Managing coast redwoods for resilience and adaptation in a changing climate

DRAFT Redwood Science Primer

Intended as supplementary information for an adaptation workshop Sept. 6, 2013

Note: This document is in draft form so please feel free to make suggestions and provide input, including new literature and other perspectives. Thank you! Please contact Marni Koopman at the Geos Institute with your input (marni@geosinstitute.org; 541.482.4459 x303).

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Purpose and Need

The North Pacific Landscape Conservation Cooperative (NPLCC) and California Landscape Cooperative (CALCC) of the U.S. Fish & Wildlife Service are part of nationwide network of 22 LCCs that were created by Secretarial Order 3289 in March 2009 to increase understanding of climate change and coordinate an effective response to its impacts on tribes, land, water, ocean, fish, wildlife, and cultural heritage resources[1]. Within this general programmatic framework, the NPLCC is guided by a five-year technical supplement to its strategic plan that directs its activities to maximize the ability of partners to make informed decisions with respect to conservation and sustainable resource management in relation to climate change and related large-scale stressors[2]. The CALCC is also guided by a five-year strategic plan with the goal of advancing and implementing actions that promote resilient and adaptable ecosystems[3]. Both LCCs provided funding for this project that is designed to meet several of the LCC priority actions; most notably, helping managers understand the availability and effectiveness of adaptation and mitigation response actions and maximizing the ability of partners to make informed decisions with respect to conservation and sustainable resource management as it relates to coast redwoods. Given that the coast redwoods are at the southern terminus of the NPLCC and within close proximity of the CALCC northern boundaries, both LCCs have an interest in project outcomes as they build a portfolio of place-based initiatives.

Although efforts are underway to study redwood response to climate change, there is no comprehensive strategy currently available for helping managers prepare coast redwoods for climate change and land-use stressors despite the global significance of these forests and their vulnerability to such disturbances. In a prior workshop co-hosted by the NPLCC and the National Wildlife Federation (NWF), conservation groups, agencies, and university researchers expressed interest in compiling redwood resilience strategies[2]. Building on recent redwood symposia (Standiford et al. 2012) and ongoing redwood restoration research[4], Geos Institute and a diverse set of partners are holding a workshop on September 6, 2013 to synthesize and translate best available science on redwood climate resilience strategies. The National Park Service is also organizing a follow-up field trip on September 7 to park sites where active restoration is underway and may exemplify key concepts discussed in the workshop.

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[1] For information on the LCCs and their boundaries click here file://localhost/-http/::www.doi.gov:lcc:index.cfm

[2] http://northpacificlcc.org/documents/Strategy Technical Supplement_Final_11-2012.pdf

[3] http://californialcc.org/about-us/strategic-planning

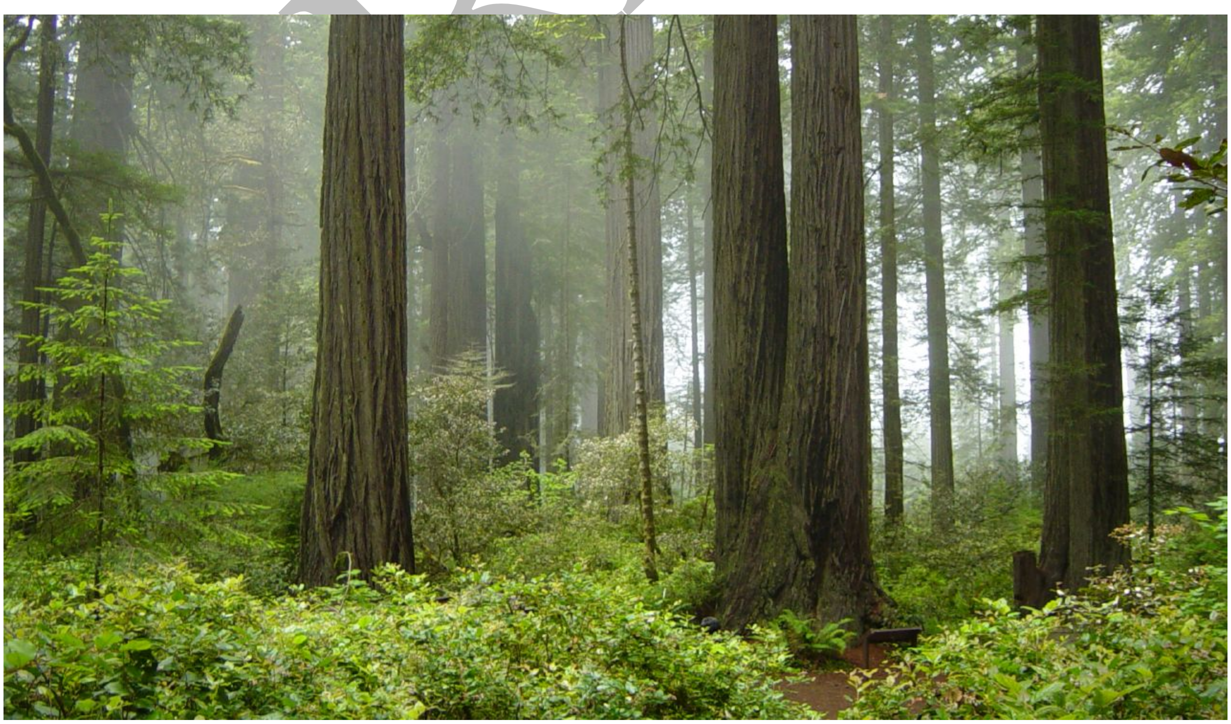
[4] http://rcci.savetheredwoods.org/

Objectives

The main objectives of this workshop are to:
(1) bring together scientists and managers with expertise in redwood ecosystems;
(2) evaluate the leading science on stressors to redwoods, including climate change; and
(3) identify and prioritize adaptation strategies for increasing the resilience of redwoods in the face of climate change.

We will meet our objectives both in a workshop format and on a field trip led by the National Park Service. Workshop output includes a follow-up white paper that will build on this primer by adding practical management actions supported by participants at the workshop. We intend to submit a manuscript to a peer-reviewed journal, will present key findings during an NPLCC and CALCC sponsored webinar, and post results on adaptation portals such as EcoAdapt's Climate Action Knowledge Environment (CAKE), Landscape Information/Data Management Portal (LC-Map), and databasin.org.

This primer is organized into subheadings designed to review latest science on redwood ecological importance, status and condition, land-use and climate change stressors, and management and restoration approaches. For the purpose of the workshop, we refrain from providing best management practices as these will be discussed during the workshop and field trip and included in the manuscript that results from this primer and workshop outcomes. Attached is a guide to Climate-Smart Conservation, with some general guidance on developing adaptation strategies that link actions to key climate impacts and vulnerabilities.



Ecological Importance and Extent

Few forests in the world have comparable species assemblages, enormous tree sizes, rich and structurally complex canopies, productive soils, and exceptional biomass as the coast redwoods (*Sequoia sempervirens*) (Noss 2000, DellaSala 2011). Coast redwood is a long-lived species, maturing between 400 and 500 years (Hickman 1993) and capable of reaching ages of 2,200 years or more (Fritz 1957).

The current distribution of coast redwood can be classified into three distinct subregions (Fig. 1) – north, central, and south, which experience unique conditions based on precipitation, snow, soils, stand structure and composition, and geographic coverage (Sawyer et al. 2000). The southern region has considerably less annual precipitation than either of the other regions (Lazzeri-Aerts 2011). Southern forests are genetically, ecologically, and compositionally different from northern and central forests, less continuous in their distribution, and smaller in tree sizes overall. Common associated species in the southern part of their range include tanoak (*Notholithocarpus densiflorus)*, Douglas fir (*Pseudotsuga menziesii)*, and Pacific madrone (*Arbutus menziesii*; Sawyer et al. 2000). Central redwood forests are more similar to nearby Douglas-fir forests while northern redwood forests are more similar to northern temperate rainforests (Barbour et al. 2001; Noss 2000). Common forest associates in the northern redwood subregion include Douglas fir, grand fir (*Abies grandis*), Sitka spruce (*Picea sitchensis*), and Western hemlock (*Tsuga heterophylla*).

Figure 1. Natural range of coast redwood showing the three subregions recognized by Sawyer et al. 2000.

Although coast redwood forests are contiguous in many areas with drier more fire-prone Douglas-fir forests, the disturbance dynamics of redwood is unresolved, and the role of disturbance in the ecology and perpetuation of old-growth stands has been debated for decades (Lorimer et al. 2009).

Status and Condition

Today's redwood forests, with their suite of associated plant and animal species, reflect a complex history of climate, biogeography, and human interaction. The narrowly distributed coast redwood is restricted to a band from Monterey County in central California to just north of the Oregon-California border, extending only ~60 km inland. This distribution is a relict from a time when redwoods circled middle and high latitudes throughout the Northern Hemisphere.

Redwood was a dominant species along the California coast for much of the Holocene (Sawyer, 2006), a period marked by fluctuations in both climate and fire regimes. Humans were present as fire-ignition sources during most of this time (Moss and Erlandson, 1995), but fire histories of individual redwood stands prior to the 17th century are not well known (Lorimer et al. 2009). Assuming that the average frequency of lightning strikes has remained relatively constant over the last few centuries, most fires prior to 1850 were likely ignited by Native Americans.

In contrast to much of western U.S., reductions in fire frequency in redwood forests is likely due to fewer human related fire-ignitions rather than fire suppression, although fire suppression has been successful in this region (Lorimer et al. 2009) and some argue it has shaped today's redwood ecosystems (Ramage et al. 2010).

It is estimated that in 1850 more than 2,000,000 acres of old-growth redwood occurred regionwide[5]. Logging of coast redwood began in the early 1800's, but much of it occurred after World War II with the upswing in the economy, development of more efficient and effective logging equipment, and increased clearing for agriculture and rural development. Heavy logging of redwoods continued for many decades. In 1968, when Redwood National Park was formed, only 10% of pre-settlement old-growth redwood remained. Today, <4% of the pre-settlement forest remains intact, and half of the remaining old-growth redwoods are found in Redwood National and state parks[5].

Climate change is now acting in concert with land-use stressors in creating unprecedented challenges to land managers wanting to maintain or restore a resilient redwood ecosystem[6]. Fog levels have declined by one-third since the early 20th century (Johnstone & Dawson 2010) and downscaled climate models project increasing temperatures and changing precipitation by century's end that could dramatically reduce the climate envelope of redwood thereby greatly limiting its resilient properties (See projected future trends; Figs. 3&4). However, recent studies have shown increasing growth of redwood in old-growth forests, presumably due to greater sunlight from reduced fog levels, longer growing seasons from climate change, and/or CO_2 fertilization from greenhouse gas emissions (Sillett et al. 2013).

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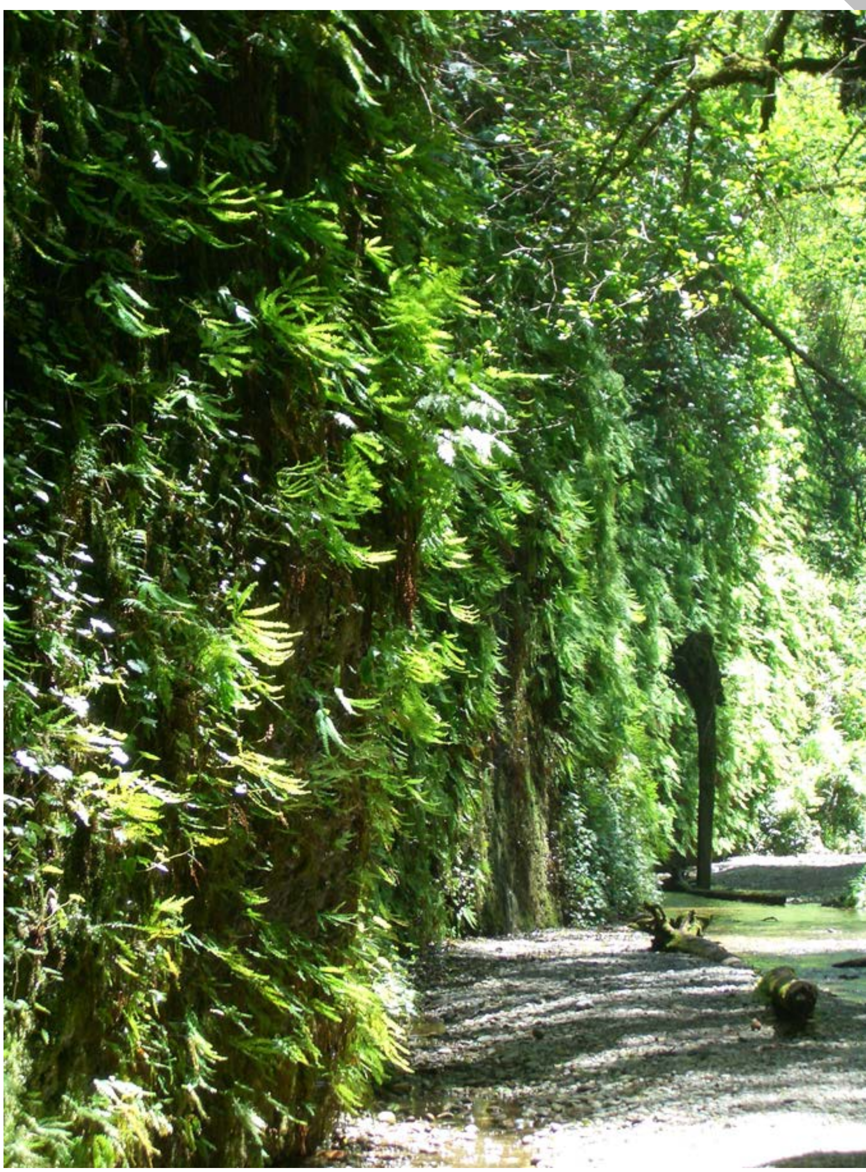
[5] http://en.wikipedia.org/wiki/Redwood_National_and_State_Parks
[6] http://rcci.savetheredwoods.org/

As many components of what has shaped today's redwood forests have changed and continue to change, so will the forests themselves. Today, coast redwood appears to be retreating in the southern part of its range and expanding to the north. Yet complex interactions shape these forests, and whether young stands mature to resemble today's old-growth forests depends on many factors. Interestingly, the current species assemblage of these forests, including Douglas-fir and tanoak, is a relatively recent occurrence, as these species have only co-occurred in this region for the last 4,000 years.



Stressors

Resilience of coast redwood ecosystems depends largely on a whole suite of current and potential human-caused stressors that can act to alter forest establishment and structure. We address some of the dominant stressors in this report, but others not covered here may also be influential in limiting redwood resilience to climate change. Workshop participants have extensive and in-depth knowledge about the impacts of current and future stressors to redwood ecosystems, so this report is intended to provide simply an introductory discussion. The in-depth assessment of the influence and interaction of and among different stressors is intended to occur and be captured at the workshop itself.

While the stressors are individually discussed in separate sections, the most important factor is likely their interactive nature. As climate change accelerates, for instance, it will greatly exacerbate issues with invasive species and wildfire management. None of the stressors can be treated in isolation, and often, the best approach to reducing the impacts of one stressor might be to remove another.

Climate Change

Climate change is expected to affect coast redwoods in a variety of ways (see section on projected future trends for model output). As temperatures rise and precipitation patterns change, redwood could initially benefit from more favorable growing conditions, but potentially could decline later due to increased drought stress and/or loss of fog, making long-term projections for this forest type potentially dire.

On a positive note, a study by the Save The Redwoods League reveals that redwoods have experienced faster growth in recent decades, likely due to longer growing seasons and sufficient moisture. Increased CO_2 concentrations are also expected to have positive benefits for tree growth.

> *"I think when we hear about climate change, and especially warming, I equate warming with dry. We know that is hard on the trees and other plants," said Burns. "What we are realizing is that when the redwoods have enough access to water, even if it does warm up, under the current amount of warming, it's a great condition for redwoods. That's a wonderful happy surprise for us."*
> – Emily Burns, Director, Save the Redwoods League

As climate change progresses, however, increased drought stress, competition from invasive species, changes in wildfire regimes, loss of snowpack at higher elevations, and other impacts are expected to accelerate, potentially having severe effects on this important forest system that may reverse current increases in redwood growth rates.

Roads

As coast redwood forests have been harvested for timber and fragmented for development, roads have become a major feature across the landscape. Forest fragmentation from roads disrupts the movement of organisms and flow of ecological processes across the landscape (Lindenmayer and Fisher 2006). In aquatic systems, roads cause increased runoff, erosion, and sedimentation (Forman and Alexander 1998; Ziegler et al. 2001). Channel morphology and substrate can be altered from sediment inputs (Beschta 1978). Native fish habitat can be severely degraded by the impacts of roads. Roads also act as a conduit for invasive species (Gelbard and Harrison 2003).

Fire and Fire Management

Wildfire is an important component of western forests, yet little is known about the effects of fire on coast redwood. During the Native American period fire return intervals were estimated to range from 6 to 82 years (Brown and Baxter 2003; Brown et al. 1999; Brown and Swetnam 1994; Finney and Martin 1989; Finney and Martin 1992; Greenlee and Langenheim 1990; Stephens and Fry 2005). Fire has been largely excluded from redwood forests since the turn of the 20th century (Stephens and Fry 2005), but prior to that, fire is thought to have been frequent. Central redwoods (near Santa Cruz) have demonstrated high fire resilience to recent fire events (Lazzeri-Aerts 2011). Through many years of observations and research, scientists know that coast redwoods tolerate, and even regenerate vigorously, after fire. However, redwoods are not considered a fire-dependent species (Arno and Allison-Bunnell 2002). In fact, Busing and Fujimori (2002) suggest that redwoods can regenerate and sustain forest stands without major disturbance events of any kind, including fire.

While fire may not be essential for redwood survival, but it may be beneficial (Lazzeri-Aerts 2011). During a fire, chemical and physical changes occur, accelerating energy and nutrient cycling processes (Brown et al. 1999). Frequent, low intensity fires help promote open stands with low tree densities in two ways (Lazzeri-Aerts 2011). First, small-diameter trees are killed before reaching canopy status (Brown and Baxter 2003). Second, frequent fire reduces the opportunities for fire intolerant species to establish (Brown and Baxter 2003).

Decades of fire suppression have increased the potential for uncharacteristically severe fire in many parts of the West. When fire is suppressed, forest debris can collect on the forest floor and around the bases of trees. This accumulation of fuel can lead to more intense fires (Finney and Martin 1993) that have the potential to harm even large redwoods. Additionally, high fuel accumulation in adjacent forest types can lead to more intense fires that may spread into redwood stands (Brown and Baxter 2003; Brown et al. 1999; Noss 2000). In late summer and early fall, after summer fog dissipates and before winter rains begin, forest debris becomes especially dry and flammable (Arno and Allison-Bunnell 2002; Stephens et al. 2007).

Lazzeri-Aerts (2011) found that fires in redwood stands were less severe than fires in other forest types, and that protecting, conserving, and restoring coast redwoods would be expected to reduce fire risk overall. Thinning in coast redwoods was not recommended as a tool to reduce fire, as canopy gaps in coast redwood stands actually act to increase the production of smaller, fire prone stems. Mature forests were more resistant to fire (Lazzeri-Aerts 2011, Douglas and Bendure 2012).

Land Use

Within state and county parks, nature reserves, and some private properties, redwood forests are protected, although more than half these lands are second growth redwood forests. In other areas, timber harvest, recreational uses, and urban expansion continue to occur. Thus, one of the greatest stressors to redwood forest ecosystems is forest fragmentation. Fragmentation occurs from clearing of trees and development of roads for a variety of reasons. One primary reason is the encroachment of housing development as people expand ever further within the coast redwood range. There is pressure for landowners to subdivide their second growth redwood forests for housing development, bringing the wildland urban interface even closer to conservation areas. With homes come invasive weeds, feral cats, more corvids (that may prey on marbled murrelet, *Brachyramphus marmoratus*, nests), motorized recreation, and altered hydrology with increased erosion. In addition, development limits the tools that managers can use in managing wildland fires, inhibiting wildfire restoration in many areas. In addition to housing development, conversion of redwood forests to agricultural lands, primarily for growing wine grapes, is an increasing stressor. Past and continuing fragmentation threatens to reduce opportunities for conservation and restoration in the future, when the need for connectivity might become a management priority.

Invasive Species

Invasive species become an issue in redwood forests mainly when clearing and fragmentation occur. Cover of exotic plant species increases after timber harvest, but decreases with natural regeneration of old growth characteristics, such as canopy cover, tree density, and understory richness that resemble old growth values (Hageseth 2008). In one study, exotics were completely absent in stands older than 60 years (Hageseth 2008).

Sudden oak death (SOD) is a recent development in coast redwood forests. It causes tree mortality caused by *Phytophthora ramorum* among tanoak, a common species in redwood ecosystems. *P. ramorum* is a generalist pathogen that infects many hosts, but hosts differ in their ability to transmit the disease and in the impacts caused by the disease. SOD leads to compositional changes in these habitats through selective mortality of tanoak (Metz et al. 2012). The presence of SOD in redwood forests could increase redwood mortality from wildfire (Metz et al. 2012).

Management Approaches

Because most redwood forests are young in age due to past and ongoing logging, restoring second-growth forests is a conservation priority. In addition, managing timber lands for old growth characteristics that provide habitat for a variety of other species is also a management priority. Many second-growth stands are dense, deficient in redwood, have lower vigor, homogeneous structure, and little biological diversity (Teraoka 2012). Active management including thinning and/or fire can have positive ecosystem benefits in second-growth redwood, as can passive management that allows succession to take place.

Current redwood management has largely focused on specific tree species rather than ecological communities and spatial heterogeneity of old-growth redwood stands and landscapes. Because remaining redwood forests are highly fragmented, restoration that is planned and implemented at a landscape scale could increase connectivity and range continuity.

Most studies of restoration focused on maximizing biomass and productivity of redwood while ignoring other aspects of forest ecology, such as biodiversity, nonmarketable tree species, soil health, wildlife, and understory species. However, some studies indicate that active forest management may actually decrease plant diversity and reduce old growth characteristics, when compared to areas where natural succession is allowed to proceed unmanaged (Hageseth 2008).

Past and current management has simplified forest structure in coast redwood systems. Managing second growth coastal redwood forests for old forest characteristics is an approach seen as beneficial to maintaining biological diversity and habitat for imperiled species. A decision between active versus passive management for obtaining old forest characteristics in younger stands needs to be made. Whether or not timber production is also a management objective may affect this decision.

Old forest characteristics vary throughout the range of coast redwoods, as well as based on specific site characteristics, such as soil type and aspect. Old forests are shaped by storms, fires, and other spatially and temporally unique disturbance events. But some general characteristics have been identified, such as tree density and size, size class distribution, forest canopy cover, number of hardwoods, species associations, cavities, and dead and downed wood availability (Berrill and O'Hara 2012). In contrast, timber harvest creates chronic disturbances that differ in frequency, intensity, scale of disturbance and biological legacies removed by most commercial forest management.

Restoration in Conservation Areas – Silvicultural prescriptions are increasingly being implemented to accelerate the development of mature forest characteristics in young stands (Keyes et al. 2010; O'Hara et al. 2010, Berrill et al. 2013). Thinned stands in Redwood National Park contained more structural diversity, with upper canopies composed of redwood and Douglas-fir and lower canopies composed of redwood and tanoak (Chittick and Keyes 2007), when compared to unmanaged stands of second-growth. These thinned stands showed the initial signs of mature forest after 25 years, while the controls exhibited intense competition in dense stands after the same time period (Chittick and Keyes 2007). Similarly other studies in Redwood National Park and Headwaters Forest Reserve showed that thinning can help achieve restoration objectives (Taraoka 2012; Berrill et al. 2013), but that some thinning approaches are more effective than others (Teraoka and Keyes 2011). In Humboldt Redwoods State Park, variable density thinning promoted heterogeneity and structural complexity (Keyes et al. 2010). In Mendocino redwood stands however, old growth features were achieved more quickly with no or little active management when compared to thinning and other active management strategies (Hageseth 2008). Natural succession, reducing disturbance, and decommissioning logging roads were recommended for restoring previously logged areas (Hageseth 2008).

Restoration in Timber Harvest Areas – Appropriate restoration methods for recovering second-growth coast redwood communities are imperative in order to recover rare species, retain biodiversity, and develop old-growth characteristics. Redwood forests are the result of complex relationships interacting at different levels of the community, which may change after a disturbance.

Timber harvest practices can negatively impact redwood communities (Hageseth 2008). Increased sunlight from the removal of canopy species can lead to an increase in opportunistic and exotic species (Rivas-Ederer & Kjeldsen). Logging practices alter soil conditions (Stone & Wallace, 1998) through compaction (Corns, 1988), and reduce nitrogen levels in previous logged stands (Jussy et al. 2004) particularly near skid roads (Ebrecht & Schmidt, 2003). Mechanical tree removal, in the form of active management or thinning, may have negative effects on redwood forest communities. Management for old forest characteristics, however, can provide positive habitat benefits for a variety of species. The challenge is to balance benefits to biological diversity with maximizing tree growth for timber production.

Precommercial thinning can lead to enhanced vigor, growth, and stability in redwood forests (Plummer 2008), also leading to improved redwood response to future thinning and a greater range of future management options. Foresters interviewed throughout the range of coast redwood recommended mid-rotation thinning and selection harvest as effective strategies for increasing timber volume (meeting economic requirements) for harvest while also maintaining key old forest characteristics, including forest canopy and multiple age stands (Berrill and O'Hara 2012). They recommended maintaining shade to reduce establishment of less desirable species, including noxious and invasive plants. Managers also identified fire exclusion as a key constraint in their failure to create old forest conditions.

Projected Future Trends

Broad-scale changes in climate are already impacting local conditions across the West and are likely to continue and accelerate in the coming decades. Changes to local conditions include the timing and availability of water, shifts in tree and wildlife species distributions, and changing wildfire frequency and intensity. Climate change presents us with a serious challenge as we plan for the future. Our current planning strategies at all scales (local, regional, and national) rely on historical data to anticipate future conditions. Yet due to climate change and its associated impacts, the future is no longer expected to resemble the past.

To determine what conditions we might expect in the future, climatologists created models based on physical, chemical, and biological processes that form the earth's climate system. These models vary in their level of detail and assumptions, making output and future scenarios variable. Differences among models stem from differences in assumptions regarding what variables (and how many) are important to include to best represent conditions we care about. Taken as a group, however, climate models present a range of likely future conditions.

The utility of the model results presented in this report is to help managers picture what the conditions and landscape might look like in the future and the magnitude and direction of change. Some model outputs have greater certainty than others (see box). Information is provided here to explore the types of potential changes, but actual conditions on-the-ground may be quite different, especially if greenhouse gas emissions rates change substantially.

Uncertainty associated with projections of future conditions, however, should not be used as a reason for delaying action on climate change. The likelihood that future conditions will resemble historic conditions is very low, so managers and policy makers are encouraged to begin to plan for an era of change, even if the precise trajectory or rate of such change is uncertain.

Levels of certainty associated with climate change model projections

HIGH CERTAINTY:

Higher temperatures – Greater concentrations of greenhouse gases trap more heat. Measured warming tracks model projections.

Lower snowpack – Higher temperatures cause a shift from snow to rain at lower elevations and cause earlier snow melt at higher elevations.

Shifting distributions of plants & animals – Many species are limited in extent or number by climatic conditions that are expected to change.

MEDIUM CERTAINTY:

More severe storms – Changes to storm patterns will be regionally variable.

Changes in precipitation – Current models show wide disagreement on precipitation patterns, but the model projections converge in some locations.

Wildfire patterns – The relationship among fire, temperature, and available moisture has been well documented, but other components also play a role (such as vegetation, below).

LOW CERTAINTY:

Changes in vegetation – Vegetation may take decades or centuries to keep pace with changes in climate.

Temperature and Precipitation

By the 2080s, projected temperature increases for the far northwestern corner of California range from 2.6 to 4.1° C (4.7° F to 7.4° F) while projected precipitation changes are highly variable ranging from -255mm to +1,164mm (-10 inches to +45.8 inches; Fig. 2). Colors on different maps do NOT correspond to the same increment of change, and decimals are used in place of commas to indicate 1,000mm and more of precipitation change.

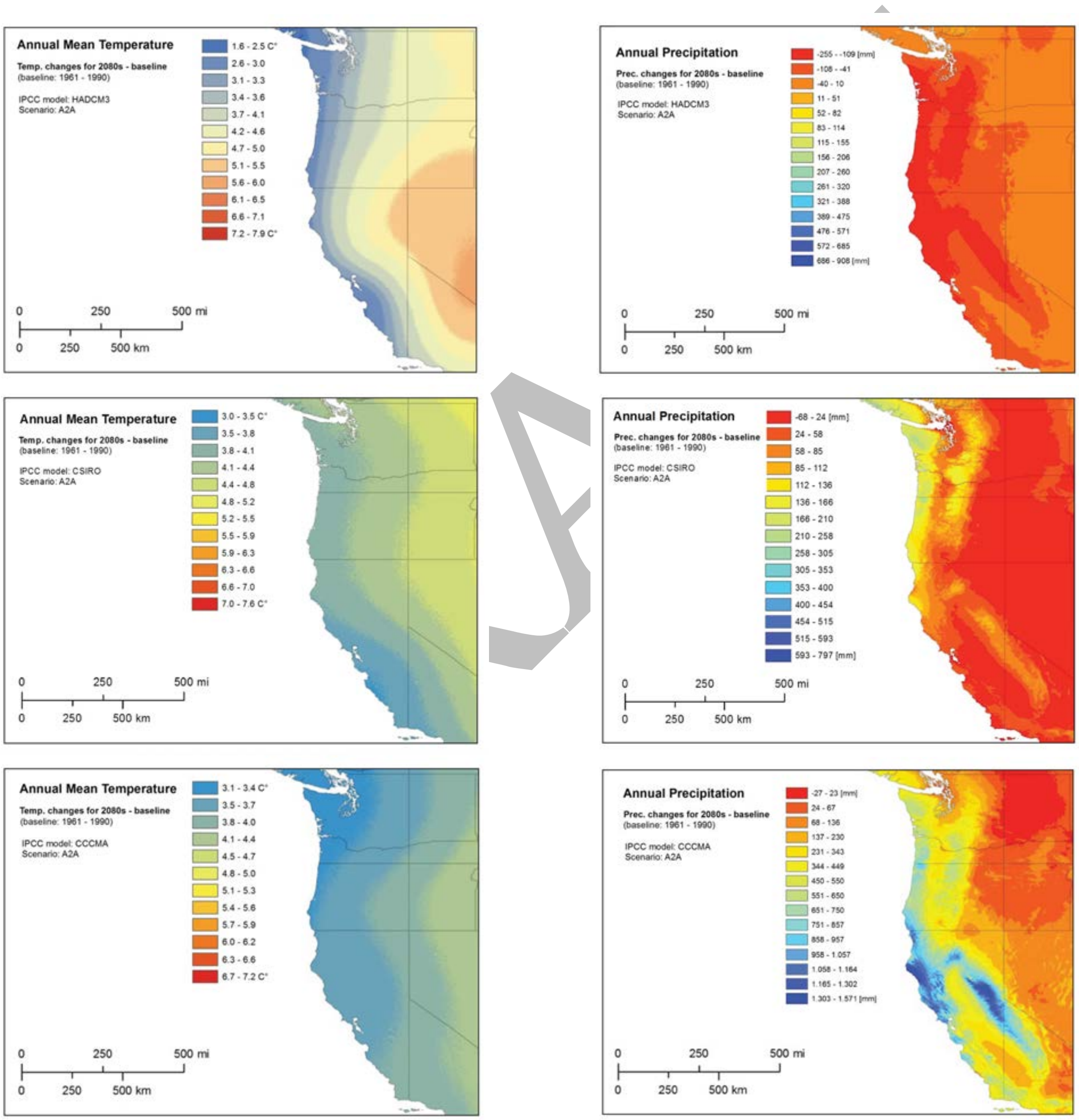
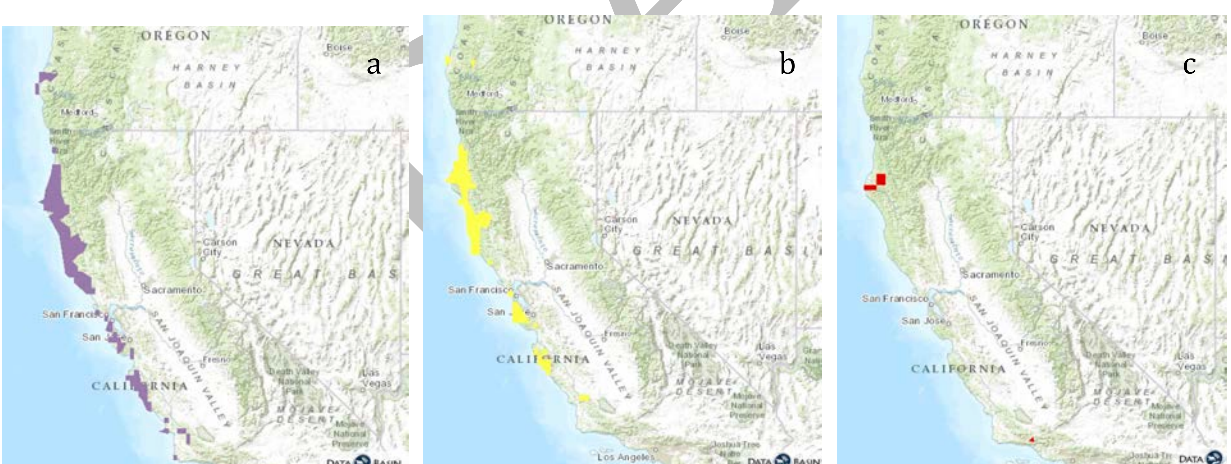


Figure 2. Temperature (left) and precipitation (right) change projections for 2080s, based on the A2 emissions scenario, using three different General Circulation Models (GCMs): HadleyCM3, CSIRO, and CCCMA (from DellaSala et al., In Review).

Climate-Related Range Shifts

One approach to assessing the impacts of climate change on coast redwood is to map the current “climate envelope” and project where the same set of environmental conditions will be found in the future, based on climate model projections. The “climate envelope” for a species is the full range of conditions under which that species is currently found. This approach has strengths and weaknesses. First, it only incorporates climatic variables, ignoring ecological variables that might affect distribution, such as competition or human influence. Also, for redwood especially because they are so long lived, the current climate envelope may not be representative of the conditions needed for new establishment, as different conditions were present hundreds of years ago when today’s forests were established. But redwood continues to flourish and become established within much of its current range, and generally at least, climate projections are expected to elucidate potential range shifts from regional climate change effects.

Scientists at the California Academy of Sciences used climate envelope modeling to project future range shifts of redwoods for three time periods – 2010’s, 2050’s, and 2090’s (Figs. 3a-3c). In their projections, the future area with a climate similar to what redwoods experience today is greatly reduced, and it does not expand northward. A small refuge with similar climate to the present is found in only 2 locations by 2080 (Figure 3c), with one location considered an unlikely outlier near Santa Barbara, CA.



Figures 3a-3c. Predicted distribution for coast redwood (*Sequoia sempervirens*) for (a) the years 2010's (ten year period average), (b) the years 2050s, and (c) the years 2080s, based on the agreement of 2 or more out of 5 niche modeling techniques (Climate Space Model, Envelope Score, Environmental Distance, GARP, and SVM) and monthly precipitation and average temperature from 12 GCM's from the A2 emission scenario. Localities used to produce the model were resampled from the known current distribution, data provided by Save the Redwood League (http://www.savetheredwoods.org/). Maps downloaded from Databasin.org.

Scientists at the Geos Institute and Leuphana University (Germany) used climate envelope modeling to project future range shifts of redwoods for three time periods – 2050's and 2080's, based on output from 3 different GCMs (Fig. 4; DellaSala et al. In review). Their projections use model agreement as an important component in identifying uncertainty. Areas of agreement include extensive range contractions throughout much of the current range of coast redwood (in red, below), and few areas of persistence by the 2080's (in dark green, below). One model of the three indicates potential for range expansion through late century (light blue).

Fog

Fog is an important component of coast redwood forests, providing water input for redwoods and associated species especially during dry months (Burgess and Dawson 2004; Dawson 1998, Azevedo and Morgan 1974). In fact, the distribution and paleoecological history of redwood indicates that this species is closely associated with summer maritime fog (Johnstone and Dawson 2010).

A recent study assessed changes in the frequency and duration of fog cover over the last century, revealing that there has been a 33% reduction in fog frequency (Johnstone and Dawson 2010). As temperatures continue to rise and evaporative demand grows, redwoods and other coastal rainforest species are likely to become increasingly drought stressed, especially in summer. This is expected even under future scenarios that show increasing mean annual precipitation because that precipitation is expected to fall during winter months, as larger storm events, and as rain instead of snow, which runs off quickly.

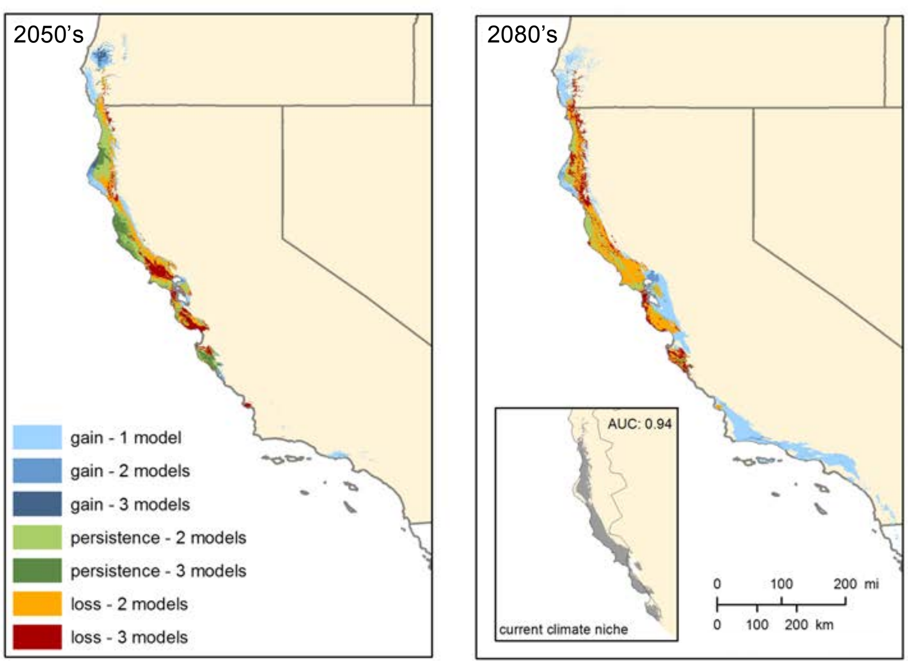


Figure 4. Projected change in redwood climate envelope based on 3 General Circulation Models, A2 emissions scenario, and 2 time periods (2050 left; 2080 right).

Wildfire

Wildfire projections for the redwood area show wide disagreement among models, indicating substantial uncertainty.

Projections for wildfire in redwood forests of Humboldt and Santa Clara Counties showed little expected change (Torn et al. 1998). However, these models did not include potential changes in fog conditions during summer. Additionally, the GCM used in this study (GISS) predicted wetter overall conditions for the redwood region, resulting in more conservative results (Torn et al. 1998, Fried et al. 2004).

In contrast, Westerling et al. (2011) found a 100-300+% increase in large wildfire in much of the northern portion of California based on projections using three different GCMs. Their projections assume that the historical relationship between temperature and wildfire risk is maintained as temperatures rise across California. In addition, they model population growth and urban sprawl as components of wildfire risk.

Carbon storage

With the passage of California's Global Warming Solutions Act (SB32), there is a need to measure the carbon stored in forest ecosystems so they can be included for carbon credits in the state's cap and trade program. Because coast redwood have the largest measured biomass per acre of all California forests (Jones and O'Hara 2012) their utility for carbon credits is very high. However, average wood density and carbon values are applied across diverse stands, and redwoods (even young stands) are systematically underestimated on the California carbon market. Recent research by the Save The Redwoods League demonstrate great potential in old growth redwood for carbon storage, as longer growing seasons and warmer temperatures have led to higher growth rates, as previously discussed.

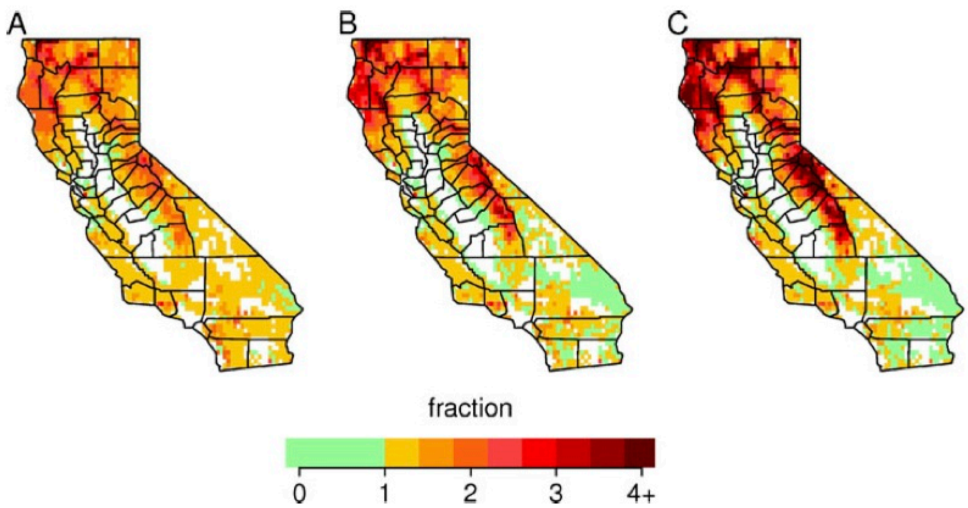


Figure 5. 2085 predicted burn area as a multiple of reference period predicted burned area for three SRES A2 climate scenarios: a NCAR PCM1, b CNRM CM3, and c GFDL CM2.1, with high population growth, high sprawl, and a high threshold housing density for defining the limit to the wildland urban interface (see Westerling et al. 2011 for more details). A value of "1" assumes that burned area is unchanged, while 4+ assumes that burned area is 400% or more of the reference period (i.e., 300% increase).

Adaptation Approach

The purpose of the September 6, 2013 workshop is to develop and prioritize an initial suite of adaptation strategies for managing redwood forests under climate change. In order to guide strategy development, we are providing a quick guide to Climate-Smart principles for conservation, developed by a diverse group of NGO and government agency scientists and managers with expertise in climate change adaptation. Climate-Smart principles are intended to provide guidance for managers as they navigate the inclusion of climate change consideration in their management procedures. The overarching principles of Climate-Smart Conservation include:

- Link actions to climate impacts
- Embrace forward-looking goals
- Consider broader landscape context
- Adopt strategies robust in an uncertain future
- Employ agile and informed management
- Minimize carbon footprint
- Account for climate influence on project success
- Safeguard people and wildlife
- Avoid maladaptation

Please see the Quick Guide to Climate-Smart Conservation for more information on these principles. The full handbook and training module will be released later in 2013. It is a companion handbook to the Vulnerability guide "Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment" (www.nwf.org/vulnerabilityguide). We have also provided a link to this document on the Geos Institute website for this workshop for those who are interested.

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