoration of groves to predetermined desired conditions (Structural Restoration); and, the restoration of ecological influences that created historically undisturbed groves (Process Restoration).
- If the goal is pre Euro-American conditions there are number of issues to deal with, such as the lack of knowledge of forest condition hundreds of years ago. Still, methods were developed to help determine historic grove conditions. These methods are most useful if mechanical or manual efforts are used to create a forest that resembles one that existed 150 years ago.
- Research suggests that groves were spatially (on a landscape basis) more complex in terms of structure, age, species composition, and fuel arrangement a century and a half ago.
- STRUCTURE: In the past, occasional high intensity/high severity events in an otherwise low intensity fire regime created canopy gaps, which then became suitable locations for the germination of shade intolerant species such as giant sequoia.
- AGE RELATIONSHIPS: As can be expected from the loss of gap diversity, there has been a loss of young trees in giant sequoia groves
- SPECIES COMPOSITION: Dominance by white fir occurred because it is able to reproduce in shaded conditions, while giant sequoia needs to reproduce in canopy gaps.
- FUEL ARRANGEMENT: The fuel load would be much lower under natural conditions. The diversity in prehistoric fire spread would have created a great deal of heterogeneity in horizontal fuel arrangement, ranging from patches of bare earth to pockets of heavy fuel loads, often found within a few meters of each other.
- CLIMATE CHANGE: The species that succeed in a new and warmer climate may not relate well to the reference conditions of the past.

Managing for Carbon Sequestration

- Recent studied have compared the net carbon values for various treatment methods (including prescribed burning, thinning at various intensities, thinning with burning, and harvesting with wood utilization) versus no treatment, with the assumption that all stands thus treated would also be exposed to wildfire within a 100-year period.
- In the absence of any wildfire, the untreated model stand was the most efficient carbon sink, but it is unrealistic to assume that forests maintained to entrap atmospheric carbon would be immune from wildfire.
- When a single wildfire is included in the various simulations, the results show that forest stands that maintain low stocking levels and favor the growth of large trees are, over time, better carbon sinks than forests with higher tree densities, or treatments that include overstory tree removal.

The Status of Giant Sequoia Groves

- THE IMPACT OF LOGGING: Of 12 groves recently inventoried by the Forest Service, those that had been heavily logged in the past tended to be those groves that had the highest proportion of ponderosa pine, in terms of percent basal area and percent of total trees, and high proportions of shrub understory, in terms of percent canopy cover.
- THE IMPACT OF BURNING: Even though prescribed burning is now recognized as an important tool to help regenerate forest and deal with high fuel loads that built up under fire suppression it remains under-utilized. Some factors that limit the use of fire include quality staff to implement prescribed burns and air quality regulations. While many agencies have used fire in the past and continue to do so, only one grove – Giant Forest – is in anyway capable of considered as having a fully restored fire regime. First, as discussed above, the desired result of seed dispersal and sequoia regeneration required higher fire intensities than were often achieved by these early fires; second, fire's ecological role at thinning regeneration in forest types found in sequoia groves was achieved by a fire regime with a short return interval. Many groves have fuel loadings and arrangements that put them at high risk from catastrophic wildfire.
- POSITIVE RESULTS FROM EARLY PRESCRIBED BURNS: After prescribed fires in the 1960s and 1970s reproduction increased, the white fir population decreased, and the risk of wildfire decreased. The best giant sequoia reproduction occurred where fire intensity was high. Initial low intensity fires were successful at killing unwanted understory trees, but success was limited in the future because mortality to understory trees was often the result of the exposure to a residual and extended smoldering combustion of a thick layer of duff that had accumulated through fire suppression, not to the low intensity fire itself. Also, the woody fuel load can increase after a single fire as the resulting mortality becomes available as a fuel. Once subsequent burns finally remove these dead trees, a more lasting reduction in risk can be obtained.

Logging Giant Sequoia

- About 25-30% of the original distribution of giant sequoia was logged. During the same time period at least 80% of the old growth mixed conifer forest of the Sierra Nevada was logged.
- The low strength and brittle nature of old-growth giant sequoia lumber made it difficult to harvest and transport and unsuitable for most construction purposes. The wood was primarily used for pencil stock, fencing, and grape stakes.

Threats to Giant Sequoia

- CLIMATE CHANGE: There are a number of potential threats including an increase in annual temperatures which will alter snowmelt patterns, change hydrology, decrease the proportion of rainfall as snow, and increase the probability that plants will experience water deficit during the growing season. Extreme heat events will increase and cold spell frequency will decrease. The increase in average temperature will be more pronounced in the summer, which will then increase the rate of evaporation of soil moisture.

- Warming conditions could improve the habitats for pests and pathogens and possibly introduce novel pathogens to the area.
- Increased wildfires due to lower humidity, drier fuels, and longer fire seasons, present the risk of an increase level of threat from a problem that is already extreme.
- The new, warmer, environment could also lead to a gradual shift in species composition to better suited plants, and these in turn may have detrimental impacts on giant sequoia ecology. Even if giant sequoias as a species can adapt in various ways to changing conditions, it is doubtful if all associated species could do so. In that case they would survive as a species while their historic ecosystem dissolves.
- There are two are adaptive responses to water stress: under drying conditions, a plant either closes stomata during the day, and thus stops carbon uptake, or the stomata remain open, thus losing additional water. Placement of plant species into either response category (technically isohydric and anisohydric plants, respectively) has not been done for tree species of the Sierra Nevada, although "anisohydrism" is more typical of species that are well adapted to drought (McDowell et al. 2008).
- As a species, giant sequoias have successfully coped with changes in climate in the past, whether local or global in nature.
- AIR QUALITY: The largest concentration of giant sequoia coincidentally occurs within the air basin with California's worst air quality. Giant sequoias sensitivity to ozone decreases with age, with seedlings less than one year being very sensitive, while sapling sized trees showing no ill effect. The potential impact of nitrogen deposition on giant sequoias is unclear.
- PEST AND PATHOGENS IN A CHANGING CLIMATE: If climate change results in increased stress to giant sequoias, it could make them more susceptible to pests and pathogens that are already a part of their ecosystem, especially if these agents benefit from warmer conditions.

Giant Sequoia Silvicuture

- Today, interest in the commercial harvesting of sequoias is renewing, as plantation trees outside of groves mature and reach merchantable size.
- Giant sequoias growing under plantation conditions routinely out-perform most other species (assuming adequate sunlight, moisture, and soil depth), when measured in terms of both height and volume. This type of performance is dependent upon site conditions however. An extended period of below average rainfall allowed the more drought-tolerant ponderosa pine to eventually overtake the sequoias at two Blodgett plantations (planted in 1966 and 1981).
- Overall, young growth sequoias have wood quality characteristics that are superior to both old and young growth coast redwood, assuming proper care is taken during early growth.

Plantations and Plantings in California

- Natural recruitment is limited by seed germination and seedling establishment (Harvey et al. 1980).
- Many plantations are located outside the environmental boundaries of native groves, ranging from Tuolumne County north to Siskiyou County, thus extending well beyond the Sierra Nevada into the Southern Cascades.
- All plantations were started with planted seedlings and survival was about a 75%. Nursery diseases and drought years were the most common causes of mortality.
- Giant sequoia are commonly the fastest growing trees when in a mix with other coniferous species.
- The genetic stock and site characteristics of most plantations have not been described, yet comparing seed source, plantation success, and site environmental variables could make a significant contribution to understanding the potential range of giant sequoia.

Plantations and Plantings Throughout the World

- Giant sequoias are found in plantations, botanical gardens, and isolated plantings throughout the world. In most cases, these occurrences are often in habitats generally colder than the native range, in some cases markedly so (Knigge 1994, Libby 1981). The survival of these trees seems to be related to genetic selection for strains better adapted to withstand low temperatures. The seeds from Atwell Mill showed the highest proportion of frost resistance of 22 groves in controlled tests (Gunon et al. 1982).

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Introduction

Giant sequoia is an iconic plant species native to California's Sierra Nevada, and is perhaps one of the most culturally important non-commercial species in the United States – and perhaps the world. It's great size, longevity, and relative scarcity captured the public imagination from the time they learned of its presence in 1852. To be sure, other charismatic plant species may be older, others may be larger, and many others are certainly more rare, but the giant sequoia seems to occupy a unique place in our culture. Perhaps this is due to its relative lack of commercial value. Giant sequoias can be appreciated not for its economic worth or the products made from it. Instead, they can be (and are) appreciated both for themselves, and for the feelings they generate in us while amongst them.

It is one of only a few species – plant or animal – that have the distinction of contributing greatly to the evolution of how humanity views its relationship to the natural world (Tweed 1994, Engbeck 1973). Since the first collection of seeds by European naturalists in 1853, sequoias have been introduced worldwide, where they remain the subject of great scientific and popular interest. In the United States, the species has also played a large role in the development of the field of environmental ethics and the philosophy of natural resource preservation (as opposed to utilization and/or conservation), and was an important stimulus to the evolution of the National Park System during at least two crucial phases: the change from the concept of a single "national park" to a nationwide system of parks (Dilsalver and Tweed 1990); and, the shift from a purely conservationist/ protectionist-based philosophy of resource management to one that allows for active, scientifically valid, intervention that emphasizes the maintenance of ecological processes.

Prior to the 1880s, the groves of giant sequoia were largely unprotected and, if managed at all, were in timber production (see Aside: Logging – a Brief Overview). There are two notable exceptions. First, the North Calaveras Grove (discovered in 1852) was already a burgeoning privately operated tourist attraction by 1853. In fact, it may be the longest continually operating tourist attraction west of the Mississippi River (California DPR 1982). The second exception is the Mariposa Grove in Yosemite National Park. In 1864, both the Mariposa Grove and Yosemite Valley were deeded by President Lincoln to the State of California for the purposes of "public use, resort, and recreation" (U.S. Statutes at Large 1864). This was an unprecedented action, coming 8 years before the creation of Yellowstone National Park, and demonstrates the level of social and cultural value placed on the species as a natural, rather than commercial, resource. (The grove and valley were taken back by the federal government in 1905 and integrated into the already established Yosemite National Park – U.S. Statutes at Large 1905). However, this recognition was not universal, and some commercial exploitation of the species did occur later in the century and up until the 1950s (Hartesveldt et al. 1975).

Important reviews of giant sequoia literature have been conducted in the past – most notably by Hartesveldt et al. (1975), Harvey et al. (1980), and Stephenson (1996). This new effort focuses more on work published since 1995. Following this introduction, the paper is organized into the following broad categories: Giant Sequoia Natural History, Management of Giant Sequoia, and the Status of Giant Sequoia Groves, and Giant Sequoia Silviculture. Two major fields of giant sequoia research are not discussed in this paper: biochemistry and physiology. However, a bibliography of the literature from these disciplines is included as Subappendix 1).

The species had not been extensively researched until a flurry of publications emerged, beginning in the 1960s. For purposes of comparison, Libby (1996) counted 251 technical publications on coast redwood (*Sequoia sempervirens*) in the seven-year period from 1988 to 1995, and mentioned how this compared with the 724 publications on potatoes during the same period. A quick comparable review by this author of a very thorough bibliography (Elliott-Fisk 1997) showed only 222 technical publications on giant sequoia during the entire 20-year period from 1980 through 1999. Most of these studies focused on such topics as distribution, biology, fire ecology, biochemistry, and silviculture. Prior to 1960 most of the research on the species had been more botanical than ecological. The review shows that of about 80 total technical papers written between the late 1800s through 1959, 52 dealt with giant sequoia biological characteristics (including silviculture) and only three dealt with giant sequoia ecology. From the 1960s through 1999, 128 papers were written on the subjects of sequoia ecology or fire ecology, 62 on biology and 49 on silviculture. [For a further brief discussion on the breakdown of giant sequoia literature, see Note 1].

Information on giant sequoia ecology and management was evaluated through the lens of possible shifts in global climate. Major concerns have been raised by managers, giant sequoia researchers, and other stakeholders over the possible impact global climate change will have on the species within its current natural range. It is reasonable to assume that the expectation of the public is in favor of efforts being made to preserve this species, and the larger ecosystem in which it is found. As has been the case before when interested citizens and organizations objected to management activities related to giant sequoia, managers can anticipate that this concern will be swift and energetic. In the late 1980s the National Park Service (NPS) was criticized by some for its use of fire as a management tool in sequoia groves, and the agency was required to suspend burning while an external review of the program was conducted (Dawson and Greco, 1994; Haase and Sackett 1998). Similarly, the USDA Forest Service (Forest Service) proposed a management plan for Sequoia National Forest (SNF) that was challenged by a number of groups over a number of issues, including the management of giant sequoia groves. These challenges resulted in a mediated settlement agreement (MSA) that committed the Forest Service to a number of future actions, including the creation of special zones around the perimeter of each grove (except those in wilderness areas), in order to provide protection to the grove ecosystem (Elliott-Fisk et al. 1996). Continued public concern over the management of groves in Sequoia National Forest eventually led to the creation of Sequoia National Monument (USDA Forest Service 2010a). It is safe to assume that the public will critically scrutinize future discussion regarding giant sequoia management in response to the challenges presented by global climate change. It is also safe to assume that any proposed action will find its share of active and vocal opponents, making the need for science-based decision making processes all the more important, along with effective communication of the reasoning behind preferred management alternatives. The public's concern for, and attachment to, giant sequoias as a cultural treasure is too strong to do otherwise (Rigg 2001; Piirto et al. 1997).

Natural History of Giant Sequoia

Paleohistory

The early literature regarding the geologic past of giant sequoia is largely the result of work by Daniel Axelrod, who recorded sites bearing the remains of sequoian ancestors throughout the western United States, and traced the westward movement of sequoia during the mid to late Tertiary Period in conjunction with the Sierra Nevada uplift (Axelrod 1959, 1962). Based on his research, it is safe to assume that giant sequoia were well established on the western slope of the Sierra Nevada by the beginning of the Quaternary Epoch, when the elevation at the Sierran crest would have prevented any opportunity for further western migration (Axelrod 1959; Hartesveldt et al., 1975). Therefore, the natural history of the giant sequoia for the last million years is found on the western Sierra Nevada, excluding the possibility of isolated and now extirpated remnants on the east slope (Davis 1999a).

The past million years have been climatologically dynamic. No fewer than eleven glacial events have occurred during this period, and their duration when compared with inter-glacial events indicate that very cold temperatures have been a dominant feature of the period. At least six of these glaciations are recognized in the geology of the Sierra Nevada, along with associated – and much briefer – warming events, and it can be assumed that each presented survival challenges to all plant species (Millar 1996). These challenges included very rapid shifts in temperature regimes. Within several years to a few decades, average temperatures had changed from 3-15° C, marking either the end of a glacial epoch or the end of an interglacial period (Millar 2003). Early Quaternary cycles averaged one cold/warm event every 41,000 years, while the last half of the epoch drew this out to about 100,000 years. Still, the proportion of glacial to interglacial time span is about 9:1, so it is reasonable to assume both that the recent past – on a geologic scale – has been characterized by ice, and that the current Holocene interglacial period is neither typical of the past million years, nor an indication that glacial cycles have ended.

Tausch et al. (1993) suggest that the history of the Pleistocene is one of biological instability. As climate shifts occurred, not only would plant communities be challenged, individual species within those communities would be differentially affected by the change. As a result, community composition would shift as some biological components were locally (or regionally) extirpated – hence, for instance, the elimination of spruce from the Sierra Nevada (Millar 2003).

Much of the early speculation about the reason for giant sequoias being so limited and localized in their current distribution worked under the assumption that the current arrangement in some way reflected the spatial arrangement of the species during the Wisconsin Ice Stage. Hypotheses developed with this in mind assumed either that the existing groves represent microclimatic refugia in which the species survived during the last glaciation (Muir 1877), or that the species was wide spread and common across their current range at the end of the last glacial period (although at a somewhat lower elevation). This last model assumes that they were subsequently forced into remaining mesic sites during the Altithermal, about 5000-8000 BP (Rundel 1969). The studies of various authors indicate a more dynamic condition of giant sequoia distribution during the current inter-glacial period. The examination and dating of pollen deposits in Sierran wet meadows and macro-remains in ancient wood rat middens has shown that the groves are a relatively recent phenomenon, that prior to about 4500 BP, giant sequoias were a more widespread, but infrequent, part of the early Holocene Sierra Nevada forest, and that occurrences of the species at the end of the last glacial event may have been at somewhat lower elevations (Anderson 1994; Koehler and Anderson 1994; Cole 1982). Given the longevity of the species, the studies of Anderson and others show that the current groves may perhaps only two to three sequoian generations old, which in turn raises some doubt as to how stable the groves are, and what their current distribution actually represents. It now seems more likely that the groves represent a reaction to transient ecological conditions specific to the past few thousands of years.

The above hypotheses were specific to the southern Sierra Nevada, and it is possible the more disjunct northern groves may reflect entirely different dynamics (Rundel 1969, Hartesveldt et al. 1975). Koehler and Anderson (1994) studied macro-fossils and preserved pollen in the strata of Nichols Meadow (near the Nelder Grove), and discovered: 1) that the Wisconsin age flora was represented by species adapted to a cold, arid climate similar to the eastern Sierra Nevada, with *Artemesia* sp. and *Sarcobatus* sp. as indicators; 2) during the period from roughly 9000 to 12500 BP giant sequoia was found there in what could be termed “grove-like” densities; and 3) subsequent drying and warming conditions resulted in a movement to higher elevations, as represented by their current arrangement in the Nelder Grove.

Giant sequoia pollen has been extracted from sediments found in the ancient Tulare Lake, and dating from before 9000 BP. Since the lake, located on the floor of the San Joaquin Valley, was fed by a number of relatively distant West Sierran drainages, this indicates the trees may have been widespread and common. The loss of pollen later in the sample chronology indicates that sequoias became much less common during the Altithermal (Davis 1999b). The climate of the Holocene at this time was warming, reaching a maximum at around 6000 BP, followed by subsequent cooling (with a few ups and downs since) (Woolfenden 1996; Anderson 1994, Millar and Woolfenden 1999a, Davis 1999b). Interestingly, a lake bed core from Mono Lake, on the east side of the Sierra Nevada, also displayed a large pulse of pollen dated from about 11000 BP to about 7500 BP (Davis 1999a). This surprising result contradicts all other literature on the geologic history of the giant sequoia.

The interpretation of data from pollen collected in Sierran meadows indicates that the present grove related distribution dates from about 4500 years BP (Anderson 1994; Anderson and Smith 1994). Subsequent climate shifts probably resulted in the same type of fluctuations of tree distribution noted elsewhere in the Sierra Nevada (Lloyd and Graumlich 1997). It is therefore reasonable to assume that if, as Rundel (1971) suggests, groves have been spatially stable for the last several hundred years, that period of stability does not represent the previous 4000 years.

Current Distribution

Giant sequoias occur naturally in a number of groves in the Sierra Nevada, although the actual number varies by author. The State of California (1952), and Rundel (1972) listed 75 groves, and this number seems to be the most frequently used in giant sequoia-related literature. Willard (1994) placed the number at 65, and then increased it to 67 in 2000, while Fins and Libby (1994) cited 72 groves. Elliot-Fisk et al. (1996) stated that there were 73 groves (although accompanying tables named 75), and the Save the Redwoods League web site (as of 2010) put the number at 77. The variation is largely due to splitting or combining nearby populations that some consider too close to be distinct, while others feel they possess characteristics that set them apart from adjacent groves (e.g., distance/proximity, occupying separate watersheds or being otherwise divided by natural features). Defining the geography of a grove is relatively easy for the northern eight groves due to their isolation, but it becomes more difficult for all of the remaining groves south of the Kings River, where the proximity of giant sequoia populations can make grove delineation murky indeed.

“Grove” is mostly a word of convenience that has no universally applied biological or ecological definition, although – by extension – it does give a general spatial definition to an area of suitable habitat for giant sequoias. It should be noted, however, that the Forest Service did adopt a set of guidelines that created an administrative definition, based on standardized approaches to dealing with special situations that create confusion. For instance, although groves are generally mapped as a polygon delineated by the outermost trees of a group of sequoias, this leaves open to interpretation the situation of whether a specimen is within the edge of a grove or an outlier of a nearby grove. The Forest Service requires that a tree be at least 1 foot in diameter and be within 500 feet of at least three other sequoias, also with the same minimum diameter. Their standards also require that any newly defined grove consist of at least 10 sequoias, four of which must be at least 1 meter (3 feet) in diameter (Elliott-Fisk et al. 1996; USDA Forest Service 2010a). It should be noted that this definition would exclude some stands of giant sequoia already defined as groves, such as the small, northernmost Placer.

A pitfall of defining a specified area as a grove is that the recent and current distribution of sequoias reflects environmental conditions of a period of time that was unique in terms of moisture and temperature, as well as (possibly) fire occurrence, several of which influence suitable habitat for the species. In short, grove boundaries may only represent the distribution of sequoias over the last few hundred years, and may not define areas around groves that are suitable habitat but not currently occupied. More importantly, they most likely do not represent the potential suitable habitat of sequoias in the future, if predictions of climate change hold true. These concepts will be expanded upon in other sections of this paper.

The natural groves of sequoia are arranged in a general North-South distribution along the western slope of the Sierra Nevada, and share generally common characteristics of precipitation, soil, and temperature. Individual specimens outside of identified groves are known, but they are still found within environmental conditions that are consistent with the groves, and are always near a grove. The groves range through the lower two-thirds of the Sierra Nevada. The northernmost Placer Grove is the smallest, with only six (possibly seven – William Libby pers. comm.) known trees. The next several groves to the south are widely spaced, with but eight from the northernmost Placer Grove and the McKinley Grove, separated by approximately 305 kilometers (190 miles). The remaining 67 groves occur south of the Kings River over a range of about 115 kilometers (70 miles), creating a band that is nowhere more that 15 kilometers (9 miles) wide. The elevation ranges of the groves are along a north to south gradient, with northern groves occurring between 1400 and 2000m (4700 – 6700ft), and southern groves generally between 1700 and 2150m (5600 – 7100ft; Rundel 1969; Hartesveldt et al. 1975). Some groves display strong variance with these figures, however, both at lower and higher elevations. Isolated trees below the Garfield Grove occur as low as 830m (2700ft; Hartesveldt 1963). There are even more instances of sequoias at elevations above 2400m (8000ft; Rundel 1969). They thus display a predictable and general rise in elevation with decreasing longitude, with one notable exception. At 1570m (5150ft), the Placer Grove is at a noticeably higher elevation than its nearest neighbors, lying about 60 air miles to the south; the second and third most northerly North and South Calaveras Groves, each at approximately 1460m (4800ft), have only a few trees that even approach 1500m (4920ft. – pers. obs.)

The area sequoia groves occupy in the Sierra Nevada has been commonly given as approximately 14,600 hectares (36,000 acres). This figure seems to derive from a report prepared by the State of California in 1952. However, as will be noted, more recent literature gives significantly different results. Stephenson (1996) found discrepancies in grove sizes, but little difference in the total grove area just given. Elliott-Fisk et al. (1996) presented grove sizes totaling 18,300 hectares (45,220 acres). The most significant change in these figures was seemingly caused by revised grove maps located in Sequoia National Forest (now in the Giant Sequoia National Monument). Most recently, the Forest Service revised the grove areas under its management down slightly, for a total grove area of about 17,500 hectares (43,250 acres, USDA Forest Service 2010a). These various figures are presented in Subappendix 2.

Regardless of these variations, the relative proportion of grove area managed by various entities is generally close to what Stephenson cited in 1996, with the Forest Service responsible for about 58% of grove area, NPS for 26%, the State of California with 7%, and the Bureau of Land Management, the Tule River Indian Reservation, and Tulare County with about 1% each. The remaining 6% is in private ownership.

Needless to say, there is confusion on the size of the current groves. More than anything, this seems to reflect both the lack of a consistent definition of what constitutes a grove, as well as the sophistication of methods used to describe a grove polygon.

Giant Sequoia Ecology

Sequoia's Role in the Sierran Forest

Describing the function of giant sequoia in the context of its ecosystem is not an easy task. First, the species is only a minor component of the much broader and extensive Sierran mixed-conifer forest ecosystem. It can even be argued that it plays no ecologically significant role at all. It occurs in very isolated locations that, while possibly an indicator of a locally mesic hydrologic regime, are not especially different from other mesic sites within the forest, other than the fact that those other sites have no giant sequoia (Hartesveldt et al. 1975; Rundel 1969; Weatherspoon 1985). They have no special associations with other plant species, and, regarding fauna, to date only a few insect species seem dependent on sequoias for at least one life stage (Harvey et al. 1980; Kerr et al. 2009). In essence, the forest of the western, mid-elevation slope of the Sierra Nevada would have developed much as it did if giant sequoia were never present.

The size and longevity of giant sequoia invite them to be considered as a late seral species – in effect, finding suitable habitat only after a series of earlier successional stages. Some have referred to sequoia groves as a fire climax community, implying that they are the ultimate ecological expression of an ecosystem dependent on fire (Parsons 1978; Rundel 1971, Harvey et al. 1980). Sequoias are, however, best described as a pioneer species – albeit a persistent one – colonizing an area only after some major disturbance occurs that removes virtually all potential competitors for sunlight (Stephenson 1994). Other shade-intolerant species, such as ponderosa pine and California back oak, may share this opportunity, but are more successful in openings that are less mesic, and therefore less likely to support the rapid and extensive growth of giant sequoia (Rundel 1972, Weatherspoon 1990; Barbour pers. comm.). White fir and sugar pine – the species that become dominant over giant sequoias, will colonize gaps along with sequoia, but at a much lower density (see Table 1). White fir, incense cedar and – to a certain extent – sugar pine, are shade tolerant, and will reproduce under a full canopy.

Within the groves, dominance is held by white fir, followed by sugar pine, then by giant sequoia (or, in some higher elevation groves, red fir (*Abies magnifica* A. Murray)). To a certain extent the current lower ecological importance of sequoias is an artifact of modern human interference (Rundel 1971; Vankat and Major 1978). The current, altered fire regime, originally caused by such factors as livestock grazing and the suppression of Native American burning practices – followed much later by effective fire suppression – has allowed non-sequoian species to increase in relative dominance. The initiation of prescribed burns has reversed this trend to varying degrees, with mortality to non-sequoia conifers being high relative to sequoias. The importance of sequoias has increased as a result (Kilgore, 1972; Keiffer 1998).

While groves are typically found on more mesic sites within watershed, that does not imply they are restricted to flats or riparian corridors. In fact, their distribution within a grove can include upland slopes that appear xeric, at least at first glance. Ponderosa pine and California black oak are sometimes cited as being associates of giant sequoia, but that may be more common in the southern groves, only. These two species seem to be absent or rare in at least the seven northernmost groves (Placer to Nelder), but are found adjacent to these groves on dryer, warmer exposures (Barbour, pers. comm., pers. obs). Ponderosa pine and California black oak are found within grove boundaries in the southern groves, but may be occupying locally xeric sites, reflecting a mosaic of hydrologic conditions (Rundel 1969; Weatherspoon 1985). Caprio and Stephenson (pers. comm.) felt that this distinction did not reflect their impressions, although they did feel that this might be the case with Jeffery pine's distribution within groves.

Soil and Hydrologic Relationships

Soil type was one of the first to be considered and eliminated as an important determinant of grove location. As Rundel pointed out, groves are found on a wide range of soils, from the ubiquitous granitic soils common throughout the Sierra Nevada to less common types derived from schist and metamorphosed basalt (Rundel 1969). At least one specimen in Spain grows on desert alkali soils (Hartesvelt et al. 1975). Regardless of type, however, texture does seem to be important, with a preference for sandy soils with low clay content (Hartesvelt et al. 1975). Beyond that, giant sequoias may also have some preference for soil chemistry. Work by Zinke and Crocker (1962) and Zinke and Stangenberger (1994) indicate that soils in giant sequoia groves are typically higher in pH, higher in calcium and lower in nitrogen than the soils associated with other neighboring conifers, although this may represent centuries of plant-soil chemistry interaction, rather than a site preference. However, Rundel (1969) felt that any preference displayed by giant sequoia for towards soil chemistry was weak, especially when compared to the variation between the chemical properties shown between groves. Finally, Zinke and Crocker (1962) indicated a site preference by giant sequoias against young, stony, poorly drained soils.

As opposed to the relatively minor role played by soil type and soil nutrients, soil moisture patterns do play an important role in grove establishment. Rundel (1969, 1971; Halpin 1995; Hucks 1999) identified a significant increase in soil moisture within the groves studied, compared to the surrounding forest. In some cases more mesic sites are easily observed (margins around meadows, riparian corridors, etc.), but upland stands of sequoia may have no obvious characteristics associated with increased subsurface moisture (Rundel 1969; Anderson et al. 1995). Halpin's work also showed that the water holding capacity of soils within groves was significantly greater than surrounding forested areas, and may also be greater than had been previously believed (Halpin 1995). Hucks (1999) monitored soil moisture across the boundaries of two groves (the North and South Calaveras), and found significant differences between white fir/giant sequoia locations and those dominated by ponderosa pine.

A study conducted at the Packsaddle Grove (Sequoia National Forest) showed that while moisture may have disappeared from soils by late summer (September), moisture reserves were still present in weathered bedrock immediately below. It was estimated that annual precipitation of less than 68 cm (27 inches) would fail to maintain this water reserve on upland sites, resulting in late summer water stress. Significantly, at the time of publication, that level had been reached in three of the previous ten years at that site (Anderson et al. 1995). Halpin also indicates the abundance of water reserves below the soil layer, and at depths even greater than Anderson's (Halpin 1995).

It has been common to delineate grove boundaries as a single polygon, although this may create the impression that all sites within the boundary are suitable for occupation, although especially in large groves this may not be the case. Giant sequoias may be occupying plots with distinct hydrologic characteristics especially suitable for colonization, and these may not be found uniformly throughout any particular grove (see also Rundel 1969, and Weatherspoon 1985).

Halpin (1995) compared interactions of giant sequoia (as well as other associated species) with the environment at spatially hierarchical levels. He found that the abiotic environmental factors he studied (percent soil, soil depth, topographic flow, potential evapotranspiration (PET), and precipitation) contributed differentially to tree distribution by species, but that the influence of each was based on the size of the area sampled. At 50 hectares (the 'catchment' level) higher topographic flow was the only significant regulating factor for giant sequoia. Topographic flow is defined as water movement over the surface and towards established channels, and this was the only factor that demonstrated any significant effect on sequoia distribution. At the patch (1 hectare) level PET was the most important, and the only value Halpin considered that was statistically significant. Interestingly, he attributed this to the soil pressure mound created around giant sequoias: when he modeled the importance of PET with this micro-topographic feature removed it was no longer significant. Thus the pressure ridges created by the larger sequoias are environmental features of great importance to the local distribution.

In essence, Halpin demonstrated that the distribution of giant sequoia was not affected by any tested environmental characteristics. However, on a smaller scale, the movement of water over the surface of the ground – before it reaches even ephemeral streams – does have an influence on creating suitable habitat. Finally, at the patch level, the determining factor is the result of interactions between giant sequoias and their environment.

Halpin went on to examine the tendency of sequoias to aggregate. This tendency had already been noted by Bonnickson and Stone (1982), Stohlgren (1991), and Stephenson (1994). Using a "nearest neighbor" point pattern analysis, Halpin found that at the 20 hectare scale giant sequoias were significantly closer than would have been expected with by random distribution, but that this began to degrade with smaller sized scales.

As is discussed in the section on the paleohistory of giant sequoia, groves as we experience them are a recent phenomenon. Over the past few thousand years the species has been able to exploit a limited range of suitable habitats. During this period, these habitats were large enough to allow for (in most cases) the occupation of fairly extensive contiguous areas, but unique enough to prevent the species from expanding beyond these sites. At least in terms of soil nutrients and soil hydrology, it is reasonable to assume that other sites within the Sierra Nevada have comparable qualities, but these have not been colonized by giant sequoia. Either the species did not occur in the vicinity to begin with, or other as yet undetermined environmental factors prevented establishment.

Weather and Climate

At the elevation of the groves a significant portion of precipitation falls as snow, typically from October through April. Total annual precipitation has historically ranged from 900 to 1500 mm (35-55 in.). Dry season precipitation has been described as being typically less than 30 mm (1.2 in., Rundel 1969). Summer precipitation is rare, but when it occurs it is commonly associated with thunderstorms. However, these storms may sometimes occur with little or no associated rain, which makes them an important wildland fire ignition source. As will be discussed later, prehistorically these ignitions were ecologically positive events for giant sequoia, but more recently have become a source of concern, due to longer fire intervals and the subsequent increase in severe fire behavior (Westerling et. al. 2006; Chang 1996; Skinner and Chang 1996). An assessment was made of the 210,277 lightning strikes recorded in the Sierra Nevada bioregion during the period from 1985 through 2000. The study indicated that 105,824 (slightly over half) struck at elevations between 1200 – 2399 meters (3900 – 7900 feet), which is the range of giant sequoia groves and slightly below (von Wagtendonk and Cayan 2008). Lightning strikes below groves are more important as potential ignition sources than those above, since fires burn upslope much more readily than downslope.

Stephenson (1988, cited in Halpin 1994) determined that precipitation on SEKIs western slope increased steadily from low elevations until about 2000m (6600ft), at which point changes in precipitation were in quality (snow vs. rain) instead of quantity. This means that total annual precipitation should be essentially constant within the elevational range of giant sequoia groves, which in turn means that precipitation records from one site will be applicable throughout.

Temperature ranges are variable across the range of giant sequoia, but in keeping with the Mediterranean Climate model, with essentially cool, wet, winters and warm to hot, dry summers. Weather records are lacking for most groves, but the indication is that average summer highs are about 29°C (84°F), with extreme high temperatures reaching 40°C (104°F). Average winter lows of about -5°C (25°F). Extreme lows can reach -24°C (-12°F) (Rundel 1969; Weatherspoon 1985). Although such extremely cold temperatures are rare within their natural range, some sequoias (though not all) planted elsewhere have survived even greater lows, with a thriving specimen in Wisconsin withstanding temperatures as low as -35°C (-31°F) (Libby pers. comm.). These figures are derived from accurate data records, but from only a few weather stations in or near groves, and only extend back into the recent past 100 years or so. Since it is clear that climatic conditions in the groves have been both colder and warmer during the past few thousand years (Swetnam 1993; Swetnam and Baisan 2003), these ranges cannot be considered as representative of the true environmental tolerances of the species. Additionally, the sensitivity of sequoias to environmental conditions is necessarily expressed differently at different life stages, with the seed reproduction and seedling stages being the most sensitive to both heat and cold (Harvey et al. 1980, Stark 1986a, 1986b).

Giant Sequoia Reproduction

Weatherspoon (1985), Harvey et al. (1980), and Hartesveldt et al. (1975), present detailed reviews of the means by which giant sequoias reproduce. Unlike most conifers, giant sequoias produce seeds with low caloric value, and are therefore not a preferred target for herbivory by birds, mammals, and insects. On the other hand (and again unlike most conifers) the cones bearing those seeds do have nutritional value, and are an important food source for one mammal, the Douglas squirrel (*Tamiasciurus douglasii*), and the larval stage of at least two insects (*Phymotodes nitides* and *Gelechia* sp.). Of the insect larvae, the Gelechiad moth does not play a role in giant sequoia reproduction, since they only develop in first year cones, at which point the seeds are not viable. Since sequoias are not genetically disposed to regularly dehisce seeds, the remaining two biological agents are important causes of any annual seed dispersal, with the long-horned beetle accounting for the larger portion, by a factor of about 3:1. The only other contributors to annual seed spread are wind damage, snow-load damage, and cone drying from sun exposure. Harvey et al. (1980) estimate that a large, full-canopied sequoia may produce about 1500 new cones per year, and each cone contains an average of 200 seeds. Assuming that the total number of cones in an undisturbed tree remains constant from year to year, this would indicate that approximately 300,000 seeds are dispersed per year, per tree. Because the Douglas squirrel usually caches cones in the ground, and storm related damage cause cones to fall close to the parent bole, seeds are not necessarily evenly distributed across the landscape, as they would be if all seeds were dispersed directly from the canopy. On the other hand, seeds that do fall from the canopy tend to sail, and can be carried distances of up to 400 meters from the source tree (Hartesveldt et al. 1975; Schubert and Beetham 1962).

A young sequoia may produce ovate cones by the time it is 10 years old, but it may take another ten years before it will produce staminate cones, and it may take about 200 years before the trees are large enough to reach maximum cone (and therefore seed) production. Although the cones are known to persist on the tree for as long as twenty years, the seeds within the cones continue to lose viability over time. Reproductive success is therefore more a matter of quantity of seed, than quality, with a large, old growth giant sequoia having a seed reserve that can number in the hundreds of thousands (Harvey et al. 1980).

It is important to bear in mind that both the viability and germinability of giant sequoia seeds is not high, due to a number of factors (per Harvey et al. 1980, unless otherwise noted):

- Seeds in newly developed cones do not become viable until the second year
- Average seed viability and germinability are naturally low, although the numbers vary by study, tree, and grove, ranging from 20 to 40% (Fins 1979; Stark 1968b; and Harvey et al. 1980)

- Although very young cones increase in viability as they age, they peak at around five years, and older cones (which can persist on the parent tree for up to 20 years or more) gradually drop in the proportion of viable seeds
- Viability increases directly with both cone size and seed size
- Cones buried by Douglas squirrels may be too deep for germinated seeds to reach the surface
- Viable seeds that fall to the ground rarely find suitable conditions (which will be discussed later), and frequently (perhaps at the rate of 99%) desiccate before germination.

Sequoia seeds that are attempting to germinate must have access to sufficient moisture to establish a root system. Seeds falling on the surface of normal forest litter may germinate if the litter and underlying duff are moist, but these surface layers dry quickly, and any young seedlings are likely to desiccate (Stark 1968b). They may also be subject to attack by soil-borne pathogens (Shellhammer and Shellhammer 2006). Conditions favorable for seed germination and seedling establishment occur infrequently, and giant sequoia reproduction is both opportunistic and episodic. This is most evident in small groves, where (using size as a surrogate for age) trees are not evenly distributed by diameter, but rather clumped into size categories. In larger groves this pattern disappears, although this may be a caused by greater sample size, which may obscure any size/age patterns within large groves (Stephenson unpublished data; Stohlgren 1991).

Of a theoretical 300,000 seeds dispersed each year from a parent tree, few will germinate, and it is highly probable that few, if any, germinated seeds will survive the seedling stage. The maintenance of viable sequoia populations cannot therefore be the result of this annual release. The fact that sequoia groves have maintained stable numbers for millennia is the result of an additional factor: fire.

Some efforts to restore fire as a stimulus for giant sequoia reproduction have had spectacular results (Biswell 1989; Harvey et al. 1980), with young sequoias sometimes forming dense thickets. Under natural fire conditions, subsequent exposure to heat and flames would thin these patches, preventing long-term competition between trees. York et al. (2006) demonstrated that sequoias saplings in plantations left un-thinned for twenty years after planting did not respond as well when finally released, although they did so eventually.

Fire Ecology

Fire's Role in Sequoia Reproduction

The positive role fire plays in giant sequoia ecology has been well documented: they are a species whose long-term viability is dependent on exposure to frequent fires (Kilgore 1972; Harvey et al. 1980; Stephenson et al. 1990; Stephenson 1996). Fire influences giant sequoia ecosystems in many ways, but perhaps the most important is as a mechanism for stimulating seed release. While the variables influencing such events are many (including fire intensity, wind, air temperature, relative humidity, and canopy height), the mechanism is convective heat from the fire, rising through the canopy, causing cones scales to part (See Note 2). The resulting seed release far exceeds the background release discussed above, and may reach 20,000,000 seeds per hectare, with one study finding over 7500 in a square meter after a fire. This compares with a background rate of slightly over 2 seeds per m^2 per day (Harvey et al. 1980).

On the other hand, if litter and duff moisture remain high, then seedlings are likely to succumb to fungal and bacterial agents. Successful giant sequoia recruitment under either circumstance is infrequent, at best (Harvey et al. 1980). Periodic fire removes the organic overload from mineral soil and sterilizes the soil of seedling pathogens, and to that end the greater the intensity of the heating, the more suitable the soil surface will be for giant sequoia establishment (Shellhammer and Shellhammer 2006) [See Note 3]. Fire also plays a crucial role in opening up the forest canopy to allow sufficient sunlight for long-term success. Finally, fire may establish beneficial chemical characteristics, such as soil nutrients and acidity (Harvey et al. 1980). Other circumstances may create soil conditions that replicate the effect of fire in some ways, but not all. For instance, root rot or high winds may cause a tree to fall and thus expose mineral soil, but these events do not alter nutrient levels, nor change soil pH. Tree failures, may, however, be the first step in creating a canopy gap, the process ending when fire consumes the fallen trees.

Since the conditions that are favorable for seed germination and seedling establishment occur infrequently, giant sequoia reproduction is both opportunistic and episodic. This is most evident in small groves, where (using size as a surrogate for age) trees are not evenly distributed by diameter, but rather clumped into size categories. In larger groves this pattern disappears, although this may be a factor of sample size, which may obscure any size/age patterns within large groves (Stephenson unpublished data; Stohlgren 1991).

As previously discussed, this dependency is most clearly associated with reproduction, first through the preparation the soil to receive seeds, then through the stimulation of seed release from the serotinous cones. Proper preparation of the seedbed is critical for recruitment (Stark 1968a 1968b; Harvey et al. 1980). Aside from removing organics through combustion at the surface, intense heating can increase soil friability by causing clays to aggregate into silt to sand sized particles, volatize soil nutrients (principally nitrogen and phosphorus), volatize or combust soil organics, and increase soil pH. At the same time, some important soil nutrients, such as potassium, calcium, and magnesium, can increase by being released from organic molecules. Soil nitrogen levels may actually recover the amount lost through volatization by the same process (Certini 2005; Wohlgemuth et al. 2006). Various studies have shown the improved survival and growth of giant sequoia seedlings when occurring in burned soils, in spite of these significant heat-caused alterations (St. John and Rundel 1976; Harvey et al. 1980; York et al. 2010).

Fire plays another role crucial to the success of giant sequoia reproduction through the creation of gaps. As discussed in more detail elsewhere, the species is essentially a sun-dependent pioneer, and gaps provide the canopy openings that allow enough light penetration to promote rapid growth. In the absence of such an opening, giant sequoias are typically slow growing and poorly formed (See The Role Of Canopy Gaps).

The Fire Regime of Sequoian Forests

[See Note 4 for a brief explanation of the Fire Regime concept]

As will be discussed in a summary of the history of giant sequoia management, after a century of fire exclusion, efforts beginning in the late 1960s to restore fire to the groves focused on keeping fire intensity low and fire spread slow. While this made them easier to control (and probably more palatable to skeptics), it became evident that these fires did little more than remove very small trees and reduce overall fuel loads. However, it was (and is) inevitable that the most carefully managed prescribed burns will have local areas of high intensity, and it was here that significant changes in forest structure occurred: openings in the forest were created, and sequoia reproduction could be intense (Parsons 1994). This pattern reflects the type of fire regime under which giant sequoias evolved.

Fire behavior on the landscape is dependent on a number of factors, including those that vary very slowly over a centennial to geologic time scale (e.g., slope, aspect, shading, regional vegetation patterns, and climate), those that change on a decadal scale (such as local species composition, fuel bed loading, and fuel arrangement); and, those that change on a yearly, seasonal, or daily basis (essentially water related variables such as drought, relative humidity, and live fuel/dead fuel moisture content). Taken together, these factors virtually ensure that natural fires, burning perhaps for weeks, if not months, and across vast portions of a landscape, will not behave uniformly. It is commonly thought that the prehistoric fire regime of the Sierran mixed-conifer forest was one of frequent fires of low to moderate intensity, with occasional areas of locally high intensity. The frequency varies with elevation, aspect, and species composition, with ponderosa pine dominated forests averaging a return interval of 4 years and a maximum interval of 6 years, while white fir dominated forests (including giant sequoia groves), averaging a 10 year interval with a maximum of 16 (Caprio and Swetnam 1995; Caprio and Lineback 2002).

Less is known about the size and frequency of high fire intensity events that occurred under the prehistoric fire regime. Based on the work cited in the following section on gaps, it is reasonable to assume that they were typically less than one hectare in extent, although they could, on occasion, be much larger. Age/structure analysis of giant sequoia groves indicates their tendency to occur in even-aged groupings or aggregates that are undoubtedly the result of major disturbance events in the past (Stephenson 1994). Such events would have to have killed enough pre-existing trees to create an opening of large enough size to be suitable for subsequent regeneration to thrive. It is reasonable to assume that localized high intensity fire would be a major cause of such gaps. Thus the characterization of the giant sequoia pre-settlement fire regime as being one of frequent, low to moderately intense fires must be granted the caveat that infrequent, localized high intensity fires did occur (Stephenson et al. 1990; Stephenson 1996, 1999).

While frequent, low intensity fires encourage germination, they also limit recruitment by thinning young trees of all species, and preventing the eventual development of a dense understory and sub-canopy. This, in turn, disrupts the type of vertically continuous fuel bed required for the development and spread of crown fires (Kilgore and Sando 1975). The thinning process favors giant sequoia, incense cedar, and ponderosa pine, which are less susceptible to fire-induced mortality than sugar pine and white fir. This mortality can be caused either through damage to the cambium layer (van Mantgem and Schwartz 2003), or the crown. In the latter case, sequoia, incense cedar, and ponderosa pine can sustain significant crown damage (up to

90%), while white fir and sugar pine are much more sensitive to crown reduction (Stephens and Finney 2002).

When considering to role of fire in a giant sequoia grove, some consideration must be given to the effect of fire severity on the species. With the understanding that severity is an indication of the ecological impact of a fire, as opposed to simply the rate and level of energy release (intensity), this particular regime attribute gives an indication of both the short and long term impacts of fire, on both a species and an ecosystem (Sugihara et al. 2006). Assuming that a tree survives exposure to fire, by regarding the change in annual increment recorded in trees immediately after a fire of known (or implied) intensity, it has been demonstrated that a giant sequoia's increase in growth is directly proportional to the level of fire severity (Mutch 1994; Mutch and Swetnam 1993), the implication being that the reduction in competition (resulting from overall mortality) and released soil nutrients (see also St. John and Rundel 1976). Mutch and Swetnam (1993) also showed a direct relationship between fire intensity and post-fire reproduction.

One singular event identified in the dendrochronological record indicates that large areas of high intensity could still occur naturally. Swetnam et al (1992), and Caprio et al. (1994) documented a major fire in 1297 AD, in what is now Mountain Home State Forest. Reconstruction of the event from fire scars and growth release patterns indicate that the area exposed to intense fire behavior might have been several square kilometers in size. Its extent may not be as surprising as the fact that the intensities were high enough to kill large portions of the overstory, resulting in the creation of very large gaps and a pulse in giant sequoia recruitment (as well as a growth release for the surviving sequoias for up to a century). This event occurred during the Medieval Warm Period (about AD 1000 – AD 1300), a time during which fire frequency was higher than normal (Swetnam 1993). The fire seems to have behaved more like the stand-replacing fires that are have always been common in forests under a fire regime characterized by a long fire return interval, such as the Rocky Mountain lodgepole pine forests and the Bishop pine forests of coastal California. Due to fire suppression, this is also the current fire regime in much of the mixed conifer forest of the Sierra Nevada. See Subappendix 3 for an elaboration on this event.

Aside: Giant Sequoia Fire History Studies

Fire history studies in sequoia forests have been conducted throughout much of the tree's range, with the best results coming from the Giant Forest, Atwell Mill, Big Stump, Mariposa, and Mountain Home groves. (Fire scar samples collected at the North and South Calaveras Groves were found to be difficult to cross date, due to complacent ring widths, even during drought years). The studies show a fairly consistent pattern of frequent fires over the past few thousand years, with a narrow range of return intervals that average about ten years (Swetnam et al. 2009; Caprio and Lineback 2002). Also common to these studies is an abrupt termination of the prehistoric pattern fire occurring in the early 1860s. The initial cause of this change is not clear, but may be the result of more than one factor. Most recently it can be attributed to the efficient suppression of fires, but this could not have been an important factor for the entire period, since the federal and state fire policies that called for active suppression of wildland fires were not in place until the first quarter of the 20th Century (Pyne 1997). Prior to the 1900s, the lack of recurring natural fires must have been caused by other events, and two possibilities have been suggested. First, the 1860s are known to be the period during which widespread grazing was introduced to the Sierra Nevada (Farquhar 1965). Touchan et al. (1995) have documented grazing to be an important factor in fire regime shifts in New Mexico's ponderosa pine forest, at essentially the same time (ca. 1880) as the regime shift in the Sierra Nevada. Grazing could have altered fuel composition and continuity, especially in the herbaceous and fine fuel categories. Second, Euro-American dominance over Native American peoples in the Sierra Nevada became so strong in the 1860s that native cultural practices were essentially ending to any important degree. Among these practices was the anthropogenic use of fire (Anderson 1996). Although no research has been conducted to verify the claim, it is safe to assume that at least some portion of the fires documented in Sierra Nevada tree ring studies include anthropogenic fire (Anderson 1996; Caprio and Graber 2000), and the removal of these from the prehistoric fire record would certainly have resulted in a shift in fire frequency. Although the strength of this shift is open to debate (see Swetnam and Baisan 2003), the important point is that, for whatever reason, fires are not occurring at a rate sufficient to sustain the Sierran mixed-conifer forest and protect it from catastrophic wildfires (Westerling et al. 2006; Miller et al. 2009).

Although fire scars on tree boles are clear and direct indications of fires, they do not necessarily present a complete record of every fire that occurs in a given stand. The discontinuous nature of low intensity fires may not reach all trees, and at the trees it does reach the pulse of energy may be insufficient to penetrate the protective bark and heat the cambium cells to a lethal temperature (depending on the length of exposure, roughly 60-65° C). However, fire scars are not the only way in which fire events can be recorded. Tree rings can also indicate direct or nearby exposure to fire through such characteristics as expanded late wood, traumatic resin ducts, ring wedging, and growth release (Swetnam et al. 2009). Because giant sequoia is such a long-lived species, the combination of fire scares and other indicators of fire events means they provide excellent documentation of fire over a broad temporal scale. Early work at examining fire history within giant sequoia groves relied on fire scars and consistently showed fires occurring with a short return interval (i.e., high frequency), although the results depended on the methods used and the

Aside: Giant Sequoia Fire History Studies (continued)

species sampled (Kilgore and Taylor 1979, Swetnam et al. 1991, Swetnam 1993, Swetnam and Baisan 2003).

More recently, previous studies have been expanded upon and re-evaluated to give a better – and longer – picture of fire occurrence in at least one giant sequoia grove. Not only did this new work provide an impressive look at fires going back 3000 years, it also gave a spatially hierarchical view of fire occurrence. Swetnam et al. (2009), working in the Giant Forest Grove, were able to document fire return intervals of 15.5 years at the 0.1 hectare scale, 7.4 years at 1, 3.0 years at 70, and 2.2 years at 350 hectare levels. This shows that fires were typically patchy and typically quite small, but indicators that share a common year indicate more widespread fire events. At the 350 hectare level, such events seem to have occurred, on average, once every 35 years. These figures, however, are averages over a millennial time frame, and do not reflect how major changes in climate alter fire frequency. Finer analysis shows that the years with the most widespread fires are associated with draught years, and that the highest fire frequencies (i.e., a shorter return interval) are associated with longer periods of warm, dry weather. Corresponding to this is a lowering of fire frequency during periods of cooler climate. Fire scars also record when a fire occurred within growth year, at least as closely as to the season. The Giant Forest study showed that most (63%) of fires were associated with either latewood ring growth or the dormant period. While this dormancy is assumed to include the early spring months, it is more likely that these fires occurred during a period from the beginning of September through December, due to the probable unavailability of fuels at the end of winter and early spring (Swetnam et al. 2009).

The Role of Canopy Gaps

A great deal of the giant sequoia literature published since 1990 has dealt with the role of gaps, especially those created by fire. Gaps are transient openings in a forest that allow for the recruitment of shade-intolerant species, including giant sequoia. Within gaps, but spatially smaller, are aggregations, or patches, of reproduction. These young trees (and shrubs) are not necessarily uniformly distributed within a gap, but instead may be clustered (Demetry and Duriscoe 1996).

Despite their great longevity and size, giant sequoias are a pioneer species, ecologically suited to colonize forest openings as opportunities arise. This fact was not well recognized during the first one hundred years of sequoia management by public and private entities, and even then its full implication did not become apparent for many years (for comparison, see Hartesveldt et al. 1975 and Harvey et al. 1980 v Stephenson 1994 and York 2007).

As knowledge of giant sequoia ecology increased during and after the 1960s, two relationships became clear: the role of fire in sequoia reproduction, and the inverse relationship between seedling/tree growth and canopy shading. It is now understood that giant sequoia performs best in transitory forest openings created in the Sierran mixed conifer environment. Various agents can produce these openings, including localized pest/pathogen induced mortality, microburst wind events, avalanches, mass wasting, and (most importantly) fire (Rogers 1996). All have the potential to create gaps in the structure of an otherwise continuous forest canopy, with the size dependent on the intensity and severity of the event, its initial spatial extent, and secondary gap expansion (Schmidt et al. 2006; Worrell and Harrington 1988). The special importance of fire in generating gaps is shown by their virtual disappearance during the period of fire exclusion; with the exception of fire and (to a lesser extent) of pest/pathogen created gaps, all other mechanisms can be assumed to have been likely to occur at prehistoric rates. Pest and pathogen generated gaps may have actually increased in recent times, but this is more a reflection of declining forest health than an affirmative sign of ecosystem vibrancy (Rizzo and Slaughter 2001). As a consequence, most current gap generation in the Sierra Nevada is only occurring at an ecologically important level through the creation of large to extremely large gaps associated with harvesting and major, stand replacing, fires.

Giant sequoias display more rapid growth towards the center of the gap. Demetry (1995) suggests that this may be related to root competition between gap patches and surrounding mature trees – the closer young trees are to the center of the gap, the less impacted by roots of mature trees at the gap edge. This conclusion was supported by York et al. (2010), who found that growth improved with additional exposure to sunlight, but only up to about 70% of full sun, after which growth rates remained steady. Thus, increased exposure to the sun in the centers of large gaps contributed to increased growth of giant sequoias only up to a limit. The trees did, however, show a continuous linear increase in growth from the gap edge to the center in response to increased subsurface resources (whether water, nutrients, or both). At the same time, giant sequoias growing in experimental gaps grew better on the northern, sunnier edges than those along the shaded southern perimeter, and displayed growth sensitivity to moisture gradients. By contrast, the growth of ponderosa pine was sensitive only to sunlight, indicating an ability to occupy more xeric sites than sequoia (York et al. 2003).

The minimum initial size of highly productive gaps seems to be about 0.1 ha (0.24a), although York et al. (2009) found that seedling survival and growth in gaps as small as 0.05 hectares (0.12 acres) were still more successful recruitment sites than under a full canopy. Sequoia growth overall improves as gap size increases, but there is a limit. York (2007) and York et al. (2010) found that both seedling diameter and height increase improved with increasing gap size until about 0.2 hectares, above which growth began to level off.

Naturally created gaps in sequoia-mixed conifer forests can, of course, vary greatly in size. In a study of eighteen fire-generated gaps (ranging in age from 7 to 15 years), Demetry and Duriscoe (1996) showed that the characteristics of gaps change with increasing size. They grouped the gaps into three size categories, ranging from 0.067 hectares to 1.17 hectares (0.17 to 2.89 acres). Larger gaps display greater species diversity, although giant sequoia was always dominant. Mean density of sequoia regeneration also increased dramatically with gap size, although other species (incense cedar and red fir) seemed to prefer medium sized gaps (Table 1). Variations by species were also noted for site preference within gaps, with some species preferring the center portion of small to medium gaps (and giant sequoias showing the strongest trend in this regard), while others seemed to prefer the area midway from the edge to the center, although it was not always clear if this was the result of preferable environmental conditions or a result of seed dispersal distances. No tree species preferred gap edges, and only one shrub, bush chinquapin

(*Chrysolepis sempervirens*), was most dense along the margins (probably a function of its ability to root sprout after disturbance).

Table 1. Mean tree density by species (stems/hectare).

Gap Size	Small	Medium	Large
(Size Range)	(0.067 - 0.097 ha)	(0.15-0.24 ha)	(0.34 - 1.17 ha)
Giant Sequoia	653	612	2956
White fir	62	70	107
Sugar pine	50	58	114
Incense cedar	0	62	5
Jeffrey pine	0	2	6
Red fir	29	90	39
Ponderosa pine	0	7	2

After Demetry and Duriscoe (1996)

Gap formation also has an impact on the surrounding, canopy-covered environment. York et al. (2010) found that giant sequoias living near recently developed gaps had an approximately 24% increase in growth over controls. This was in spite of the fact that the test trees had all emerged from the surrounding canopy, thus indicating that light availability was probably not a factor.

Gaps evolve over time and space. After the initial disturbance, secondary effects may expand gap size for a period of time, as surrounding vegetation adjusts to the new conditions. Factors that can cause gap expansion include sunscald, wind damage, and insect attack. Population sizes are typically large after colonization of the gap by pioneer species. Over time attrition reduces these populations, and this reduction may fragment the patches or reduce the patch size (Worrell and Harrington 1988; Stephenson 1994). For long-lived species such as giant sequoia, what had started as large patches (with many trees) will reduce significantly in size and population, until they may consist of a single tree (Stephenson 1994).

If natural gaps are usually created by fire, and if creation of such a gap implies high fire intensities, then it follows that much of the soil surface immediately after the establishment of a gap would have been exposed to extreme temperatures. In fact, the success of seeds and seedlings is low in areas of artificially created gaps that were not burned, compared to areas that were (York et al. 2010).

Pathogens and Pests

Much of the popular literature regarding giant sequoia proclaim the great resistance of the trees to disease, and in fact no particular biological agent has been found to be an important threat to the species within its normal range. Still, sequoias are susceptible to various pests and pathogens, and are especially sensitive at the seedling and small tree stages of life. The following discussion considers these agents to be a part of the sequoian ecosystem, and not an unusual threat. However, climate change may enhance the susceptibility of sequoias, and so pests and pathogens are also discussed in the section dealing with potential climate related threats to the species. It is important to note, however, that the current unnaturally crowded conditions throughout the Sierra Nevada has reduced the health of most forests, making them more susceptible to disease and insect attack, particularly among the other conifers with which sequoias share habitat (Ferrell 1996). Unfortunately, it also seems as if fire and thinning efforts used to address the high density of trees found in the range may make retained trees more susceptible to attack, at least in the short term (Maloney et al. 2008).

This section presents information regarding biological threats to giant sequoia experienced in its natural range, and in plantings elsewhere. As experienced with the spread of the Eurasian white pine blister rust, which was introduced to western North America from a single shipment of nursery stock to Vancouver, British Columbia in 1910, non-native diseases can spread quickly, be resistant to control, and can have devastating results in species with poor natural resistance (Kinloch 2003). Many similar examples exist of non-native diseases and pests establishing themselves in both terrestrial and aquatic ecosystems, and there is no reason to suspect that these introductions will decline in the future. Importantly, giant sequoias planted in non-native habitats are susceptible to locally endemic pathogens. As will be discussed in the section dealing with threats to giant sequoia, any of these that prefer a warmer climate may find the new conditions resulting from global climate change opening up new habitat within the current range occupied by sequoias. This may be especially the case with diseases that prefer warmer winters (Evans et al. 2008; Harvell et al. 2002). For both of these reasons, this section will not only address pathogens that share currently the native environment occupied by sequoias, but those that are known to infect sequoias world-wide.

<u>Pathogens</u>

The most commonly cited pathogen to giant sequoia is annosus root rot *(Heterobasidion annosum,* more commonly known by its former binomial, *Fomes annosus),* (Bega 1978). This fungal disease can infect all conifers, and is a common cause of death through structural failure, although mortality can also be the result of annosus weakened trees being more susceptible to insect attack (Slaughter and Parmeter 1989; Piirto 1994). The disease is commonly spread by intra- and inter-specific root contact, and is characterized by the weakening of wood tissue in either the roots or bole (depending on the host) that can result in structural failure. In sequoia the effect is found in roots, and has been recognized as being present in (although not clearly the cause of) many sequoian failures (Piirto 1974, 1977; Parmeter 1986). The disease can also spread aerially, when spores fall on freshly exposed sapwood. For this reason, infestations are commonly associated with thinning operations, especially if freshly cut stumps are not quickly treated with borate salts (Kliejunas 1989). Its status as an important disease of conifers has been linked to increased stand densities, which create greater opportunities for root contact both within and between species. This as has been demonstrated in sequoia groves, where *H. annosum* has passed between giant sequoias and white fir, which is especially susceptible to the disease (Piirto et al. 1998). This report also cited many other fungi associated with giant sequoia fire scars, but these did not present any phytopathological symptoms.

Interestingly, *H. annosum* infestations, which can be localized and intense, have been linked to the creation of "well over" 200 canopy gaps of up to 0.4 hectares (1 acre) in Yosemite Valley since 1970. It is not known if any data exist that indicates similar levels of mortality in giant sequoia groves. This may be unlikely, since the spread of the disease seems to be greatly enhanced by activities that involve tree removal (Slaughter and Rizzo 1999).

Armillaria mellea, more commonly known as Armillaria root disease is another fungal disease known to infect giant sequoia within its natural range, and has been linked to the creation of small canopy gaps in other forest types, as well. It is ubiquitous in a forest environment, with (in some cases) up to 100% of trees showing root infection (Slaughter and Rizzo 1999).

Poria incrassata, a decay-producing fungus usually associated with wood structures, has occasionally been found in living or recently fallen trees, including coast redwood. A single failed giant sequoia in Whitaker's Forest had *P. incrassata* in the extensively decayed roots (Piirto et al. 1977).

Some of the literature dealing with giant sequoia pathogens is speculative, in the absence of firm research. For instance, Parmeter (1986) expresses his belief that research will show damping-off and root rot fungi to be major factors in preventing seedling establishment. He further notes that these two diseases are difficult to differentiate from normal seedling desiccation.

Information on giant sequoia pathogens occurring outside of its natural range is limited, and focused largely on various fungi that attack nursery seedlings in young trees. *Cercospora sequoiae,* a needle blight found in the eastern and southeastern United States (Mulder and Gibson 1973) was identified in the 1880s on young sequoias planted in a garden in Pennsylvania. Charcoal root disease, caused by *Macrophomina phaseoli*, (Parmeter 1986) and *Botrytis cinerea*, commonly known as gray mold (Smith et al. 1973) have also been identified in nursery stock, as has *Phytophthora citrophthora*, which caused both needle blight and root rot (Sandlin and Ferrin 1993). A canker, *Botryosphaeria dothidea*, that kills stems and tops has been identified in giant sequoia plantations in California (Worrall et al. 1986), and it is possible that this pathogen in particular could move upslope into existing groves with a warming climate. *B. dothidea* has also been identified in Europe, where it has caused branch dieback to sequoias (Kehr 2004; Vajna and Schwartzinger 1998[*]), as has *Armillaria mellea*, which, as mentioned, is found in giant sequoia groves (Parmeter 1986).

<u>Pests</u>

Forest pests are not unknown in giant sequoias, although their importance may have increased in recent decades due to the increased population of trees overall (Piirto 1994; Parmeter 1986,). The most commonly cited pest is the carpenter ant (*Camponotus modoc*), which form galleries in the wood and bark of the tree. While the ants are not directly harmful to the tree, the galleries can weaken tree structure, potentially leading to failure. Historically this may not have been a

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[*] Citations taken from article abstracts

serious problem for giant sequoias, but the fire suppression-induced increase in white fir may have compounded the problem by expanding the ant's habitat. Carpenter ants are known to rely on sugars secreted by aphids, which are known to be common inhabitants of white fir and giant sequoia (Ferrell 1996; Piirto 1994; Tilles and Wood 1982; Tilles 1979). The increase in white fir populations within groves may therefore directly lead to a corresponding increase in carpenter ant galleries in giant sequoias.

Other pests focus on seedlings and saplings of giant sequoia, including various insects that graze on seedlings, potentially contributing greatly to the seedling mortality. These include the camel cricket (*Pristocauthophilus pacificus*) and two geometrid moths (*Pero behresarius* and *Sabuloides caberata*) (Harvey 1980). Laboratory tests have also shown that a number of nematodes present in the soils of giant sequoia groves have significant to very significant affects on above ground growth of seedlings (Maggenti and Viglierchio 1975). Finally, Shellhammer et al. (1970) recorded high rates of mortality from rodents (likely either meadow mice, *Microtus* sp. or gophers, *Thomomus* sp.), feeding on young sequoias (@ ten years) growing in a heavily burned site in the Atwell Grove in Sequoia National Forest. They described this as a unique event in a giant sequoia grove, although previously noted elsewhere on white fir elsewhere on the national monument.

Genetics of Giant Sequoia

Compared to other topics within the literature addressing giant sequoia, papers dealing with the genetics of the species make up perhaps the smallest block, and it would be virtually non-existent but for the work of William J. Libby (Professor Emeritus of Forest Genetics, University of California, Berkeley), and Lauren Fins (Professor, Department of Forestry, University of Idaho).

Much of the study related to sequoian genetics has examined physical performance in plantations and nurseries, compared with the provenance of the propagules (Fins 1979; Fins 1981; Fins and Libby 1982; Du and Fins 1989; Fins and Libby 1994; see also Guinon et al 1982, as well as Dekker-Robertson and Svolba 1993, for the results of studies conducted in Germany). Traits studied include isozymes, qualitative and quantitative morphology (e.g., color, crown shape, and taper for the first, and branch angle and crown diameter for the second), physiology (especially germination, frost resistance and winter damage, and shoot growth patterns), and overall growth traits (with height and stem volume as variables).

These studies showed a low to moderate degree of genetic variability between groves, with some degree of variation from southern to northern populations. There is no clear indication, however, that this North-South variation is associated with fitness based on latitude (Fins and Libby 1994). On the other hand, within grove variation does seem to display some degree of topographic stratification, with a tendency for families in a grove located at higher elevations performing better in cold-related tests (Melchior and Herrmann (1987); Guinon et al 1982). The two groves that display the greatest degree of genetic variance from all other populations also happen to be the northernmost (Placer) and southernmost (Deer Creek), although their geographic location may be less of a factor than their small size, which may have resulted in inbreeding.

Heterozygosity displayed a significant correlation with latitude, with the northern groves being less variable than the southern populations. Given the relative isolation and generally smaller sizes of the northern groves, this result is not surprising (Fins and Libby 1982).

Within-grove variability was often higher than between groves, with a tendency for this to be distributed around family groupings, indicating some degree of inbreeding. The variability was demonstrated by isozyme studies, which in general showed a lower degree of heterozygosity than is found for other long-lived woody species, as well as other species with elongated, narrow distributions. The strongest indication of homozygosity was found in germinated seeds, but this trait weakened when parent trees were examined, which is attributed to the failure of inbred specimens to reach maturity (Fins and Libby 1982, 1994).

Concern has been raised over the threat to genetic integrity presented by the presence of non-native sequoia plantings near existing groves (Fins 1979; Libby 1986; Fins and Libby 1994). An extreme example of this threat – and possibly the most troubling – is the large number of sequoias planted in the early 1950s in and around the Placer Grove. The source of these seedlings is not known, but they are known to not be from that population. Since the Placer Grove is the most genetically distinct, the possibility of genetic contamination is high. Fins (1979), and Stephenson (1996) argued that these sources of non-native trees be removed – in spite of the great public outcry that would undoubtedly result. Likewise, the distinct genetic characteristics of families within groves indicate that artificial regeneration in and around native populations should only proceed with nearest-family propagules (Libby 1986).

Management of Giant Sequoia

Public Agencies

This section will discuss the management of sequoias by various public agencies. While not comprehensive, it does cover the vast majority of both groves and grove lands. Absent are privately owned groves, and public agencies that manage single, small groves, and those that did not respond to requests for information. Public agencies include the Tahoe National Forest, Sierra National Forest, the Bureau of Land Management, the Tule River Indian Reservation, and the County of Tulare. Available information regarding the management of giant sequoia by these agencies is summarized in Subappendix 2.

Each of the following entities manages their groves in ways that reflect their overall mission and philosophy, and, as importantly, their ability to actually carry out that mission. Internal limitations on that ability include funding, staffing, staff expertise, and competing demands for each. External factors, such as public attitudes and environmental regulations may also hinder or deny the use of desired management practices. As a result, there is little consistency in the methods used to manage sequoias between, and sometimes within, agencies.

The National Park System

In September of 1890, citing as justification "…the rapid destruction of timber and ornamental trees… some of which are wonders of the world," the federal government "set apart as a public park, or pleasure ground" in what became known as Sequoia National Park (U.S. Statute at Large 1890a). This was followed within a matter of days with an additional similar act that, while generally lacking in exuberant prose, created both Yosemite and Kings Canyon National Parks, charging the Secretary of Interior with "the preservation from injury of all timber, mineral resources, natural curiosities, or wonders within … and their retention in their natural condition" (U.S. Statute at Large 1890b). As mentioned earlier, the original establishment of Yosemite NP did not include Yosemite Valley or the Mariposa Grove.

Interpretation of these statutory mandates has evolved over time. First practices were limited to patrol and enforcement conducted by the U.S. Army against trespass and unauthorized use of land and resources. With the creation of an organized National Park System in 1916, management of giant sequoia groves became more oriented towards providing greater recreational opportunities for the public, but was otherwise generally passive as far as the species itself was concerned.

The overall philosophy displayed by NPS regarding giant sequoia management during the period from 1916 to 1963 was one of resource protection: principally from the public and from wildfire. Interestingly, however, the sense that fire was detrimental to the well being of sequoias was not universal, and there was some recognition that allowing fires to burn might, in fact, be beneficial. Sequoia National Park Superintendent John C. White voiced such thoughts in the 1920s, and actually allowed burns to be conducted in sequoia groves to reduce fuels (Rothman 2007; Sellars 1997). However, this view was not in keeping with the common wisdom of the day, certainly not as expressed by the Forest Service, and not as practiced by NPS in future years. The various influences that led to the elimination of fire from the mixed conifer forests of the Sierra Nevada in general, and the groves of giant sequoia in particular, were to have a profound ecological impact. The application of ecological principles to forest management was not possible during much of this period: at first because there were none, and later because the early principles of ecology were based on the erroneous premise that a community of organisms' ecological trajectory was towards equilibrium and stasis, instead of a dynamic system that was always in some degree of flux (M. Barbour, personal communication). The result was an extended period during which resource management was based on the hypotheses that natural systems were healthiest when they displayed no rapid shifts in composition or density, and that human intervention was only needed to ensure that no such changes happened.

Two seminal events occurred in 1963 that overturned the concept of 'resource management by benign neglect.' The first was the publication of a document entitled "Wildlife Management in National Parks," which was a significantly understated way to describe its content. Now commonly known as the Leopold Report (after the principle author, Dr. Starker Leopold [University of California, Berkeley]), it was issued in March of that year. The second event was the so-called Robbins Report, published a few months later.

The Leopold Report

Originally asked to simply prepare recommendations to NPS on the management of Rocky Mountain elk (*Cervus canadensis nelsoni*) in Yellowstone and Grand Teton National Parks, the authors took the opportunity to offer the agency a review of its management of natural resources in general, even offering a criticism that it was "incongruous that there should exist in the national parks mass recreation facilities such as golf courses, ski lifts, motorboat marinas, and other extraneous developments which completely contradict the management goal." Their premise was simple: that NPS had based its management on the care of charismatic objects (e.g., elk in Yellowstone, giant sequoias in the Sierra Nevada parks), removed from the context of the overall ecosystems within which these 'objects' occur. According to the authors, the focus on object management had allowed significant (though often gradual) changes in ecosystems that potentially threatened the long-termed viability of the objects themselves. Leopold and his colleagues never dwelt on maintaining ecosystem integrity *per se* in the report, but instead urged that NPS focus on trying to restore as closely as possible the "biotic associations … that prevailed when the area was first visited by the white man." These changes might occur so slowly as to be essentially unobservable (as decadal shifts in forest composition) or might be mistakenly interpreted as beneficial (as a decrease in elk predator populations.) In fact, the example of a long-term shift in forest composition might be seen in both ways: either not observed at all, or, if recognized, interpreted as a desirable indication of improved forest productivity. Interestingly, the Leopold Report only mentioned the used of prescribed burning once, and only in the context of the cost effectiveness of burning as an alternative method of vegetation management. Still, the document was instrumental in identifying fire as a potentially positive feature in some ecosystems, and lead to the creation of prescribed burn programs in the Sierra Nevada (Leopold et al. 1963). NPS began burning at SEKI in 1968, and Yosemite NP in 1970 (Kilgore 2005, Rothman 2007, Sellars 1997).

The Robbins Report

The Robbins Report was issued in August 1963, by the National Academy of Sciences in response to a request from the Department of the Interior, to make recommendations regarding the expansion of "…[a] program of natural history research by the National Park Service." Headed by William J. Robbins, then Associate Director for International Science Activities for the National Science Foundation, the committee examined the structural capacity of NPS to both conduct research and integrate the results into useful management strategies. The results of the study were not encouraging. To quote from the report's abstract:

> *"An examination of natural history research in the National Park Service shows that it has been only incipient, consisting of many reports, numerous recommendations, vacillations in policy, and little action."*
>
> *"Research by the National Park Service has lacked continuity, coordination, and depth. It has been marked by expediency rather than by long-term considerations. It has in general lacked direction, has been fragmented between divisions and . . . has failed to insure the implementation of the results of research in operational management."*
>
> *"It is inconceivable that property so unique and valuable as the national parks, used by such a large number of people, and regarded internationally as one of the finest examples of our national spirit should not be provided adequately with competent research scientists in natural history as elementary insurance for the preservation and best use of the parks."*

In essence, the Robbins Report suggested that NPS reorganize to better integrate science into its management structure, creating a "permanent, independent, and identifiable research unit," and that important actions and decisions taken by NPS would be based on sound research (Robbins et al. 1963).

Together, these two reports resulted in a major change in the philosophical and practical approach to resource management in NPS, and the long-term result has been profound, not just for NPS, but for all public agencies with a responsibility for the stewardship of the nation's natural heritage. Both documents are also significant to the history of giant sequoia management, not only through the introduction of ecosystem-based management, but in stimulating some of the most important research conducted on the species.

The prospect of major ecological upheaval in and around units of the National Park System due to global warming creates a new challenge to the modern NPS, but it is very possible that the agency that existed prior to the publication of the Leopold and Robbins reports would have been unable to respond effectively, or at all, to this threat.

Current NPS Sequoia Management

Currently NPS is pursuing a management philosophy that emphasizes ecological restoration of management groves. The agency strives to maintain natural processes as a critical component of the sequoian ecosystem, in particular the role of fire, and is essentially relying on fire as both a maintenance and a restoration tool. In other words, they have made the decision to not use mechanical treatments either in conjunction with fire (i.e., as a restoration accelerator) or as a replacement for it (i.e., as an ecological surrogate). However, SEKI is working under the strain of being able to create a functioning fire regime during a period when concern over air quality severely restricts the opportunity to restore fire. Under these circumstances, prioritization is unavoidable. Based on SEKI records, some groves have received a succession of fire treatments since 1968, others only one or two, and the remainder, none to date.

USDA Forest Service

The Forest Service has followed a similar path in the evolution of is management practices in regard to giant sequoia, although with different influences and time frames. Established through the Forest Reserve Act of 1891 (U.S. Statute at Large, 1891), the Organic Act of 1897 (U.S. Statute at Large, 1897), and the Transfer Act of 1905 (U.S. Statute at Large, 1905), the Forest Service was with the goals of managing the nation's federally owned forest lands to sustain and improve both timber production and water generation. As a result, the resources contained within the forests – including giant sequoias – were viewed as commodities to be utilized in a sustainable manner. Three national forests were eventually that contained giant sequoia groves: the Tahoe National Forest with the small Placer Grove; the Sierra National Forest, with the two widely spaced Nelder and McKinley Groves, and the Sequoia National Forest, with approximately 33 groves. The rest of this section will focus in particular on the groves within Sequoia National Forest (now, more properly, the Giant Sequoia National Monument, or GSNM).

Unlike NPS, pubic enjoyment and recreational use were not important mandates when the Forest Service assumed authority over its lands. Instead, the Forest Service was intended to ensure that forests were managed wisely to maximize sustained timber production, instead of the unregulated "cut-and-run" type of harvesting that had been characteristic of the last half of the 19th Century. Until the creation of Forest Service, timbered land in the United States had been viewed as an endless resource that could be consumed at will, requiring only that the consumption continually moved west from logged over lands. The destruction of ancient forests eventually became a source of concern, however, and the need for the federal government to establish control and regulation over its forests became urgent.

One of the first actions taken by the Forest Service was to implement a policy of fire suppression. This was an expression of the view of the agency's first Chief Forester, Gifford Pinchot, who believed that allowing fires – either naturally or deliberately set – negatively impacted forest productivity and was an example of 'un-enlightened' forest management, as practiced by itinerant and/or unschooled timber men, particularly those in the Southeastern United States and Northern California (Pyne 1997). Voices within the agency who considered the possibility that fire might be not only a useful, but perhaps essential, management tool were few, although it is interesting to note that one of the few was a young Forest Service wildlife biologist, Aldo Leopold, the father of Starker (Leopold 1924).

Over time the federal fire policy evolved from one of discouraging the use of fire as a management tool to one of strict fire abhorrence. Implementation of the 10:00 AM policy (under which forest fires were to be contained and controlled by 10 AM after discovery, or each subsequent 10 AM thereafter) was followed by other modifications, all oriented towards the suppression of wildfire as quickly as possible. As a result, the use of prescribed fire as a tool in giant sequoia forests was not integrated into management practices until 1975, and even then only on a limited basis (Rogers 1986). On the other hand, commercial harvesting of giant sequoia was allowed up into the 1950s, and the harvesting of other merchantable species within groves continued until the early 1990s, when a presidential executive order stopped the practice (USDA Forest Service 2010a). In fact, the controversy over harvesting within the groves was a major stimulus to a legal action that created a major shift in the Forest Service's management direction.

In 1988 the Forest Service prepared a management plan for Sequoia National Forest. Although approved, it was legally challenged by a various stakeholders, eventually resulting in a mediated settlement agreement (MSA) that committed the Forest Service to a number of actions, including (but not limited to) a number dealing with giant sequoias. Of these, four of the most important were the cessation of prescribed burning in groves until a number of conditions had been met: the creation of an ecological database for the groves, the implementation of ecologically based management, and the development of a new management plan (Elliott-Fisk et al. 1996; Piirto 1992; USDA Forest Service 2010a). Completing these requirements has been a major focus for the Forest Service since then. In the meantime, President George H. W. Bush issued an order that stopped all logging in sequoia groves by 1992, and in 2000 President Clinton, through a presidential proclamation, created the Giant Sequoia National Monument (GSNM) (USDA Forest Service 2010a).

The requirements of the MSA and the establishment of the GSNM required that a new management plan be prepared. A draft plan was filed in January 2004, but was once again challenged in court. The plan was remanded back to the Forest Service, with a finding that it was not in compliance with both the proclamation and the National Environmental Policy Act (NEPA) (State of California v United States Forest Service, 2006). In August 2010, the Forest Service submitted a new plan for public review. This will be discussed later.

During the same period (the 1990s) the Forest Service took the lead in establishing cooperation among agencies that manage giant sequoias. The Giant Sequoia Ecology Cooperative was established in 1995 to bring together giant sequoia managers and researchers, in an effort to (among other things) determine sequoia-related research needs, provide grove managers with access to "quality science," demonstrate that ecological knowledge can be applied to address practical management needs, and provide an infrastructure that would foster interagency cooperation and coordination of effort. The original signatories of the memorandum of understanding included agency administrators for Sequoia National Forest, Sequoia-Kings Canyon National Parks, Mountain Home State Demonstration Forest, the (now) Western Ecological Research Center, and the Pacific Southwest Research Station. Joining later were the University of California, the Bureau of Land Management, California Polytechnic State University

(San Luis Obispo), and the California Department of Parks and Recreation. Unfortunately, the Cooperative was unable to sustain momentum, and has been inactive as a group since 2000. Still, cooperation between some members remains high.

The Proposed Giant Sequoia National Monument Management Plan
[Note: due to the length of the proposed plan and the attendant documents, volumes and pages will be included in the citations. Italics were added and some punctuation was altered, for clarity].

As mentioned above, the Forest Service was required to prepare a management plan for the national monument. In fact, this requirement is related to a number of mandates, including the Clinton declaration, the 2006 District Court decision, and the National Forest Management Act. In conformance with NEPA, the Forest Service issued a proposed plan (GSNMP) for the Giant Sequoia National Monument is initially presented as a preferred alternative, discussed within a draft environmental impact statement (DEIS Vols. 1 and 2) (listed in Literature Cited as USDA Forest Service 2010a, 2010b, 2010c, respectively).

In general, the plan and accompanying DEIS volumes are focused on fire risk reduction, and does not place a great deal of emphasis on re-establishing giant sequoia regeneration, at least through the effect of fire. For instance, in prioritizing areas for fuels treatment, giant sequoia groves are ranked forth, behind wildland-urban interface (WUI) defense zones (ranked first, and defined as a roughly ¼ mile perimeter around developed areas), fuel reduction along the boundary with the Tule River Indian Reservation (ranked second), and WUI Threat Zones, (ranked third, and defined the area roughly 1 ¼ miles beyond WUI defense zones). Then comes giant sequoia groves not incidentally located in the first three areas (DEIS Vol. 1: Table 30, p116). The plan does allow for planting of giant sequoia as an alternative to fire-stimulated reproduction, although – as mentioned earlier – the DEIS does not show any net increase in regeneration acreage under the preferred Alternative B, at least through direct actions called for in the plan (see DEIS Vol. 1: Table 47, p. 151).

DEIS:
The DEIS volumes present descriptions of the current and desired conditions for the monument. For instance, Volume 2 offers summaries of the current conditions found within the groves, including fuel loading, and species composition by frequency and basal area (DEIS Vol. 2: pp. 570-583). The DEIS Vol. 1 (pp. 104-108) calls for significant shifts in the future proportion of giant sequoia basal area relative to other species, from the current 25% to 65% (largely at the expense of white fir), and an increase in the early seral stage proportion of mixed conifer, montane hardwood (essentially California black oak), and red fir. Presumably this would require mechanical treatments.

It should be noted that both volumes were reviewed by a scientific advisory panel, whose report was mixed in terms of the overall accuracy of the DEIS. A major concern was over the use of scientific literature, which is summarized as follows (Skinner et al. 2010):

Overall, review panel members judged the DEIS to be generally consistent with available scientific information with some important exceptions. The exceptions to consistency are primarily related to:

1) A general lack of citations (the link to scientific information) to support statements made in the DEIS
2) Concern that the cited scientific literature was at times outdated and the DEIS would be improved by using more recent literature
3) Lack of sufficient detail in the discussion of monitoring plans that might be used to check whether unacceptable outcomes associated with risk and uncertainty under various alternatives will occur or not
4) Lack of a clear connection or association of the scientific literature with the activities proposed to achieve the goals of the plan.

The draft EIS was developed in two ways. On one hand, a list of important issues was developed, based upon comments received from entities external to the Forest Service, and, on the other, a range of alternative management scenarios that were developed internally. The summary of the EIS (Vol. 1, pp. 10-34), presents a list of the issues (nine in all), the alternatives (six in all), and then a comparison of how each alternative addresses each issue. Of the various alternatives considered, one (Alternative B) was presented as preferred, and this served as the basis for the draft Giant Sequoia National Monument Management Plan.

Only one of the listed issues referred directly to giant sequoias (Issue 6: Methods for Giant Sequoia Reproduction), although others could include the species, depending on how that particular issue was addressed by the various alternatives. This is especially true of Issue 4, which deals with fuel reduction. Both are reviewed here, quoting from the DEIS, followed by a discussion of how each is addressed in Alternative B.

Issue 4:
The following statement regarding Issue 4 is taken from the DEIS Vol. 1, page 47:

> *Issue 4: Fuels Management/Community Protection*
>
> *Fuels reduction as proposed, to protect communities and the objects of interest in the Monument, may not be effective in terms of how much is treated and the kinds of treatments used.*

Alternative B calls for the most area of the monument treated of all alternatives, by a combination of mechanical and prescribed fire treatments, over a seven decade span (74.3% of the total land area). A total to 40.3% is proposed for treatment by fire. These treatments would be prioritized on the basis of risk to (1) wildland/urban interface (WUI) defensive zones, (2) a buffer area against the Tule River Indian Reservation, (3) an extended WUI threat zone, (4) giant sequoia groves not incidentally covered by priorities 1 through 3, and (5), which covers the rest of the monument. No indication is given as to how many grove acres would be treated in the first three priorities.

Issue 6:

The following statement regarding Issue 6 is taken from the DEIS Vol. 1, page 49:

> *Issue 6: Methods of Giant Sequoia Regeneration*
>
> *There is ongoing debate about the methods that would successfully promote the regeneration, establishment, and growth of giant sequoias.*

In regard to giant sequoia regeneration, the estimate is that Alternative B will result in no increase in acreage during the life of the plan. By contrast, Alternative E, which is fashioned after the full implementation of the MSA, would result in an estimated 4532 acres of regeneration.

Interestingly, a discussion of Issue 6 on the same page makes the following statement (DEIS Vol. 1, page 49):

> *There are differences in opinion as to what balance of forest disturbances and what combination of fire and mechanical treatments would help promote and establish giant sequoia regeneration. There is even some disagreement as to whether openings in the canopy are necessary.*

There is no elaboration, nor are any citations offered in support of these claims. However, it is noted that the value of canopy gaps is especially well documented by a number of authors, including Battle, Demetry, Stephens, Stephenson, and York.

A more detailed discussion of the Draft GSNMP is presented in Subappendix 4.

Current Forest Service Sequoia Management

As mentioned, the MSA requires the Forest Service to prepare a management plan, and proscribes many actions necessary to manage giant sequoias. Until such a plan is approved, the MSA directs the Forest Service to manage the grove in compliance with a number of pre-existing documents, including two presidential proclamations and no fewer than five others, creating what the DEIS Vol. 1 describes "…multiple sources of direction … that resource managers must consider each time a project level decision is developed. This is a time-consuming process, and it is not always clear which source of direction takes precedence, and how it interacts with other sources" (USDA Forest Service 2010a, page 70). The current management scheme is included in the DEIS as Alternative A – the traditional "no action" alternative, but that term may have a certain irony in this case.

Based on the current draft plan, the forest service would manage the groves within the monument with more attention to direct manipulation of populations through manual and mechanical methods, with little emphasis on the restoration of ecological processes. In this they are consciously making a distinction between themselves and NPS, and address this directly in the DEIS. Alternative C was designed with the specific intent of patterning the management of the national monument after that used by SEKI. This alternative was not preferred because it was felt that such a management philosophy would be inconsistent with the Forest Service's mandate (USDA Forest Service 2010a, page 1).

Bureau of Land Management

The Bureau of Land Management (BLM) is responsible for the Case Grove, variously described as 55 acres (22 ha) by Elliot-Fisk et al. 1996, 780 acres (315 ha) by the California Department of Natural Resources (1952), and as 180 ha (450 acres) by Meyer and Safford (2011). The grove had been extensively logged of all species, but no longer is (Elliot-Fisk et al. 1996). About 90% of the grove was burned in the 1987 Case Fire, which was described as being of moderate severity by Meyer and Safford (2011), meaning an overall tree mortality of 25-75%. These authors also report statistically significant giant sequoia reproduction following this fire, when compared with within-grove control plots (which had no reproduction).

California Department of Forestry and Fire Protection

The California Department of Forestry and Fire Protection (CAL FIRE), operates the nearly 2000 hectare (4900 acres) Mountain Home State Demonstration Forest (MHSDF), located in southern Tulare County. The area includes two sequoia groves (Mountain Home and Silver Creek), as well as the typical conifer and conifer/hardwood forests found at these elevations in the Sierra Nevada: white fir, sugar pine, ponderosa pine, incense cedar, and California black oak (State of California 2010).

Timber had been harvested on the land in the late 1800s until the early 1900s, and then stopped for an extended period that lasted into the 1930s. The harvesting focused primarily on pines, but around 1900 old growth sequoias were also being logged. This practice resumed after the 1930s hiatus, and accelerated in the early 1940s. Public concern over the harvesting of sequoias stimulated the state legislature to authorize the purchase of the land as a demonstration forest, which was accomplished in 1946. Since then, the MHSDF has protected old growth sequoias, and generally limited the harvested of young ones.

Current Giant Sequoia Management by CAL FIRE

As is true of all state demonstration forests, MHSDF conducts research into the growth and harvest of forest products, and as such it is a working forest (although public recreation is an important component of land use there). Because of the presence of giant sequoia, MHSDF has a broader mandate than other demonstration forests operated by Cal Fire. Aside from conducting research into forest timber management, MHSDF has also conducted non-commercial investigations into giant sequoia ecology and silviculture, and has encouraged the use of their forest for research by others. Recognizing that interest is increasing in the commercial use of giant sequoia lumber, a focus of their research is on the growth, yield, and utilization of the species (State of California 2010).

Differentiating young from old by size and shape, MHSDF allows for the commercial harvest of sequoias from plantations outside of natural groves, and within groves only for the purpose of thinning dense stands of young trees to ensure a stable old growth population. Young trees are defined by such factors as a height of less than 60 meters (200 feet), a conical shape, small branches (generally less than 10 cm (4 inches) diameter), a branch distribution along most of the trunk, and a diameter at breast height of less than 2 meters (80 inches). New generations of sequoia are established primarily by the mechanical creation of forest gaps within groves during harvests of other species, although some limited use of prescribed fire occurs, primarily for the purpose of fuel reduction (State of California 2010).

California Department of Parks and Recreation

The North and South Calaveras Groves are managed by the California Department of Parks and Recreation (DPR). This agency has managed the North Calaveras Grove (North Grove) since 1931, and the South Calaveras (South Grove) since 1954. The North Grove is one of the smallest in the range, at about 25 hectares (60 acres), while the South Grove is larger, at 180 hectares (450 acres). Since its discovery by Euro-Americans, the North Grove has been managed for tourism, starting as a private enterprise in 1853, and continuing to this day. The South Grove, on the other hand, has always remained much less accessible, and so less visited. The North Grove remains accessible to winter visitation, while the South Grove is only accessible via a twenty mile round trip cross-country ski. Thus, the North Grove is subjected to significant human impact throughout the year, while the South Grove has limited use for six to seven months of the year, and virtually none for the remainder. Because of its remoteness and generally pristine condition, the South Grove, and its surrounding watershed, was declared a natural preserve in 1985. This is a rarely used classification, selected only for areas within state parks that have important resource values. Allowable development is limited to the minimum needed to provide for public access.

Fire was initiated as a management tool in the South Grove in 1975, when a series of low intensity fires were started within the watershed of approximately 500 hectares (1200 acres). The entire basin had been burned by 1982. During that period, when conditions did not support the use of prescribed fire, crews thinned the forest within the grove itself, eventually removing over 20,000 trees, mostly white fir of up to 30 cm (12 inches) diameter at breast height (DPR Files). The decision as to which trees to remove was made by the project manager on largely aesthetic considerations. Second entry burns were started in 1990, and continue. In 2000, a plan to accelerate structural restoration of the South Grove using manual methods was started, but DPR managers asked that the project focus initially on fuel management and the reduction of fire risk, so work has progressed since then (when funding was available) on that basis, primarily reducing ladder fuels in vertically continuous fuel beds. The only practical way of dealing with the resulting biomass was to burn it on site, and project managers call for arranging biomass from this reduction in rows, rather than the more typical piles. This was an attempt to mimic the arrangement of the naturally occurring heavy fuels: downed logs. These "windrows" were then ignited to start and spread a prescribed burn.

The smaller North Grove has been more challenging for resource specialists to manage as natural system. This is partly due to heavy visitor use, infrastructure development (including a nearby state highway), and the close proximity of visitor use areas and nearby communities (none of which is true for the South Grove). It is also due to the mesic nature of the grove itself – absent a thorough examination, the North Grove should rank high or highest among the wettest giant sequoia groves (personal impression). The grove was burned in 1985, although smoldered might be a more accurate description, as little flaming combustion occurred.

As an aside, some of the literature reviewed for this paper indicate that the North Grove was acquired via an act of Congress, citing an act passed in 1909 to establish the "Calaveras Bigtree National Forest." Even the Forest Service's Region 5 website states that the forest was established in 1909 (see the link in Note 5). This is not the case. Both the North and South groves of giant sequoia were acquired by the State of California (in 1931 and 1954, respectively), and the congressional act, which authorized the Secretary of Agriculture to arrange with the private landowner for the acquisition of the groves, remained unused until 1954. It was then brought forward to acquire 153 hectares (379 acres) immediately north of the South Grove, as a means of preserving two rare old growth stands of sugar pine-dominated forest. [The entire history is interesting, but not relevant to this paper. For more information and references, see Note 5].

Current DPR Giant Sequoia Management

The overall management philosophy for natural resources at Calaveras Big Trees State Park is the maintenance of natural processes, especially in the

The North and South Calaveras Groves are managed under a combination of manual thinning and prescribed burning, often done in tandem, as described above.

Manual removal is the primary method used in the North Grove, with the logistically challenging prescribed burns limited to small and infrequent efforts. Burns will therefore need to be strategically located, probably removing the opportunity to restore a fully functional ecosystem. No use of mechanical restoration methods is planned at this time, although such activity is not precluded.

The South Grove offers an excellent opportunity for ecosystem restoration, and this has been the goal for DPR since 1975. Since is classified as a natural preserve, prescribed burning is the preferred treatment method, although manual thinning is sometimes used to augment restoration efforts. No heavy equipment can be used within the preserve, so traditional logging methods cannot be applied. However, it is possible that helicopter logging may by attempted in the future, in an effort to create desired stand composition. Once restored, the preserve will be managed through the use of fire only.

University of California

Whitaker's Forest is managed by the University of California Center for Forestry. It is a 130-hectare (320 acre) portion of the Redwood Mountain Grove, and has the oldest continuously monitored forest plots in the Sierra Nevada, and was the site of the earliest prescribed fire trials in a sequoia grove. It was also the site of the first experimental prescribed burn (in 1965) in a sequoia grove (Biswell 1989). The area was harvested extensively prior to 1900, a practice that continued through much of the 20th Century. Today the forest includes extensive second growth sequoia, as well over 200 old growth specimens. At the present time there is not yet a management plan for Whitaker's, although it is anticipated that research into giant sequoia ecology will play an important part of any future activities (Whitaker's Forest website).

Management Methods

Managing Giant Sequoias with Fire

The first deliberate, scientific application of fire to a giant sequoia grove occurred as an experimental burn at Whitaker's Forest in 1965. It was conducted by Dr. Harold H Biswell, then range management professor at UC Berkeley.

Biswell had been a determined advocate for the use of fire in California's wildlands, but one with few supporters in the forestry community during most of his career. In fact, for much of his career his advocacy, not to mention his research, was met with great hostility. His research, conducted primarily in ponderosa pine forests in California's coast range and in the mixed-conifer forests of the Sierra Nevada, focused more on the methods of controlling and applying fire than on fire ecology, and throughout the 1950s and early 1960s, he was the only person in the state carrying out such work (see Prescribed Burning in California Wildlands, H.H. Biswell, 1989).

At the same time Biswell was conducting his early research, concern was being raised by some about the effect the suppression of forest fires in the Sierra Nevada. For instance, in 1955, UC Berkeley Professor of Botany Herbert Mason argued that the absence of fire was threatened sugar pine populations with the expansion of white fir (Mason 1955), and, as early 1901, the relationship between fire and giant sequoia reproduction had been noted (Muir 1901). It is not surprising then, that, on the heals of the 1963 Leopold Report, burning in giant sequoia groves was given a high priority – so high, in fact, that those with reservations about burning in the Sierra Nevada at all only acquiesced in the subject re-establishing giant sequoia reproduction, and not for any other reason (Biswell 1989; pers. obs.).

As has been already presented, burning in groves began in earnest in 1968, and it was as a result of these initial burns (including the 1965 Whitaker's Forest burn), that the direct relationship between high fire intensity and reproduction became established (Agee and Biswell 1969; Parsons and Nichols 1985, Harvey et al. 1980; see also Stephenson et al. 1991, and Shellhammer and Shellhammer 2006). Later studies also demonstrated the side benefits of these burns, including reduction of fire risk (Kilgore and Sando 1975, Kilgore 1973; van Wagtendonk 1985; Skinner and Chang 1996, Keifer 1998, Miller and Urban 2000a), and more diverse habitat utilization by wildlife (Kilgore 1971). Fire managers began to recognize and document the value of patches of high intensity (Stephenson et al. 1991, Christensen, et al. 1987).

A goal of early prescribed burns was to reduce fire hazards that had built up in groves over the previous century, and initially this goal was achieved (Kilgore 1973). However, it soon became clear that this benefit was, to an extent, short lived, as trees killed by the first fire fell and accumulated on the forest floor over ensuing years. At this point, the total woody fuel load may actually have been higher than it was before the burn. However, once subsequent burns finally remove these dead trees, a more lasting reduction in risk was obtained (Parsons 1978; Kiefer 1998; Schmidt et al. 2006).

What is now evident is that fire can be an effective restoration tool when used with an appropriate return interval and sufficient severity to alter forest structure in the short term, and remain within a desired range of variability in the long-term (Miller and Urban 2000b). Unfortunately, this is not always possible, especially when external constraints on conducting prescribed burns limit the frequency and intensity at which they can occur. These constraints include, but are not limited to, funding, the allocation of resources within the managing agency, agency policy, staff training and continuity, air quality regulations, competing land uses, and grove accessibility (Caprio and Graber 2000). Some of these constraints can be minimized if other management tools are used (i.e., manual and/or mechanical thinning) in conjunction with fire (Miller and Urban 2000b; Stephens and Moghaddas 2005).

Reconstructing Groves: Defining Targets and Selecting Methods

The realization that giant sequoia groves had experienced significant and perhaps threatening shifts in composition and ecosystem functionality not only created a substantial discussion about which techniques are most suitable for restoration efforts, it has also created some debate about how to best model a post-restoration forest. The Leopold Report recommended that NPS return the ecosystems it manages to pre-settlement conditions, meaning the period immediately prior to the arrival of Euro-Americans to any particular area, although a more precise definition might be the period when Euro-American land use practices introduced new ecosystem features or processes. The range of impacts cover a broad spectrum, such as the complete alteration of land use practices (e.g., farming, logging, and urbanization), the accidental introduction of ecosystem-altering alien species, and the disruption of dynamic ecosystem processes (e.g., fire or seasonal flooding).

In the case of the Sierra Nevada's giant sequoia groves, the primary alterations were logging (for some) and the elimination of fire, the latter beginning somewhere in the 1860s: changes that led to forest significantly different in character (Bonnickson and Stone 1978, 1982; Swetnam 1993; Swetnam et al. 1992; Caprio and Swetnam 1995). However, there are problems associated with adopting as a restoration target a forest from an era that ended nearly 150 years ago. First and foremost among these considerations is the lack of available data defining what forest conditions were like at that time. Researchers and managers have explored different methods to provide some means of establishing restoration targets, usually expressed in species composition and age class densities. These methods range from the use of the few available (and non-quantitative) written accounts from the period and historic photographs, to growth regressions and computer modeling (see Stephenson 1996 and 1999 for reviews and critiques of each). Each has important shortcomings: data-driven models are too labor intensive to be of practical use on a landscape basis, others are too qualitative to be reliable, and all end up describing a period of time when Euro-American influences were already active (the late 1800s to early 1900s). Still, strides were made during the 1990s at developing methods to provide forest managers with useful guidelines (see especially Millar 1997 and Stephenson 1999).

Of the various studies that have attempted to reconstruct sequoia groves as they may have looked in the past, there is some degree of congruence in the results (e.g., Bonnickson and Stone 1978, 1982; Stephenson, 1994). While the results may vary to some extent, they all seem to agree that the groves were spatially (on a landscape basis) more complex in terms of structure, age, species composition, and fuel arrangement a century and a half ago. In effect, the intervening time has seen the forests become more complex locally, but more uniform on a large scale. The following discussion summarizes of a list of 21 descriptors of past forest conditions compiled Stephenson (1996):

Structure

The natural fire regime provided a mechanism for the creation of canopy gaps. Occasional high intensity/high severity events in an otherwise low intensity fire regime created these gaps, which then became suitable locations for the germination of shade intolerant species (especially giant sequoia, ponderosa and Jeffrey pines, and California black oak). The modern fire regime has limited the production of gaps, which in turn has created an environment that favors the recruitment of shade tolerant species. As the trees in old gaps continued to grow, the forest gradually became uniformly shaded.

The evolution of a series of gaps across the landscape over time created a mosaic pattern that varied by species composition, tree size, tree age, and the presence (or absence) of herbaceous and shrub species. When gap creation stopped this mosaic pattern became less distinct, more uniform, and much more difficult to define spatially.

Aside from creating gaps, fire was an important factor in reducing the numbers of trees, particularly in gaps dominated by reproduction. The failure of the current fire regime to naturally thin stands of young trees has allowed the forest to become more densely populated with trees that have grown beyond the size were they can easily be killed by low intensity fires.

Age Relationships

As can be expected from the loss of gap diversity, there has been a loss of young trees in giant sequoia groves, as well. Essentially, over one hundred years of regeneration has been lost. In the case of sequoias this is a noteworthy loss, but it may reflect the type of perturbation seen naturally in the species, at least in small groves (Stephenson unpublished data), and will become significant only if left uncorrected. When seen in a less long-lived species, this hiatus in reproduction may be a major negative factor in their ability to maintain a stable population over time, with ponderosa pine as a case in point. As is true of any fire dependent plant species, ponderosa should have an age distribution with very large numbers of very young trees, then a rapid decline in numbers by age, until the large tree classes are reached. By then the trees are resistant to most mortality-inducing threats, and only a few trees are lost over time. Ponderosas pines may be considered a relatively long-lived species, with a life expectancy of from 300 to 600 years (Burns and Honkala 1990). Therefore, the loss of a 100-year cohort of young trees has resulted in a serious disruption to both the species itself, and its associated ecosystem.

Species Composition

As has been mentioned, the ancient groves of sequoia were typically dominated by white fir, followed by sugar pine, then giant sequoia. The fact that these forests lost the influence of fire for several decades did not rearrange this pattern, but instead exaggerated it- allowing white fir to gain significantly in ecological importance, due its ability to reproduce in shaded conditions. As a result, dominance (at least as measured by numbers of trees and proportion of basal area) has increased substantially over sequoias, while species such as ponderosa pine and California black oak have receded. In the past there were generally more trees in small size classes, but fewer medium sized trees (described by Stephenson as <10m and 10-35m height classes, respectively), and a more even distribution of small trees among all species.

Finally, shrubs of various montane chaparral species occupied a larger portion of the past forest, while the floor of forested areas had larger numbers of herbaceous plants.

Fuel Arrangement

The condition of forest fuels has changed dramatically from 150 years ago. Under a natural fire regime for the Sierran mixed conifer forest, frequent fires would have kept overall fuel loading much lower than is seen today, and the lack of uniformity in prehistoric fire spread would have created a great deal of heterogeneity in horizontal fuel arrangement, ranging from patches of bare earth to pockets of heavy fuel loads, often found within a few meters of each other. Between these extremes were a continuum of fuel arrangements, types, and loading (Kilgore and Sando 1975; van Wagtendonk 1985). Fuels also had less vertical continuity, both from fewer numbers of understory and sub-canopy trees, and the tendency of fire to "prune" the lower branches of all individual trees. This discontinuous fuel bed would have limited the crown fire potential to localized torching (Kilgore and Sando 1975).

The attempts to determine historic grove conditions were all of potential use for managers attempting "structure restoration," as defined in detail by Stephenson (1996 and 1999), their outputs being most useful in providing managers a target for mechanical and/or manual efforts to create a forest that resembles one that existed in the past. Stephenson goes on to compare structure restoration with "process restoration" as alternative means of achieving the same end. In essence, they represent two schools of thought about how best to restore forest ecosystems that are at risk of serious devolvement.

Proponents of structure restoration argue that time is running out for forests that are steadily declining in health and at serious risk of total loss from wildfire. They recognize that structure restoration is labor-intensive and expensive, but it also provides immediate rewards. If trees removed are merchantable and sold as a commodity, then it might be possible to cover at least reduce, and perhaps cover, the costs of restoration. If, as would be the case with ponderosa pine, age structure has been seriously disrupted, then restoration might include plantings.

Proponents of process restoration argue that: 1) since the elimination of fire as a factor in forest dynamics has led to the current condition, then returning fire to its natural role is essential to any restoration effort; 2) mechanical restoration only mimics fire effects on forest structure, but not other effects, such as nutrient cycling; 3) because of the tools and methods used, structure restoration creates an inherently artificial landscape, and this may be in conflict with agency policies and mandates; and, 4) once returned to its natural role, fire will eventually create a forest that is (*de facto*) in the desired condition, even if forest managers never have a clear, detailed picture of how that forest should look. Studies on the effects of prescribed burns show that they can indeed alter forest structure towards historic conditions if allowed to burn with a diverse range of intensities (Schmidt et al. 2006; Mutch and Parsons 1998; Keiffer 1998). This caveat deserves expansion: fires aimed at forest restoration (whether prescribed or managed unplanned ignitions) can only be effective if they create canopy gaps, and achieving that requires areas of very high intensity.

It is important to state the structure restoration and process restoration are not mutually exclusive, and it is possible for a combination of both fire and mechanical/manual tools to be used. In a study by Meyer and Stafford (2011) of giant sequoia reproduction at locations that had experienced various disturbance activities (low, moderate and severe wildfire, retention harvesting followed with some form of management fire (pile or broadcast), and unchanged controls), it was shown that groves that experienced moderate to severe fire and groves that had been harvested of non-sequoia species followed by management fire had orders of magnitude more young sequoias than both lightly burned and control samples (see also Stephens et al. 1999).

In reality, forest managers may be unable to establish reliable estimates of what a sequoia forest targeted for restoration should look like, but this should not stop them from the attempt. The alternative of leaving a grove in an untreated condition simply leaves it open to long-term ecological degradation from the loss of giant sequoia reproduction, changes in species composition, stand densities that compete for limited resources, and inevitable exposure to extreme fire events.

Global climate change has added a new dimension to the question of how to describe characterize a restored forest, as the manner in which species "fit" in a new and warmer climate may not relate well to the reference conditions of the past. This threat now requires forest managers to consider not only restoring existing forests, but also creating ones with perhaps unprecedented characteristics (within our range of vision) that will be self-sustaining and stable under new climate regimes. Forest managers are therefore faced with new uncertainties, and must develop new management strategies (Baron et al. 2009; Cole et al. 2008; Millar et al. 2007). Adaptive strategies can be applied to forests in a variety of ways, including increasing resilience within a forest or, if necessary, transitioning ecosystems through migration and colonization (Stephens et al. 2010).

Finally, any restoration effort must include mechanisms for the creation of canopy gaps. These have been identified as critical features of groves, providing locations for regeneration of giant sequoias in sufficient numbers to assure long term species success (see especially Stephenson 1999, Demetry 1995, York et al. 2006, and York et al., 2009).

They can be deliberately created by the manual or mechanical means, or by allowing fires to burn with localized high intensity fires (Schmidt et al. 2006).

Managing for Carbon Sequestration – A Special Circumstance

Given the link between CO_2 and global climate change, it is not surprising that attention is being paid to the role forests can play in carbon sequestration, and that a healthy, productive forest will result in greater short- and long-term carbon uptake. Management techniques that reduce stand densities might then be viewed as having a negative effect on the goal of using forests to control greenhouse gas levels in the atmosphere. Techniques that limit future growth, produce additional CO_2, or (in the case of prescribed burning) do both, are viewed with suspicion, and – as shown in the California Climate Action Registry Forest Sector Protocol (CCAR FSP 2007) are considered net sources of emission. Conversely, being an unplanned and unmanageable event, wildland fire is not. However, recent studies have looked at the net carbon values for various treatment methods (including prescribed burning, thinning at various intensities, thinning with burning, and harvesting with wood utilization) versus no treatment, with the assumption that all stands thus treated would also be exposed to wildfire within a 100-year period. In the absence of any wildfire, the untreated model stand was the most efficient carbon sink, but it is unrealistic to assume that forests maintained to entrap atmospheric carbon would be immune from wildfire. When a single wildfire is included in the various simulations, the results show that forest stands that maintain low stocking levels and favor the growth of large trees are, over time, better carbon sinks than forests with higher tree densities, or treatments that include overstory tree removal. Various factors are put forward. First, net productivity of large trees on lightly stocked forests is high. Second, stands with large trees and no ladder fuels are more resilient to wildfire. Third, the carbon release caused by wildfires is far higher on heavily stocked, untreated sites, even when compared with the amount of greenhouse gases released through the use of mechanical equipment and periodic prescribed burning on treated sites. Furthermore, stands that were not only thinned but fully restored to a theoretical replicate of 1865 forest conditions (and maintained with periodic prescribed burning) were by far the most effective long-term carbon sink (Hurteau and North 2009, North et al. 2009, Hurteau et al. 2008).

Parallel to the hoped-for benefit of carbon sequestration is another commonly held idea that the increase in atmospheric CO_2 will likewise increase overall forest growth (essentially acting as a fertilizer), and in a number of cases this may be true. However, in areas subjected to high levels of exposure to ozone and air-pollution derived nitrogen – possibly acting in concert with each other, the inhibition of carbon utilization was enough to offset any sequestration gain (Fenn 2007).

While the foregoing is not necessarily a compelling argument in favor of restoring giant sequoia groves to a pre-settlement condition, given the superior growth characteristics of the species, such a restoration would also create a very effective carbon sink.

The Status of Giant Sequoia Groves

[Note: The following is a general discussion of the status of sequoia groves. Greater detail is provided (in spreadsheet format) on each grove in Subappendix 2]

Forest managers, researchers, and the public at large are understandably concerned about the status of giant sequoia groves, and these concerns are now becoming intensified in the face of the global climate change. Are they stable and in reasonably good condition, or are giant sequoia populations in decline? Are they under threat of unnaturally severe wildfire? What is the status of other elements of the grove's ecosystem, particularly the biological components? This section will explore these questions.

To begin this discussion, it is important to briefly review the history of giant sequoia management. Prior to the 1960s management was essentially divided into two categories. The first consisted of those agencies that scrupulously protected sequoia groves (or grove areas) from disturbance – essentially the publicly owned parklands. The second group consisted of the public and private managers that allowed logging within groves, which may or may not have included harvesting of sequoias. After the 1960s, most public agencies integrated some form of disturbance-based management (i.e., fire, fire surrogates, or a combination of both), while the number of managers that practiced logging – whether of sequoias or other conifers – dwindled (Elliot-Fisk 1996). In some cases, ownership changed as well, typically from private timber ownership to public agencies. Allowing for these changes in management philosophy and/or ownership, groves can then be classified into one of four categories (based on Stephenson 1996):

<u>Logging History:</u>

- Groves that had been protected from any disturbance, including logging
- Groves where sequoias were logged in the past, but not any longer
- Groves where sequoias were still logged
- Groves where species other than sequoia were still logged

<u>Fire History:</u>

- Groves that have received no fire or fire-surrogate treatment
- Groves where fire-surrogate management practices have been initiated (i.e., manual or mechanical thinning)
- Groves that are being managed by some combination of prescribed fire and manual or mechanical thinning
- Groves where fire has been adopted as the preferred management tool, but where treatment constraints have limited the reintroduction of fire to less than optimal fire regime, principally in terms of fire return interval, intensity, and complexity
- Groves that have been restored to the desired fire regime, at least to within an acceptable range of return interval variability

Both groups of categories will be discussed in terms of the status of groves.

The Impact of Logging

Elliott-Fisk et al. (1996) identified 18 groves that had been heavily logged of both giant sequoia and other conifers in the past, with most of this occurring prior to 1950. Seven other groves have a history of light harvesting of sequoia. Any logging since 1950 has usually been light, and (with a few exceptions) involved the harvesting of species other than sequoia. From 25% to 30% of all grove area have been logged to some degree (Stephenson, 1996, State of California, 1952; Elliott-Fisk et al. 1996). As discussed earlier, in some cases logging was extensive, while in others selective harvest methods limited disturbance. Today few groves are subject to logging, especially since the MSA and subsequent classification removed most of the former Sequoia National Forest groves from commercial harvesting.

Of 12 groves recently inventoried by the Forest Service, those that had been heavily logged in the past tended to be those that had the highest proportion of ponderosa pine, in terms of percent basal area and percent of total trees, and high proportions of shrub understory, in terms of percent canopy cover (sources: logging history – Elliott-Fisk et al. 1996; composition figures – USDA Forest Service 2010c). This may have important implications for future restoration efforts that include prescribed burning, since these changes in composition may significantly alter fire behavior.

Aside: Logging – A Brief Overview

The logging of giant sequoia groves is of interest from a purely historic point of view, but a detailed discussion of the logging history of giant sequoia is beyond the scope of this paper. It is well presented elsewhere (see Elliott-Fisk et al. 1996, the State of California 1952, and Hartesveldt et al. 1975). Following is a brief summary of this literature.

Although logging was extensive in some groves, the fact remains that the commercial uses of sequoias were limited, and that harvesting was costly and problematic. These factors likely limited the appeal of giant sequoia as a merchantable species. The literature commonly uses a figure of 25% of the tree’s original distribution as being logged (State of California 1952, and others), although Elliott-Fisk et al. (1996) put the number at 30%. By comparison, in roughly the same period that giant sequoias have been logged, at least 80% (probably much more) of the Sierra Nevada’s old growth mixed conifer forest has been logged, or over 1.35 million hectares (SNEP 1996). Most – though not all – of the remaining unlogged 20% is under NPS jurisdiction and virtually all is under public ownership (SNEP 1996).

Historical uses of sequoia lumber were often mundane compared to other conifers in the region, especially sugar and ponderosa pines. Uses for the wood ranged from pencils and roofing shakes to grape stakes and fencing, with the fibrous bark being used for wall insulation. Although old growth sequoia wood was sometimes used in construction, its uses and characteristics were similar but inferior to the much more plentiful and accessible coast redwood *(Sequoia sempervirens)*. While the heartwood does share the resistance to decay characteristic of coast

Aside: Logging – A Brief Overview (continued)

redwood and incense cedar (*Calocedrus decurrens*), the low strength and brittle nature of old-growth giant sequoia lumber made it unsuitable for most construction purposes (Piirto and Wilcox 1981). Further detracting from commercial utilization were the difficulties of harvesting and transporting such large and fragile trees. The energy built up by a mammoth giant sequoia while falling often caused it to shatter upon impact, and large log segments often had to be split with explosive charges to reduce them to manageable sizes. Still, there was enough value in the wood to warrant harvesting, even with the need for substantial investment in infrastructure, since a single tree could supply so much raw material. The fact that milling was not required for most products, which could mostly be produced by simply splitting the wood into smaller sizes, was undoubtedly an attraction. At the same, time the charismatic nature of the species was creating a public reaction against continued harvesting. A growing appreciation of natural beauty was developing the United States at this time, with hydrologic features such as Niagara Falls, geologic features such as Yellowstone, and biologic features such as giant sequoia, being cited as prime influences (Hargrove 1988). From a combination of both practical and political views, it was probably inevitable that commercial interest in giant sequoias would decline. In all, approximately one fourth to one third of all grove acreage was harvested, with the harvest intensity reaching 100% in some groves (Stephenson 1996; Elliott-Fisk et al. 1996; Hartesveldt et al. 1975). Eighteen groves are recorded as having been heavily logged of giant sequoia in some portion of the grove, while seven are recorded as having lightly logged sequoias in the past, with less than a third of all grove area logged to some degree (State of California 1952; Stephenson 1996; Elliott-Fisk et al. 1996).

It is interesting to note, by way of contrast, that of the approximately 875,000 hectares (2.1 million acres) of original coast redwood distribution, only about 10% remains as old growth forest. Most of the rest is second growth, but 6% (57,000 hectares, or 136,000 acres – more than the total giant sequoia grove area) have either changed to an entirely different forest-type or been taken out of forest production entirely (Fox 1996). Giant sequoia groves have therefore received much more benign treatment, as a whole.

The Impact of Prescribed Fire

Starting in 1968, prescribed burning became an increasingly used management practice. Agencies recognized the importance of applying fire within groves, primarily to stimulate giant sequoia regeneration, but also as a means of treating the serious (and potentially devastating) fuel build-up that had occurred during the period of fire exclusion (Kilgore and Sando 1975; Keifer 1998). Fire also thinned stands that had become overgrown with conifer reproduction (Keifer 1998; Mutch and Parsons 1998) although a review of permanent plot data at SEKI shows that self-thinning had begun (Roy and Vankat 1999).

Table 2. Factors limiting the use of prescribed fire by public agencies.

Internal Factors	External Factors
Insufficient funding	Air quality regulations
Lack of trained personnel	Listed species regulations
Difficulty in accessing sites	Antagonistic special interest groups
Conflicting management priorities	Lack of public faith in the agency
Lack of support from upper management	Wildland Urban Interface issues
Restrictive policies	Competition with other agencies for "burn days"
Previous negative experiences with prescribed burns	Difficulty in coordinating with
Cumbersome planning requirements	cooperating agencies
Competing land use issues	Lack of understanding of fire's role by regulatory agencies

In spite of the best of intentions, fire remains a vastly under-utilized tool. A wide range of factors limits the use of fire, including both internal and external considerations (See Table 2). The result is that, while many agencies have used fire in the past and continue to do so, only one grove – Giant Forest – has been burned frequently enough to be considered as having a fully restored fire regime (Anthony Caprio pers. comm.).

As a result of the difficulties in conducting prescribed burns, only a handful of groves have received fire treatments, and some forest managers seek to either augment fire as both a restoration and maintenance tool, or expect to rely primarily on non-fire treatments altogether.

The Status of Giant Sequoia Reproduction

As has been discussed, the absence of disturbance, and especially the absence of fire, has critically limited the release and germination of sequoia seeds, as well as the establishment and growth of young trees. This then becomes an additional way in which the status of groves can be evaluated. The lack of reproduction has been identified as a long-term threat to giant sequoia populations by a number of authors (Axelrod 1968, Harvey et al. 1980, and Stephenson 1996, to name a few), but data on grove populations and the status of reproduction are problematic. With the exception of very small populations such as the Placer, the only groves that have been subjected to complete (100%) sequoia inventory and mapping are those that were those located at SEKI in the 1960s (Stohlgren 1991), and even some of these data are questionable, at least as far as mapping accuracy is concerned (N. Stephenson pers. comm.). Of the remaining grove populations that have been mapped, most had a minimum diameter applied as a filter, and so little can be gleaned from them regarding the status of reproduction (USDA Forest Service 2010b, DPR Files, State of California 2010). Some agencies, such as CAL FIRE, DPR, UC, and NPS have established permanent plots that will provide some level of data on reproduction over time. The Forest Service's draft management plan calls for monitoring regeneration success in the future (Forest Service 2010a), but, in general, sequoia recruitment at GSFNM is described as “not common” (Forest Service 2010b, p. 440).

Of all agencies managing giant sequoia, only NPS has made a concerted effort to restore giant sequoia reproduction to the level required to maintain a stable grove population. With the advent of ecological based management in the 1960s, and through the application of prescribed fire, SEKI has been successful at stimulating large areas of recruitment in some groves (SEKI 2004b), although the actual amount of parkland treated with fire (counting both unplanned and planned igntions) has fallen substantially below the level required to approach a normal fire regime (Caprio and Graber 2000). As mentioned earlier, only the Giant Forest Grove can be assumed to have a restored fire regime, and it is reasonable to assume that only it is likely to have a restored natural reproduction pattern.

An indirect method of estimating the status of sequoian reproduction is to make this assumption: groves that have been (and will likely continue to be) subjected to periodic fire are likely to have some degree of reproductive success as a result. Subappendix 2 summarizes what is known about the recent fire history of sequoia groves. This approach seems reasonable, since comparisons of treatment methods that include or exclude fire indicate that regeneration is much less successful when some form of fire is absent (Stephens et al. 1999; Meyer and Safford 2011).

Threats to Giant Sequoia

Climate Change

Giant sequoias have long been regarded as a species largely immune to the typical threats to plants: disease, pests, fire, extreme weather, and age. While this may have been generally (but not absolutely) true in the past, predicted climate changes may make some of these previously low-level threats more serious, and may also expose sequoias to new challenges.

Various scenarios have been put forward regarding the impact of global climate change on Sierran ecosystems. Following is what is predicted by the technical literature:

1) Average annual temperatures will continue to rise for at least the next several decades, and this rise will be expressed in the environment through altered rain/snow characteristics, earlier and more rapid snow melt, changes in subsurface and surface hydrology, and an increased probability that plants will be in water deficit earlier in the growing season (Cayan et al. 2008; Cayan et al. 2006; Franco et al. 2005)
2) Extreme hot temperature events will become more common and of longer duration (and this will be most pronounced in non-marine influenced regions of California), while there will be a corresponding decrease in cold spell frequency and intensity (Mastrandea et al. 2009)
3) Annual precipitation will either show modest changes or no change from the levels seen from 1961 to 2000. Models that do show a change are divided between predictions of a minor increase or a minor decrease, although the proportion of precipitation falling as snow will likely decrease (Cayan et al. 2008; Cayan et al. 2006)
4) While all seasons will become warmer, the increase will be most extreme in the summer, and least extreme in the winter (Cayan et al. 2008)
5) Changes in temperature and precipitation patterns will result in fire seasons that start earlier and end later, more large fires, and more local areas of high fire intensity (Westerling et al. 2006; Westerling et al. 2009; Miller and Urban 1999)
6) Warming conditions will at least change, and likely improve, habitat for various species already considered pests and pathogens to giant sequoia, and may possibly introduce new ones into their existing natural range (Evans et al. 2008; Ferrell 1996; Gutierrez et al. 2005)
7) No shift away from a Mediterranean climate towards a summer monsoon pattern is predicted, nor an increase in severe storms (Cayan et al. 2006, 2009).

All of the above have implications for giant sequoia managers, but additional potential concern is that the rate of temperature change would be so rapid that giant sequoias would not find enough suitable nearby habitat to allow natural reproduction to effectively "move" a grove upslope. Millar (2003) points out that temperature changes at the beginning and end of past glacial/inter-glacial cycles were very abrupt, occurring within years or a few decades. In some cases, this led to the extirpation of plant species from some areas. This may prove to be the case for some, many, or all sequoia groves, and, if this happens, agencies managing groves will be faced with profoundly challenging decisions in responding to such a crisis. However, the range of possible actions agencies could make in such an extreme event, while needing to be based on sound science, would also need to be considered and winnowed by the application of political, practical, and ethical screens. For this reason a discussion of the range of potential management actions was deemed to be a subject beyond the scope of this paper, and is mentioned here only in passing.

Virtually all computer models show a trend towards some degree of warming and altered hydrology. Both of these are of concern to managers of giant sequoia forests (Cayan et a. 2006; Cayan et al. 2008). Given the sensitivity of giant sequoias to soil moisture, especially during reproduction, the projected changes in California's climate are cause for concern. Added to this concern is the increased threat of severe fire weather caused by lower relative humidity, drier fuels, longer fire seasons, and earlier snowmelt. Less clear is how changing patterns in snow-to-rain proportion might impact the species.

Current conditions in the Sierra Nevada are already showing a clear pattern of warming, earlier drying, and more rapid snow pack melt. In the 78-year period from 1930 to 2008, snow pack melting has been accelerating during the winter and early spring months. This is caused by a reduction in snow albedo resulting from increased aerosol deposition of dark particulates (Walliser et al., 2009), the direct effect of higher average daily temperatures and the change from late season snow to rain events (Kapneck and Hall 2009). Even if global climate change did not result in a significant lowering of overall precipitation, the earlier draining of the snowpack will likely result in lower soil moisture reserves at the beginning of the growing season, with earlier late season soil drying. Projections are that California's climate will continue to warm, with changes of from 2°C (3.6°F) to 8°C (14.4°F) by the end of this century (Cayan, et al. 2008).

Many feel that warming and changes in snow pack are already being experienced in the Sierra Nevada (and elsewhere), and have been happening for some time (Millar 2003). However, Christy and Hnilo (2010) analyzed snowfall, temperature, and water equivalent data for the southern Sierra Nevada for an eighty year period, and found no significant changes in any values beyond historic variability, since 1916 (see also Christy et al. 2006).

An important point to consider in regard to the ability of giant sequoia to succeed in the face of global climate change is the condition of their groves. As is noted elsewhere, giant sequoia groves face an increased threat from inter-species resource competition, a disruption in fire-stimulated reproduction, and the threat of previously rare extreme fire events. While there may be no data to support this claim, it is reasonable to assume that giant sequoias residing in groves that have experienced some degree of restoration will be better able to exist under the more stressful conditions that may be created in the future, assuming that water stress may be a critical factor that could be relieved by lower stand densities. Regardless, well-established giant sequoias may be able to cope, due their tendency to develop a vertical root system on drier sites, exploiting deep reservoirs of subsurface water (Todd Dawson, pers. comm.).

The new, warmer, environment could also lead to a gradual shift in species composition to better suited plants, and these in turn may have detrimental impacts on giant sequoia ecosystems. At the very least, it would mean that the short-lived plant species living in association with giant sequoia would be replaced with others better adapted to the new conditions, thus changing the character, if not the amount, of biological diversity present in the groves. The current associates may either be extirpated or retreat upslope (and north) in response to their existing habitat becoming inhospitable, and some indication of this has already been seen in the retreat of ponderosa pine upslope in the Sierra Nevada (Thorne et al. 2006). Thus, even if giant sequoia as a species can adapt in various ways to changing conditions, it is doubtful if all associated species could do so. In that case they would survive as a species while their historic ecosystem dissolves.

Recent studies are already showing an increase in the number of trees dying in the Sierra Nevada. Van Mantgem et al. (2007), document significant increases in tree mortality at a number of sites in the Sierra Nevada, as well as much of the rest of the western United States (van Mantgem et al. 2009). These studies indicate that smaller diameter trees have a higher mortality rate than larger, that pine species are the most susceptible, as are mid elevation trees (1000 -2000 m, or 3300 – 6600 ft). The causes of mortality are explored and, by inference, attributed to water stress directly or indirectly induced by higher temperatures (van Mantgem et al. 2007; van Mantgem et al. 2009). They could not find any indication of a clear downward trend in precipitation, but were able to identify meaningful increases in temperature and water deficit, created when a forest's annual evaporative demand is larger than annual water availability. This is a function of altered hydrologic regimes (i.e., earlier snowmelt and reduced snow proportion), and an extended growing season. Another study by Lutz et al. (2009) focused on mortality rates for large diameter tree species at Yosemite National Park, and found declines in their densities over a multi-decadal period (roughly the 1930s through the 1990s). These declines were noted to be most pronounced in sub-alpine and upper montane forest types, and less so for the lower mixed conifer forest.

Some effort has gone into determining temperature and water-stress related changes in a plant's physiology that could lead to death. McDowell et al. (2008) present an exploration of this question (which is summarized in Adams et al. (2010) as part of a larger work), and identifies three temperature regulated causes of death. The first is essentially biotic, with an extended annual warm period being beneficial to forest pest and pathogens by weakening defense mechanisms, reducing over-winter pest mortality, and giving biotic agents additional time for reproductive cycles. The next two are adaptive responses to water stress: under drying conditions, a plant either closes stomata during the day, and thus stops carbon uptake, or the stomata remain open, thus losing additional water. In the first instance, plants are forced to rely on carbon reserves during that period, which could lead to carbon starvation. In the second, additional water stress can lead to hydraulic failure of the xylem. As far as this author could determine, placement of plant species into either response category (technically isohydric and anisohydric plants, respectively) has not been done for tree species of the Sierra Nevada, although “anisohydrism” is more typical of species that are adapted to periodic drought conditions (McDowell et al. 2008).

As mentioned earlier, the latest climate models have no clear indication of whether warming conditions will be accompanied by reduced precipitation. However, if past drought events are any indication, current giant sequoia groves have experienced periods of extreme and frequent drought in the past. Hughes and Brown (1992) present a nearly 2100 year dendrochronological record of extreme drought events for three southern Sierra groves (Camp 6, Giant Forest, and Mountain Home), including 14 in a 125 year period (AD 699 through 823), 11 droughts in 142 years (AD 236 through 377), and 11 in 113 years (AD 1468 through 1580). They also identify five instances of two consecutive drought years occurring at all groves. Of course, it is not possible to determine conditions within the groves during these periods of frequent extreme drought, except that the sampled trees survived to modern times. Unknown is the frequency of giant sequoia seed germination during these periods, as well as the survivorship of their seedlings, and possible changes in forest species composition.

In considering how sequoias will respond to current and future changes, it is important to also look at what is known about how past changes might have affected them. While the best evidence only extends through the Holocene, inferences about the climate during the entire Quaternary Period (Holocene and Pleistocene) may be useful, since this was known to be a time of rapidly occurring extreme changes in climate. Woolfenden (1996) did this, and Millar (1996) even probed the Tertiary Period for valuable information.

As a species, giant sequoias have successfully coped with changes in climate in the past, both in their natural range and in plantings around the world. They migrated south and west in response to the slow rise of the Sierra Nevada, establishing themselves in new areas as conditions became hospitable, leaving old habitats as conditions became unsuitable (Axelrod, 1959, 1964). They have survived multiple periods of Sierra Nevada glaciation and periods of extreme drought. They have been able to do so even though drastic changes – at least in temperature – occurred very swiftly, on the order of years to decades (Millar 1996; Millar 2003). Even so, it was possible for them to always find suitable habitat - for all life stages - close enough to allow for arboreal migration. It is unknown if this will be the case over the next decades – the possibility exists that climate change will still be so rapid and extreme that the species will not be able to find suitable conditions for reproduction within their range of natural seed dispersal. What is also unclear is if giant sequoias will naturally reestablish themselves in something similar to their current grove structure, or in a more dispersed pattern as hypothesized for their early Holocene distribution (Anderson 1990; 1994).

Finally (and to reiterate an earlier point), it is unclear how many of the species currently in association with giant sequoia ecosystems will remain. Climate shifts do not necessarily affect all species equally. Put another way, the current assemblage of plants and animals associated with giant sequoias can be viewed as a community of species that have overlapping environmental requirements. As conditions change, some species may still be found together, others may move and no longer share a common habitat, and still others may disappear altogether (Millar 2003; Millar et al. 2007).

Climate Change and Fire

The impact of climate change on wildland fire may be considerable since warmer temperatures will likely reduce average relative humidity (and therefore fuel moisture), and earlier drying will create a longer fire season. Changes in fire behavior over the past several decades in the western United States (including the Sierra Nevada) has been noted by various authors (Westerling et al. 2006; McKelvey et al. 1996, Skinner and Chang 1996). These changes include higher fire intensities, greater severity, increased resistance to control, and larger fire size. Although these changes can be attributed in some areas of the west to increased fuel loading due to a century and a half of infrequent fire, at least a portion is due to higher spring and summer temperatures, coupled with earlier snow melt (Westerling et al. 2006). Various studies have shown the link between climate changes and fire pattern on the landscape of the Sierra Nevada since the beginning of the Holocene, showing an increase in fire during warmer climatic episodes (Swetnam 1993; Meeker et al. 2005; Hallett and Anderson 2010). It is reasonable to assume that this trend will continue into the future as warming continues.

Pests and Pathogens in a Changing Climate

If climate change results in increased stress to giant sequoias, it could make them more susceptible to pests and pathogens that are already a part of their ecosystem, especially if these agents benefit from warmer conditions. On the other hand, it is possible that some pests or pathogens will be negatively affected by warmer conditions. In fact, examples of both responses have been seen in various ecosystems around the world. At the same time, warmer conditions throughout the year could create suitable habitat for other agents not found currently in sequoia groves (Evans et al. 2008; Harvell et al. 2002; Gutierrez et al. 2006). Modeling of the potential suitable habitat for various agricultural pests indicate they may experience very large increases in their ranges – mostly to the north and upslope – due to the loss of inhibiting winter cold weather (Gutierrez et al. 2006).

As global climate change expands its impact, it will create conditions that will enhance the ability of forest pathogens to exploit the mixed conifer species in general, most of which are already in declining health from high site competition and water stress. This may also be of direct concern to giant sequoia, since some diseases such as annosus root rot can affect them, as well. One direct impact to forest trees is the probability that many mixed conifer species will experience heat and water stress, making them more susceptible to attack. Even if precipitation remains relatively stable, the lengthening of the growing season, earlier snowmelt, and increased rates of evaporation could mean that forest trees will be under more frequent and earlier water stress, making them more vulnerable to insects and disease. Warming associated with climate change will create conditions that will likely be more favorable to existing forest pests – including insects and vertebrate herbivores – and pathogens (Evans et al. 2008; Ferrell 1996). For instance, although not a pest of giant sequoia, mountain and western pine beetles are naturally occurring invaders of sugar and ponderosa pines, and their reproductive cycles are temperature regulated, with multiple generations per year possible under longer and warmer summer conditions. Therefore, the likelihood is that pine beetle populations will be larger each year than historic levels. Population explosions of this type make it more likely that already stressed trees will be unable to defend against the resulting intense attacks (UC Davis IPM website). This type of impact is definitely predictable for species currently undergoing high mortality rates from pests and pathogens, including all Sierran pines and firs, but the possible threat to giant sequoia is unclear.

Air Quality

The largest concentration of giant sequoia coincidentally occurs within the air basin with California's worst air quality. The topography of the southern San Joaquin Valley makes it geographically and meteorogically designed to not only be unable to easily disperse emissions created there, but also to act as a trap for air pollutants transported in from surrounding parts of California, including the San Francisco Bay Area, the northern San Joaquin Valley, and the Los Angeles air basin. Of the criteria pollutants (those for which federal and state standards have been established) that are of particular concern to forest managers, ozone ranks the highest, and this also is one of the most serious pollutants in the San Joaquin Unified Air Pollution Control District (SJUAPCD). This district includes Madera, Fresno, and Tulare counties, where 69 of the 75 groves of giant sequoia are found. Ozone levels (typically measured at the one and eight hour exposure rates) exceed federal and state standards in these counties, while the other air basins where giant sequoias are found do not exceed federal or state standards (CARB).

Trees affected by elevated ozone levels typically display reduced carbon uptake and lower photosynthetic activity, resulting in slower growth (Miller 1996; Grulke et al. 1998). In the most sensitive species this reduction in biomass production can be seen throughout the life cycle. By contrast, giant sequoias sensitivity to ozone decreases with age, with seedlings less than one year being very sensitive, while sapling sized trees showing no ill effect ((Kolb et al. 1997). The reduced growth of seedlings during the first year after emergence can be critical to the success of the tree, especially if the initial rootlet is unable to reach sufficient depth to find reliable soil moisture (Grulke et al. 1996; Miller 1996). This is not to imply that giant sequoias do not respond to high concentrations of ozone in their environment: ozone uptake does occur, and this rate varies within a sequoia population, indicating some degree of genetic control. Still, in spite of this there is no observable resulting damage in older trees (Grulke et al. 1998).

Another air pollutant commonly thought to be of concern is nitrogen, which can settle out in particulate form onto foliage and the soil surface, or in solution with precipitation, sometimes at high concentrations. The SJUAPCD is considered to be in attainment for NO_2 (the chemical precursor for the various forms of nitrogen that settle out of the atmosphere), which means measured values do not exceed federal or state standards. However, this does not mean that no deposition of nitrogen occurs – in fact it occurs throughout the Sierra Nevada (Bytnerowicz et al. 1997). There are sites within SEKI that may receive the highest levels of nitrogen deposition measured in the Sierra Nevada (Cahill 1996). The most commonly cited impact of nitrogen deposition is to aquatic systems, where the nitrogen accumulates and essentially fertilizes the water, promoting the growth of algae and aquatic plants, often with serious consequences (Cahill 1996). The potential impact on giant sequoias however is unclear. Anthropogenic-related increases of soil nitrogen might have a beneficial impact at low levels (Fenn et al. 1997), which may be of some benefit to seedlings (even, possibly, counteracting the deleterious effects of ozone). At the same time, nitrogen deposition increases the rate of litter and duff decomposition, and in the forests where Jeffrey or ponderosa pines are present, increase the rate of needle cast, thus adding additional sources of nitrogen. Combined, these effects produce even more soil nitrogen, with side effects such as more acidic soils. Since ozone also stimulates early dehiscing of needles (2 – 4 years earlier), and young needles are naturally higher in nitrogen and lower in calcium, this effect could have a negative impact on forest soils so affected by providing a less than optimal environment for giant sequoia seed germination (Miller et al. 1996). At high levels of deposition it is possible that nitrogen and ozone in combination might inhibit growth of plants, countering any potential increase realized from increased levels of CO_2 (Fenn et al. 2006). A final potential impact of increased deposition of nitrogen into soil is the lowering of pH levels, which may create a less hospitable environment for sequoia seedlings (Fenn et al. 1997).

While it may appear that giant sequoias will be relatively immune from harmful impacts related to poor air quality, this may not be said of the ecosystem in which it occurs. At least important members of that system are extremely vulnerable to ozone: sugar, ponderosa, and Jeffrey pines. The vulnerability of these species must be of concern to forest managers in their own right. When addressing giant sequoia, however, the threat to these other trees becomes one of stability of the ecosystem in which the big trees are found, which can have unforeseen long-term serious impacts.

Giant Sequoia Silviculture

Giant sequoias were logged extensively in the late 19th and the first half of the 20th centuries. This was in spite of the problems related to harvesting the large trees, the limited market for the lumber, and the narrow profit margin. These problems were largely associated with operations in natural groves, and were exasperated by strong public sentiment in favor of protecting the species. Today, however, interest in the commercial harvesting of sequoias is renewing, as plantation trees outside of groves mature and reach merchantable size.

Giant sequoias growing under plantation conditions routinely out-perform most other species (assuming adequate sunlight, moisture, and soil depth), when measured in terms of both height and volume (Dulitz 1986; Gasser 1994). For example, young (ca. 10 years) mixed conifer plantations at Blodgett Forest showed giant sequoias typically out-grew all other species, with the nearest competitor being ponderosa pine. Sequoia growth in height was about 20% greater than ponderosa pine on the same site, and almost double that of other native conifers. Sequoia diameter growth was also 20% greater than ponderosa, and nearly three times greater than white fir, Douglas-fir, and sugar pine (Gasser 1994). Fins (1979) estimated that sequoias in Sierra Nevada plantations grew between 0.5 and 0.7 m (1.6 – 2.3 ft) in height per year, with an annual increment of from 1.3 – 2.0 cm (0.5 – 0.8 in.). This type of performance is dependent upon site conditions however. An extended period of below average rainfall allowed the more drought-tolerant ponderosa pine to eventually overtake the sequoias at two Blodgett plantations (planted in 1966 and 1981), and in some cases the sequoias became chlorotic, which was assumed to be a sign of water-stress (Gasser 1994).

Since plantations of sequoia are relatively young, data for long-term growth is necessarily derived from natural groves. Studies indicate that growth in height is rapid for at least the first 100 years, and under good conditions may continue for 400 years, when trees may be nearing maximum height (Weatherspoon 1990). However, as these “young” sequoias age, the characteristics of their wood begins to change, particularly in qualities of importance to the timber industry, in terms of resistance to decay, strength and density (Piirto and Wilcox 1981). Overall, young growth sequoias have wood quality characteristics that are superior to both old and young growth coast redwood, assuming proper care is taken during early growth (Table 3). Trees must be pruned, since limb senescence is rare in young sequoias, and the resulting abundance of knots makes the wood of limited value (Piirto and Wilcox 1981; Knigge 1994).

Table 3. Mechanical properties of giant sequoia and coast redwood (After Gasser 1994).

Mechanical Property	Giant Sequoia		Coast Redwood	
	Old Growth	Young Growth	Old Growth	Young Growth
Specific Gravity	0.3	0.35	0.38	0.34
Static Bending Modulus Rupture (psi)	5200	6670	7500	5900
Modulus of Elasticity (Million psi)	0.56	1.14	1.18	0.96
Work to Maximum Load (in-lb/in^3)	5.3	6.7	7.4	5.7
Compression Parallel to Grain (psi)	2700	3510	4200	3110
Compression Perpendicular to Grain (psi)	230	380	420	270
Sheer Strength Parallel to Grain (psi)	730	740	800	890

Although the rapid increase in volume and wood quality makes young giant sequoia a potentially important commodity, it still does not possess the strength required for construction. In general, the market for giant sequoia will likely be for uses similar to coast redwood, such as decking and fencing.

Giant Sequoia Plantings and Plantations in California

As pointed out by Harvey et al. 1980, much of the speculation and investigation into the environmental factors that might regulate grove development, distribution, and stability considered the species without regard to its life cycle. In fact, seed germination and seedling establishment are two very sensitive stages that seem to greatly limit natural recruitment (Harvey et al. 1980). Of interest then, are the occurrences of plantations elsewhere in the Sierra Nevada, where the specimen seems to thrive. At least one of these examples is adjacent to a mapped grove (the North Calaveras), and gives the appearance of natural expansion into the surrounding forest following a fire that swept the grove in the early 20th Century – yet they were planted by the Civilian Conservation Corps, ca. 1940, and left virtually unattended afterward (Joseph Engbeck pers. comm.). Furthermore, starting in the 1950s, commercial logging operations began post-harvest planting of the species, usually mixed with other conifers, in locations far geographically far removed from natural groves, and seemingly removed from them ecologically, as well.

Most (if not all) of these plantations are now owned and managed by Sierra Pacific Industries (SPI), although many of them were established when the sites were under other ownership. A total of 460 plantations have been catalogued by SPI, ranging from Tuolumne County north to

Siskiyou County, thus extending well beyond the Sierra Nevada into the Southern Cascades. They also range in elevation from 880 meters (2900 feet) on a northeast aspect in Butte County, to 2550 meters (6300 feet) on an east aspect in Tuolumne County. In all cases these plantations were established by planting seedlings, which were then left without unusual care afterwards, other than what is normally provided any other plantation tree (i.e., reduction of herbaceous and shrub competition, thinning, and pruning). The seedlings survived at about a 75% rate, with nursery diseases and drought years the most common causes of mortality. They are commonly the fastest growing trees when in a mix with other coniferous species (Dan Tomascheski, pers. comm.). The two oldest identified plantations were established in 1953, while most are less than thirteen years old. The decision to plant is typically based on such factors as soil type, aspect, and soil moisture regime. Unfortunately, these sites have not been characterized on the basis of extensive ecological characteristics, although SPI is currently re-inventorying their plantations for additional information. Seed provenance data is only available for plantations established after 1975 (SPI unpublished data). The success of these plantations creates new avenues of speculation, and the possibility that close study of them could make a significant contribution to the knowledge of giant sequoia ecology.

Initial planting densities are crucial to the initial performance of seedlings. Spacing of from 7 to 10 feet (2-3 m) resulted on roughly half the height increase and about one-third the annual increment, when compared to trees planted at twice those distances (Heald et al. 1999).

The Forest Service has also included giant sequoia seedlings in plantations throughout the Sierra Nevada (Rogers 1986), although no specific information as to when and where these plantings were established has been located, at this time.

The University of California Center has established giant sequoia plantations under more scientifically rigorous conditions, at both Blodgett and Whitaker's Forest Reserves. Various studies have been conducted on trees at both locations, with the focus at Blodgett (in El Dorado County) more on productivity and possible commercial use, and at Whitaker's Forest on conservation and regeneration (Rob York pers. comm.).

Plantations of giant sequoia have also been established at Mountain Home State Demonstration Forest (managed by the California Department of Forestry and Fire Protection). As is the case with plantings at Whitaker's Forest (part of the Redwood Mountain Grove), Mt. Home plantings occur within an existing grove and are not anomalous to natural distribution.

Giant Sequoia Plantings and Plantations Throughout the World

In 1853 John Matthew, having traveled to the North Calaveras Grove to view the recently discovered "mammoth trees," sent a packet of seeds back to his father at Gourdie Hill in Scotland, and so became the first person to introduce giant sequoia – in a modest way – to Europe. The naturalist William Lobb, collecting for the English nurseryman James Veitch, sent back a much larger supply of seeds, again from the North Calaveras Grove, which were to become the stock for many of the first sequoias planted throughout the British Isles and the European continent (Hartesveldt et al. 1975). Since then, sequoias have become a popular ornamental in gardens and arboreta in almost every country in Europe, including Belgium, the Netherlands, Luxembourg, Germany, Norway, Poland, Spain, Italy, the Balkan nations, Austria, the Czech Republic, and Switzerland (Hartesveldt et al. 1975; Knigge 1994; Libby 1981).

Giant sequoias are found in plantations, botanical gardens, and isolated plantings throughout the world, often in environments that have little in common with the conditions typical of their natural range. Turkey, Egypt, Japan, Argentina, New Zealand, and Australia are examples. There is even a reference to a thriving, single tree planted ca. 1930-1935 in the mountains of Kashmir, India, at an altitude of 2500m (8200ft). The vigorous growth of the tree caused the author to suggest establishing entire forests of sequoias in the western Himalayas (Dhar 1975). The worldwide occurrence of the species in conditions that differ so significantly both from the Sierra Nevada and between each other indicate the importance of examining the cause of limitations to natural distribution, and the resiliency of the species to possible environmental challenges related to global climate change. In most cases, these occurrences are in habitats generally colder than the native range, in some cases markedly so (Knigge 1994, Libby 1981). The survival of these trees seems to be related to genetic selection for strains better adapted to withstand low temperatures, in a species commonly described as being frost-sensitive (Libby 1981). Gunon et al. (1982) found that seedlings generated from Atwell Mill seeds in particular showed a high proportion of frost resistance in controlled tests, although all tested groves (22 in all) showed some degree of frost resistance.

Sequoia plantations in Europe (Knigge 1994) and New Zealand (William Libby pers. comm.) are being considered for commercial utilization.

Conclusion

Giant sequoias are a major feature of the cultural landscape of California, and are a symbol to many Americans of our nation's rich natural and cultural heritage. Its role was pivotal in the birth of the American conservation movement, the National Park System, and the evolution of ecosystem-based natural resource management. It has become an important forest species internationally for aesthetic, ecologic, and inspirational reasons, and may be on its way to becoming economically important as well. For all of its lack of biological importance within its own ecosystem, giant sequoias have a cultural importance that stretches around the globe.

During the era of fire exclusion, which, in the Sierra Nevada ran from the 1860s to the 1960s, the groves of giant sequoia suffered significant environmental degradation. Reproduction virtually stopped, except in those groves that experienced logging or the inevitable wildfire. Fuel build-up and expansion of white fir populations provided additional threats. Agencies that manage sequoia groves have recognized the need to reverse these trends through restoration efforts, yet (in spite of their best intentions) most groves are either untreated or insufficiently treated. The will is there, but the lack of means requires that the priority for grove restoration be subject to triage. Added to this is a new challenge. A great deal of effort could be placed into restoring a grove's ecological health, but a grove is as much a geographic feature as an ecologic one, and climate change could threaten both. As a result, managing agencies may end up focusing more on protecting the species than its current distribution.

Much has been learned about the natural history of giant sequoia, especially over the past several decades, but this breadth of research has done little to provide an answer to what has now become the most pressing issue for giant sequoia managers – how it will respond to a changing climate. Finding an answer to this requires long term and in depth research and monitoring. Such an effort is currently underway, through the Save the Redwoods League Redwoods and Climate Change Initiative. This multi-year study, being conducted by researchers from Humboldt State University and the University of California, Berkeley, is perhaps the most comprehensive investigation into giant sequoia since the team of Hartesveldt, Harvey, Stecker and Shellhammer began their work in the 1960s. This latest effort will not only establishes permanent, large-scale plots for ongoing examination, it studies giant sequoia from the macro scale (including three-dimensional mapping of the sequoias) to the micro scale (including isozymal analysis of inter-and intra annual increment variation). This is also the first study specifically designed to address the issue of the species' response to climate change.

Fire remains a significant threat. Although large giant sequoias may be particularly resilient to even severe fire, their ecosystem is not, and the increasing tendency of fires in the Sierra Nevada to become severe is a cause for concern. Fuel treatments will reduce some of the intense fire behavior by reducing fuel loading and continuity (both horizontally and vertically). These treatments can include prescribed burning, the rearrangement or removal of fuels by manual or mechanical means, or a combination of methods.

The long fire-return interval common in much of the Sierran mixed conifer forest presents another problem for giant sequoia: that the resulting low level of recruitment will be insufficient for maintaining a viable population. The paleoecologist Daniel Axelrod predicted the extinction of sequoias, due to the absence of fire-stimulated regeneration (Axelrod 1986). Issues of global climate change aside, if the current altered fire regime common to most groves continues unabated it could eventually result in the local extirpation of the species, unless artificial methods of recruitment are used. When climate change is added to the equation this matter becomes more complex: efforts to restore natural giant sequoia reproduction will need to expand efforts beyond grove boundaries to allow for the possible migration of the species. Unfortunately, the strict hydrologic requirements of the species may foil the effectiveness of this.

As has been shown from its ability to grow under so many different environmental conditions, sequoias have demonstrated a great deal of genetic plasticity. Whether or not this range of adaptability is sufficient to naturally adjust to anthropomorphic climate change is, by contrast, unclear. For this reason alone it would seem worthwhile to conduct ongoing research and monitoring into the numerous sequoia plantations located throughout the central and northern Sierra Nevada and southern Cascades.

If it cannot do so naturally, then the species will only continue with significant human intervention. It definitely will continue as a species for as long as it is germinated and tended in yards, botanical gardens, or timber plantations, but that does not mean that it will be a functional part of a thriving ecosystem. The least and easiest thing humans can do is preserve giant sequoias as a biological entity, but this reflects the environmental ethics of the Victorian Era. Preserving the species in the context of a functioning, self-sustaining ecosystem is a more honorable and noble pursuit.

Notes

1) This literature review used the database created as part of the MSA. This document listed over 700 citations related to giant sequoia, from the mid 1850s to 1999. The summary I made was cursory, and relied first on citation titles, then on the name on the publication, and finally on author to categorize them. Citations that seemed to indicate that giant sequoia was only incidentally mentioned within the publication were eliminated. Even though the sorting was determined qualitatively, I feel it is a reasonable representation of giant sequoia literature over time. Broadly speaking, the literature was placed into categories of "popular," scientific," and "management." The scientific category was further divided into topics such as biology, silvics, ecology, fire, dendrochronology, and so forth. The results showed interesting distributions of literature topics over time, some of which are presented in the main body of this paper. For instance, citations in popular literature have remained fairly constant since the 1850s, while technical papers only became numerically important since the 1950s. Literature about the management of giant sequoia was almost non-existent until the 1970s, but then became co-dominant with all other subjects between 1980 and 1999 (no citations after 1999 were included in the bibliography).

1) The authority to create the Calaveras Bigtree National Forest (CBtNF) was granted to the Secretary of the Interior by an act of Congress in 1909, but no action was taken under that act until May 11, 1954. Even then, the intent of the act – to protect the North and South Calaveras Groves – was only notionally followed. What became the smallest national forest was established to protect one of the best stands of sugar pine remaining in the Sierra Nevada. The fact that three giant sequoias are also found there, as outliers of the South Grove, lent credence to using the act. The impetus for protecting the pines came from a World War II veterans group, who wanted to protect the trees as a living memorial to fallen comrades. The group had approached the California Department of Parks and Recreation (then the Division of Beaches and Parks), but DPR was by then focused on acquisition of the South Grove, and was not interested in having to raise additional funds to purchase both areas from the owner, Pickering Lumber Company. (In fact, it was not until a last-minute and sizeable donation was obtained from the Rockefeller Foundation that the South Grove could be purchased, also in 1954). No record exists of how the decision to use the 1909 act was made, but Pickering accepted the offer of a land exchange, and the forest was established. The terms of the act were specific on two points: first, that the lands acquired under its authority had to be called Calaveras Bigtree National Forest, thus ensuring much future confusion (see, for instance, http://www.fs.fed.us/r5/about/history/forest-dates.html). Second, the law required that the Forest Service "prolong the existence, growth, and promote the reproduction of said big trees." Here there was no confusion: while, for all practical purposes, the forest was established because of sugar pine, it was to be managed for giant sequoia. In fact the Calaveras District of the Stanislaus National Forest, which administered the CBtNF, interpreted the law to limit all management activities to strict resource protection, but, in the event of a stand-replacing wildfire, the District would replant with giant sequoia – not the sugar pines (DPR Files).

DPR and the Forest Service entered into negotiations to exchange land for CBtNF, and an agreement was reached for DPR to give up a section of land it owned adjacent to Klamath National Forest lands. The exchange took place in July 1993.

3) The exact means by which fire causes scales to part has not been demonstrated, as far as I can determine. Harvey et al. (1980) described drying of the cone through heating as the means by which this happens, and this is a commonly accepted view. As anyone who has left a green cone on the sunlit dashboard of a car can attest, it is an attractive theory. Heated cone scales brown and open very quickly. Libby (pers. comm.) however questioned whether heat damage to the peduncle might not be worthy of consideration. In theory, at least, it would take less heat to bring the cells of the peduncle to a lethal temperature than to dry a cone. It might also result in a slower opening of the cone, potentially allowing seeds to fall on a cool ash bed. However, this need not be an either/or situation, and both mechanisms may be at play.

4) Harvey et al. (1980) emphasize the idea that exposure of mineral soil has become dogmatically viewed as an absolute requirement for seed germination and seedling establishment, and express skepticism. To support their contention, they cite instances of extensive areas of giant sequoia reproduction being found in litter and duff "over 20 cm deep," as well as examples of mineral soil exposure persisting for extended periods with no signs of germination. However, they agree that successful recruitment at the population level does require fire, and, as they add, "the hotter the better." Thirty years later, the view that fire is required to simply to expose mineral soil, which in turn leads to successful reproduction, is still part of giant sequoia lore, but one that is perhaps incorrect only in nuance. Fire may make reproduction more successful by exposing mineral soil, but it is certainly contributing much more, such as making soil surfaces more water absorbent (by reducing biochemical hydrophobicity and causing clay particles to accrete), eliminating pathogens, and favorably altering soil chemistry.

5) Discussions of the role of fire in an ecosystem were hampered in the past, due to a lack of a common frame of reference. Systematically describing the ecological role of fire was significantly improved by incorporating the concept of "fire regimes." Various efforts have been made to define the characteristics of natural fire regimes, including Heinselman (1981), Agee (1993), Chang (1996), Hardy et al. (2001), and Sugihara et al. (2006), with the latest, being the most detailed. It describes fire in seven attributes: seasonality, fire return interval, fire size, spatial complexity, fire type, fire intensity, and fire severity. As fire regimes change, plants and animals must be adapted to the new one already, adapt to it, or migrate to areas with regimes for which they are already adapted. In general, however, it can be assumed that an existing plant community will not be well suited to a new regime that is significantly different than its predecessor, and that and adjustment in composition will occur, over time. Some species may experience radical shifts if numbers, and some may disappear entirely. In short, an entirely new plant community will emerge (Sugihara et al. 2006).

At first glance the last two fire regime attributes – fire intensity and fire severity – may seem very similar, but in fact they are quite different. Fire intensity is a mathematical function describing energy release over time during the combustion process (the simplest formula being i=hwr, where intensity (i) is equal to the heat capacity of the fuel (h) times total fuel loading (w) times the rate of energy release (r)), while fire severity describes the ecological damage caused by the fire. They may be directly related, but not always - as in the case of grassland fires that typically burn at a low intensity, but can completely consume the plant community in which they burn (i.e., with high severity).

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Subappendix 2: Giant Sequoia Grove Data

A great deal of information exists in various categories specific to individual groves, but not in all categories for all groves. Differences in management style and management history are examples of factors that may contribute to these differences. The following table attempts to summarize information in a variety of categories available from a number of sources. These categories include grove size; the status of giant sequoia mapping and inventory; a summary of available information on management history covering: logging, the use of fire as a management tool, and reproduction. Finally is an indication of current risk of damaging wildfire.

Grove names followed the nomenclature of Elliott-Fisk et al. (1996). This led to a certain degree of confusion, since names have changed frequently as groves have been combined or been renamed. It is interesting to note that the the Elliott-Fisk 1996 listing, Rundel's enumeration (1969), and the California Department of Natural Resources 1952 publication all identified 75 groves, but there the similarity ends. Largely because of combining groves, the 1952 list only has 57 groves that are found in Elliott-Fisk. Less clear is the fate of three of Rundel's groves (North Cold Springs, Ten-Mile, and Parker Peak). Willard (1996) contends that the Ten-Mile Grove contained too few trees to qualify, and subsequent authors have agreed. However, the North Cold Spring and Parker Peak Groves are apparently still with us, on the southern edge of the Tule River Indian Reservation, but were not on the 1996 SNEP list. Conversely, the 1996 list adds previously un-named Clough Cave, Wishon, and Forgotten groves. Finally, Willard (1994) valiantly attempted to standardize both grove names and characteristics, and reduced the number to 65, later adding Wishon and the recently delineated Monarch Grove (Willard 2000).

Some grove managing agencies did not have information readily available for completing this inventory, and at this time those fields have been left blank.

Giant Sequoia Grove Data

Grove Name	Agency	Area[3] (Acres)	1952[4] (Acres)	2010[5] (Acres)	GS Inv[6]	Mgmt. History[7]	Fire Risk[8]	Authorities[9]
Abbott Creek	GSNM	20		25	C	f	MOD.	
Agnew	GSNM	112	120	43	C	f	MOD.	
Alder Creek	GSNM	420	620	409	C	c	MOD.	
Atwell	SNP	1335	1520		A	c- -*i*	HIGH	
Bearskin	GSNM	186	90	187	C	b	HIGH	
Belknap Complex	GSNM	3077	40	3084	C	c	HIGH	
McIntyre	GSNM	180	130					SNEP, Rundel, SC
Wheel Meadow	GSNM	500	610					SNEP, Rundel, SC
Big Stump	KCNP	757	100		A	f- -*i*	HIGH	
Big Stump	GSNM	485	540	431	C	f	VERY HIGH	
Black Mountain	GSNM	2771	1730	2614	C	c	MOD.	
Black Mountain	TRIR	500	640					
Burro Creek	GSNM	299		278	C	f	MOD.	
Cahoon Creek	SNP	14	10	?	A			
Case Mountain	BLM	55	780		A	a	MOD.	Meyer
Castle Creek	SNP	197	345		A	f- -*i*		
Cherry Gap	GSNM	190		170	C	a	MOD.	
Clough Cave	SNP	0.5			A	f- -*i*		
Coffeepot Canyon	SNP	5			A	f- -*i*		
Converse Basin	GSNM	4520	3040	4666	C	a,e-7-*ii,iii*	VERY HIGH	
Cunningham	GSNM	32	10	32	C	f	MOD.	
Deer Creek	GSNM	144	180	144	C	f	MOD.	
Deer Meadow	GSNM	276	140	168	C	c	MOD.	
Dennison	SNP	11	40		A	f- -*i*		
Devil's Canyon	SNP	6	30		A	f- -*i*		

Grove Name	Agency	Area[3] (Acres)	1952[4] (Acres)	2010[5] (Acres)	GS Inv[6]	Mgmt. History[7]	Fire Risk[8]	Authorities[9]
Dillonwood	GSNM	572		373	C	a	MOD.	
Dillonwood	SNP		1180(?)			a- -*i*		
East Fork	SNP	751	940		A	f- -*i*		
Eden Creek	SNP	361	900		A	f- -*i*		
Evans Complex	GSNM	4370	3030	4256	C	a	MOD.	
Boulder Creek	GSNM	80						SNEP, Rundel
Burton	GSNM	40						
Horseshoe Bend	GSNM		50					SC
Kennedy	GSNM	200	200	226				SNEP. Rundel, SC
Little Boulder	GSNM	80	80					SNEP, Rundel, SC, Willard
Lockwood	GSNM	130	120					SNEP, Rundel, SC, Willard
Forgotten Grove	SNP	1			A	f- -*i*		
Freeman Creek	GSNM	4186	780	4192	C	c	MOD.	
Garfield	SNP	1130	2230		A	f- -*i*		
Giant Forest	SNP	1800	2400		A	f-1-*i*		
Grant	KCNP	154	510		A	f-1-*i*		
Grant	GSNM	130	-	292	C	c	HIGH	
Homer's Nose	SNP	245	180		A	f		
Horse Creek	SNP	42	110		A	f- -*i*		
Indian Basin	GSNM	449	700	448	C	a	EXTREME	
Landslide	GSNM	50	100		C	b	LOW	
Long Meadow	GSNM	568	150	568	C	b	MOD.	
Lost	SNP	54	60		A	c- -*i*		
Maggie Mountain	GSNM	68		64	C	f	MOD.	
Mariposa	YNP	333	230			f-1-i		
Mckinley	SIERRA NF	100	80			c		

Grove Name	Agency	Area[3] (Acres)	1952[4] (Acres)	2010[5] (Acres)	GS Inv[6]	Mgmt. History[7]	Fire Risk[8]	Authorities[9]
Merced	YNP	40	100			f- -*i*		
Middle Tule	GSNM	293	170	301	C	f	MOD/LOW	
Monarch[1][2]	GSNM			54			MOD.	NM, Willard (b)
Mountain Home	MHSDF	2644	1825		B	a,e		
Mountain Home	GSNM	1255	415	1295		a	HIGH	
Mountain Home	TULARE CO.	200	160		C			
Muir	SNP	272	300		A	f- -*i*		
Nelder	SIERRA NF	400	520			a		
New Oriole Lake	SNP	21			A	f- -*i*		
North Calaveras	CAL. DPR	60	62		B	f-4-*i*	MOD/LOW	
North Cold Springs[1]	TRIR							Rundel, Willard
Oriole Lake	SNP	147	230		A	f- -*i*		
Packsaddle	GSNM	527	240	533	C	c	MOD.	
Parker Peak[1]	TRIR		640					Rundel, SC, Willard
Peyrone	GSNM	902	340	741	C	f- -*i*	MOD.	
Pine Ridge	SNP	94			A	b		
Placer	TAHOE NF	5	20			f		
Putnam-Francis	SNP	0.10			A	f- -*i*		
Red Hill	GSNM	765	310	602	C	c	MOD.	
Redwood Creek	SNP	105	120		A	f- -*i*		
Redwood Meadow	SNP	223	400		A	f- -*i*		
Redwood Mountain	KCNP	3154	4000		A			
Redwood Mountain	GSNM	1040	200	1036	C	a	MOD.	
Redwood Mountain	UC	280	320			a,d		
Sequoia Creek	KCNP	21			A	f- -*i*		
Silver Creek	MHSDF	32				f		

Grove Name	Agency	Area[3] (Acres)	1952[4] (Acres)	2010[5] (Acres)	GS Inv[6]	Mgmt. History[7]	Fire Risk[8]	Authorities[9]
Silver Creek	GSNM	101		108	C	c	MOD.	
Skagway	SNP	94	45		A	f- -*i*		
South Calaveras	CAL. DPR	445	415		B	f-2-*i*	MOD/LOW	
South Fork	SNP	210	450		A	f- -*i*		
South Peyrone[1]	GSNM			115	C		MOD.	GSNM, Willard
Squirrel Creek	SNP	4	10		A	f- -*i*		
Starvation	GSNM	181	200	182	C	f	MOD.	
Powderhorn	GSNM	5	40	-				
Surprise	SNP	4	400		A			
Suwanee	SNP	100	70		C	f- -*i*		
Tuolumne	YNP	35	60			f- -*i*		
Upper Tule[1][2]	GSNM			22		?	LOW	GSNM, Willard
Wishon[2]	GSNM	170		171	C	f	MOD.	SNEP, GSNM, Willard(b)

[1] Groves not appearing in Elliott-Fisk et. al (1996)

[2] Groves not appearing in Rundel (1969)

[3] Acreage from Elliot-Fisk et al. (1996)

[4] Acreage from California Department of Natural Resources (1952)

[5] Acreage from USDA Forest Service (2010a) - hence these data only apply to GSNM groves

[6] **Giant Sequoia Inventory**

A: Mapping of both groves and all sequoias

B. Mapping of both groves and sequoias above a minimum diameter

C. Mapping of groves only

[7] **Management History**

This column summarizes the history of grove management in three categories: Logging History (represented by a lower case letter), Use of Fire (represented by a number) and the preferred method of achieving regeneration (represented by italicized roman numerals).

Logging History

a. Extensive historic logging of all species (including giant sequoia), but no longer

b. Extensive historic logging of non-sequoia (giant sequoias some or none) but no longer

c. Limited historic logging of any species, but no longer

d. Logging of non-sequoia species is allowed

e. Logging of all species is allowed

f. No history of logging

Use of Fire

1. Fire restored as ecological process, or nearly so
2. Grove has been prescribed burn, and future burns planned

   but fire as ecological process not yet restored
3. Grove has been burned, but no future burns are planned
4. Fire is (or will be) used in conjunction with manual/mechanical treatments (may include limited

   commercial harvesting)
5. No history of management of fire, but fire preferred management method
6. Unplanned ignitions will most likely be suppressed

7. No prescribed burns are planned

8. Only fire surrogate methods are planned

9. No use of fire or fire surrogates are planned at this time

Regeneration

i. Regeneration depends on fire alone

ii. Regeneration is or (will be) stimulated by mechanical treatments

iii. Regeneration may include planting of seedlings

(8) **Fire Risk**

Rankings are based on input from managing agencies. Agencies may have used different assessment methods, so rankings are based on the author's interpretation.

(9) **Authority**

NM = USDA Forest Service 2010a; Rundel = Rundel (1969); SC = California Department of Natural Resources (1952); Willard = Willard (1994); Willard (2000) = Willard (2000) SNEP = Elliott-Fisk (1996); Meyer = Meyer and Safford 2011.

Subappendix 3: Modeling the 1297 Fire Event

Using tree ring analysis, Caprio et al. (1994) documented a major fire event that occurred in 1297, in the vicinity of Mountain Home State Forest. The fire was both extensive and intense, and resulted in high mortality to all species, except for mature giant sequoias. As discussed in the text, this type of fire behavior is not consistent with the commonly held belief that, under the pre-settlement fire regime, fires in the mixed conifer forest of the Sierra Nevada burned frequently and with low to moderate intensities, an only rarely would isolated pockets of high intensity occur. This assumption is supported by fire behavior modeling, which shows that forests that are today considered to be a reflection of pre-settlement conditions are not capable of supporting an active, running crown fire. Therefore, the fact that the 1297 could burn with such intensity indicates that some unusual conditions must have been present that created the opportunity for crown fire behavior.

Using BEHAVE Plus software (version 3.0.1), fire behavior was described for eight different forest fuel models, ranging from very low fuel loads in a mature forest to high fuel loads in a forest with a shrub/timber understory (Subappendix 3: Table 1). Extreme environmental values where selected to represent an estimate of the 97.5th percentile conditions (Subappendix 3: Table 2), using data from Stephens and Moghaddas (2005). These were derived from weather records from a station near Blodgett Forest, and it is likely that data derived from a station nearer to Mountain Home would give slightly different values. Also, algorithms that predict crown fire potential require the input of crown height, and since there is no good way of estimating this for a forest that existed over 700 years ago, four different runs were made for crown heights of 1, 2.5, 5, and 10 meters (3.3, 8.2, 16.4, and 32.8 feet, respectively). Finally, an estimate of ground slope – another required input – was made from topographic maps of the area, and assigned a value of 30%.

The results (Subappendix 3: Table 3) indicate that, for a forest with a 10 meter crown height, only one fuel model (tu5) had the potential for crowning. Reducing the crown height by half only adds one other fuel model (10) as being likely to crown. Only by reducing the crown height to 2.5 meters are results reached that produce crown behavior in half the models (9, 10, tu5, and tu8). At the one meter level, crowning is likely in all but two models (8 and tl1). These two are reasonable representations of how the Sierran mixed conifer forest appeared in the pre-settlement period (Sid Beckman, pers. comm.).

Subappendix 3: Table 1. Forest fuel models used.

Fuel Model	Description
8	Closed Timber Litter
9	Hardwood Litter
10	Timber with Litter Understory
tu1	Low Load Dry Climate Timber-Grass-Shrub
tu5	Very High Load Dry Climate Timber-Shrub
tl1	Low Load Compact Conifer Litter
tl7	High Load Conifer Litter
tl8	Long-Needle Litter

Source: BEHAVE Plus ver. 3.01

Subappendix 3: Table 2. Behave plus inputs.

dry bulb*	33°C
RH*	15%
1 H FM*	1.80%
10 H FM*	2.30%
100 H FM*	4.20%
Herb FM*	30%
Foliar FM*	75%
Woody FM*	41%
Max. 1 min, Wind Spd*	31 km h^{-1}
Slope	30%

* Source: Stephens and Moghaddas (2005)

Subappendix 3: Table 3. Likelihood of a surface fire transitioning to a crown fire in various forest fuel models for four different crown heights.

10 M Crown Height

Fuel Model[1]	Max ROS (m/min)[2]	FL (m)[3]	Trans. Ratio[4]	Trans. To Crown	Fire Type
8	1.4	0.5	0.02	No	Surface
9	6.2	1.4	0.16	No	Surface
10	7.8	2.8	0.68	No	Surface
tu1	3	1.1	0.08	No	Surface
tu5	7.4	1.1	1.24	Yes	Crowning
tl1	0.6	0.3	0.00	No	Surface
tl7	1.9	1	0.06	No	Surface
tl8	4	1.6	0.19	No	Surface

5 M Crown Height

Fuel Model	Max ROS (m/min)	FL (m)	Trans. Ratio	Trans. To Crown	Fire Type
8	1.4	0.5	0.05	No	Surface
9	6.2	1.4	0.44	No	Surface
10	7.8	2.8	1.91	Yes	Crowning
tu1	3	1.1	0.23	No	Surface
tu5	7.4	1.1	3.50	Yes	Crowning
tl1	0.6	0.3	0.01	No	Surface
tl7	1.9	1	0.18	No	Surface
tl8	4	1.6	0.52	No	Surface

2.5 M Crown Height

Fuel Model	Max ROS (m/min)	FL (m)	Trans. Ratio	Trans. To Crown	Fire Type
8	1.4	0.5	0.14	No	Surface
9	6.2	1.4	1.25	Yes	Crowning
10	7.8	2.8	5.41	Yes	Crowning
tu1	3	1.1	0.64	No	Surface
tu5	7.4	1.1	9.91	Yes	Crowning
tl1	0.6	0.3	0.03	No	Surface
tl7	1.9	1	0.51	No	Surface
tl8	4	1.6	1.48	Yes	Crowning

1 M Crown Height

Fuel Model	Max ROS (m/min)	FL (m)	Trans. Ratio	Trans. To Crown	Fire Type
8	1.4	0.5	0.55	No	Surface
9	6.2	1.4	4.95	Yes	Crowning
10	7.8	2.8	21.38	Yes	Crowning
tu1	3	1.1	2.54	Yes	Crowning
tu5	7.4	1.1	39.18	Yes	Crowning
tl1	0.6	0.3	0.14	No	Surface
tl7	1.9	1	2.00	Yes	Crowning
tl8	4	1.6	5.87	Yes	Crowning

(1) Fuel Model Descriptions:

(2) Maximum Rate of Spread - typically upslope and with the wind

8 - Closed Timber Litter

9 - Hardwood Litter (may also be used for conifer litter)

10 - Timber with Litter and Understory

tu1 - Low Load Dry Climate Timber-Grass-Shrub

tu5 - Very High Load Dry Climate Timber-Shrub

tl1 - Low Load Compact Conifer Litter

tl7 - High Load Conifer Litter

tl8 - Long-Needle Litter

(3) Flame Length - measured from the base to the tip of a flame. Flame length is used as a measure of fire intensity.

(4) Transition Ratio - an indication of the probability that a surface fire will transition to a crown fire. Values greater than or equal to 1 indicate that the surface fire intensity is sufficient to transition to a crown fire.

Subappendix 4: How the Draft Giant Sequoia National Monument Plan Addresses Giant Sequoia

The draft management plan is an elaboration of Alternative B, and provides greater detail how it would be applied within the monument. Of necessity, it is not limited to giant sequoias, either in groves or as a species, but includes all other natural features of the monument, along with cultural features and other management activities, such as recreation.

The GSNMP presents the following as a description of the desired condition for sequoias (GSNMP: p. 29):

> *Giant sequoias exist within the mixed conifer forest and vary in density and arrangement, as do associated forest species. Being especially long-lived, giant sequoias dominate their surroundings. Smaller and younger sequoias are present. Early seral habitat exist and promotes giant sequoia regeneration.*

The draft plan goes on to explain strategies to reach these desired conditions, as follows (GSNMP: Table 7, p. 53, 54):

> *As part of the giant sequoia grove-specific fuel load reduction plan, emphasize the protection of large sequoia trees and trees of other species, including pines, red firs, incense cedars, and black oaks.*
>
> *Protect naturally occurring isolated giant sequoias located outside of grove administrative boundaries from vegetation management activities, giving special consideration to the root systems. Make every reasonable effort to protect these trees from road construction. When practical, preserve them within wildlife clumps or within areas reserved to meet seral stage diversity requirements.*
>
> *Protect only named sequoias – Boole, President Bush, and Chicago Stump – from fuels reduction activities, wildfires, and from human disturbance that can damage tree health, such as peeling bark and trampling on roots. Protect these specific trees by pulling fuels away from the base and removing ladder fuels that can promote a crown fire in them.*
>
> *Give the designation of "grove" to any detached naturally occurring group (10 or more giant sequoia trees, with at least 4 years with a dbh of 3 feet or larger) located outside of existing grove's administrative boundary. Develop a zone of influence (ZOI) where mechanical treatments are restricted. If previously unknown giant sequoia trees of any size and number are discovered outside of a grove's administrative boundary, modify the boundary according to the standards and guideline.*

Giant sequoias are also mentioned incidentally or addressed indirectly within the strategies for other topics, such as:

Climate Change/Carbon Sequestration (GSNMP: Table 8, p. 54):

Design forest management techniques to promote ecosystem regional changes in temperature and precipitation. Include adaptive management strategies to forestall effects to high value resources (i.e., retention of named giant sequoia trees), to improve the potential for forest ecosystems to return to desired conditions following natural perturbations (such as fire-enhanced giant sequoia regeneration), and to facilitate ecological transitions to new and novel conditions;

Ecological Restoration (GSNMP: Table 9, p. 54):

Integrate ecological restoration with fuel treatment, giving priority to areas that are most in need. Prioritize ecological restoration to improve the resilience of ecosystems in the Monument so they can adapt to natural change agents such as fire and climate change, ensuring the protection of objects of interest;

Tree Species Regeneration (GSNMP: Table 10, p. 55):

Encourage natural regeneration of tree species. In areas where natural regeneration is not likely, use planting as determined in site-specific project basis.

After defining management strategies, the draft plan goes on to identify specific, numbered objectives. Those dealing with giant sequoias are:

Specific to giant sequoia (GSNMP: Objectives, p. 55):

1. *Within 5 years, complete a giant sequoia grove-specific fuel load reduction plan for every grove within the monument.*

Incidental to giant sequoia (GSNMP: Objectives, pp. 56-57):

Mixed Conifer

1) *Within 5 years, manage vegetation to change 1.1 percent, or approximately 257 acres, of the mixed conifer types to an early seral phase in giant sequoia groves.*
2) *Within 5 years, manage fire and thinning treatments on 11.3 percent, or approximately 2,575 acres, of the mixed conifer types to reduce fuels and increase growing space in groves.*

Montane Hardwood-Conifer

1) *Within 5 years, manage vegetation to change 1.8 percent, or approximately 45 acres, of the montane hardwood-conifer vegetation types to an early seral phase in giant sequoia groves.*
2) *Within 5 years, manage fire and thinning treatments on 22.5 percent, or approximately 574 acres, of the montane hardwood-conifer vegetation types to reduce fuels and increase growing space in groves.*

Red Fir

1) *Within 5 years, manage vegetation to change 2.5 percent, or approximately 25 acres, of the red fir vegetation types to an early seral phase in giant sequoia groves.*
2) *Within 5 years, manage fire and thinning treatments on 22.5 percent, or approximately 228 acres, of the red fir vegetation types to reduce fuels and increase growing space in groves.*

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