Managing an Ancient Ecosystem for the Modern World: Coast Redwoods and Climate Change

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ABSTRACT

Coast redwoods (*Sequoia sempervirens*) and their many associated species create an iconic ecosystem, yet the impacts of stressors, including a variety of land use practices and climate change, threaten their continued persistence on the landscape. In September 2013, we held a workshop with researchers, managers, and other redwoods experts to explore the likely impacts of climate change and develop some initial strategies for adaptation. Workshop participants from diverse backgrounds identified four primary strategies to increasing the resilience of redwood ecosystems in the face of climate change. These included (1) restoring old-growth characteristics that protect stands from many stressors; (2) improving connectivity among intact redwood forest patches throughout the range of redwoods; (3) reducing stressors that exacerbate the impacts of climate change, such as roads, fragmentation, development, and fire exclusion; and (4) coordinating management across the redwood range, and across land ownership, allowing for conservation and/or restoration of climate change refuges and areas of connectivity. Workshop participants expressed great interest in continued meetings that provide for sharing of information; informational "hubs" that allow for online sharing; and coordinated research and monitoring efforts that inform management and restoration of redwood ecosystems. The Landscape Conservation Cooperatives (LCC's) that supported this work, including the California LCC and the North Pacific LCC are well aligned for supporting these needs and providing increased coordination across land ownership of the redwoods region.

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INTRODUCTION

On September 6-7, 2013, thirty participants attended a workshop cosponsored by Geos Institute, the North Pacific Landscape Conservation Cooperative (NPLCC) and California Landscape Conservation Cooperative (CALCC) of the U.S. Fish & Wildlife Service, the Environmental Protection Information Center (EPIC), and the Society for Conservation Biology – Humboldt State University Chapter. The purpose of the workshop was to share information among researchers and practitioners (land managers) about coast redwood (*Sequoia sempervirens*) conservation and management needs in a changing climate and develop an initial suite of strategies to manage redwoods for persistence under climate change.

In the context of the LCC's, this effort was focused on synthesizing existing redwood science in a climate change context to further evaluate the effects of changes in air temperature and precipitation on forests and also the impacts of invasive species and their effects on biological communities. It is consistent with the NPLCC guiding principle, "helping managers understand the availability and effectiveness of adaptation and mitigation response actions" and S-TEK Strategy Objective "maximize the ability of partners to make informed decisions with respect to conservation and sustainable resource management or priority natural and cultural resources subject to climate change and related large-scale stressors in the NPLCC region" (NPLCC 2012).

Few forests in the world have such rich species assemblages, enormous tree sizes, rich and structurally complex canopies, productive soils, and exceptional biomass as coast redwoods (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). Coast redwood forests, with their suite of associated plant and animal species, reflect a complex history of climate, biogeography, and human interaction. In prehistoric times, as far back as the Tertiary period,

Figure 1. Historic and current range of Coast Redwood forests in California. Data assistance provided by Save the Redwoods League. The range also extends slightly into Oregon (not shown).

redwoods flourished throughout much of the globe. Due to past changes in climate, which occurred over much longer timescales than human-caused climate change is occurring today, the range of redwoods contracted to only a sliver of the northern California coastline, extending only ~60 km inland in historic times.

For many thousands of years, Native Americans lived in independent villages among the redwoods, playing a significant role in fire ecology and management of redwood and other important subsistence food and cultural resources (Frederickson 1984, Norman 2007). Once European settlers arrived, and especially after World War II, redwood harvest and clearing intensified. Today, old growth redwood covers less than 4% of its historical range (Noss 2000). Native Americans in the region continue to depend on redwood ecosystems for important subsistence food and cultural resources, making sustainable management of this ecosystem vital.

As many components of what has shaped today's redwood forests have changed and continue to change, so will the forests themselves. For example, the incidence of fog may have declined by 33% over the last century (Johnstone and Dawson 2010). Redwood forests newly invaded by Sudden Oak Death (SOD), an emerging infectious disease, may have altered fuel structure and fire risks (Metz et al. 2013). Yet northern redwoods appear to be growing faster under current conditions than they have in the recent past (Carroll et al. 2014). Climate change likely plays a role in these recent changes but the mechanism is unclear. Climate change is expected to accelerate in the coming decades, potentially disrupting redwood ecosystem assemblages and function as the speed of change exceeds the potential for ecosystems to adjust and adapt.

Workshop participants came from a variety of different backgrounds and areas of expertise. Most were associated with state and federal land management agencies, city government, university research institutions, private forestry, Native American tribes, and non-governmental organizations. This workshop is intended to be one of many to develop sound adaptation strategies for the coast redwood ecoregion, with a strong basis in stakeholder engagement (Bierbaum et al. 2013).

We conducted a review of the relevant science on climate change, providing workshop participants with information on current conditions, ongoing change, and expected future trends. We also discussed how existing stressors interact with climate change to exacerbate impacts to redwood forest species and ecosystem function. Finally, we weighed different approaches to managing redwoods for persistence and collectively developed recommendations for best practices and information needs. The science review, information from participants, and results of their brainstorming effort are summarized here.

Distribution and Management Legacy

The current distribution of coast redwood can be classified into three distinct subregions (Fig. 1) – north, central, and south. Each subregion experiences unique conditions based on precipitation, soils, stand structure and composition, and geographic coverage (Sawyer et al. 2000). Southern redwood forests are genetically, ecologically, and compositionally different from northern and central forests. They experience less annual precipitation, have a less continuous distribution, and support smaller tree sizes overall (Lazzeri-Aerts 2011).

It is estimated that in 1850 more than 2,000,000 acres of old-growth redwood occurred regionwide (Fig. 1). Logging of coast redwood began in the early 1800's and accelerated after World War II (Noss 2000). In 1968, when Redwood National Park was formed, only 10% of pre-European settlement old-growth redwood remained. Today, <4% of the pre-settlement forest remains intact (Noss 2000), and half of the remaining old-growth redwoods are found in Redwood National and State Parks. Other old-growth redwood forest occurs on public lands managed for conservation (Fig. 1) and private lands primarily managed for harvest.

Past harvest practices, development, and forest fragmentation have created a management legacy that greatly influences redwood distribution, age class, ecosystem function, and forest composition. Accelerating climate change will further shape these important forests over time. The interactions among past management, ongoing stressors, and climate change are complex, yet together they will determine overall persistence probabilities and future management options. For instance, many redwood forests were clearcut in the mid-1900's and then re-seeded with Douglas-fir (*Pseudotsuga menziesii)*. Consequently, typical second-growth forest structure features dense, even-aged Douglas-fir distributed amongst coast redwood stump sprouting. These conditions prevent the rapid recovery of old forest characteristics, such as the dominance of redwood, distinct canopy layers and diverse understory vegetation (O'Hara et al. 2010, Teraoka and Keyes 2011).

Managing and restoring for old forest characteristics is particularly important in the context of climate change. Mature redwood forests are more resilient to climatic change, fire, and drought. They also provide refugia for many species that are threatened by climate change. As the climate changes, these pockets of mature forest will be increasingly important as the forests around them continue to change at a faster rate (DellaSala et al. in review). Managers have only begun to experiment with forest treatments that can improve forest development trajectories to more quickly reflect old forest composition and structure. However, it is not known whether these practices will allow redwood to persist in a changing climate.

Another legacy of land use and past management is lack of late-seral connectivity among the remaining old-growth forest patches at the regional and subregional scale (Fig. 1). As forest restoration continues, one goal is to reconnect intact forest patches to allow for connectivity, gene flow, and species movement. Areas are prioritized for restoration based on their proximity to intact forest patches and aggregate contribution to connectivity across the landscape. One unknown factor is whether specific restoration areas will remain climatically suitable for redwood over the next century. Connectivity could become even more vital for species that need to shift to new areas to find suitable climate conditions as climate change progresses (Malcolm and Pitelka 2000). Whether or not connectivity will be sufficient in providing for movement of redwoods and their many associated species in a quickly changing climate will depend on species-specific dispersal capabilities, permeability of the landscape to species movement, biotic and abiotic factors such as competition, predation, and soils, and many other factors.

ONGOING STRESSORS TO REDWOOD ECOSYSTEMS

Coast redwood ecosystems also are impacted by a variety of ongoing stressors that limit restoration efficacy, overall ecosystem function, and distribution potential. During our workshop on redwoods and climate change, we asked participants to identify ongoing stressors and their impacts (the full list is available in Table 1). A better understanding of the suite of ongoing stressors was vital to developing sound adaptation strategies for redwood forests in a changing climate. Some of the more pervasive stressors include:

Roads – As coast redwood forests have been harvested for timber and fragmented by development, roads have become a major feature across the landscape. Roads can have many negative impacts to species and ecosystems (Trombulak and Frissell 2000). Forest fragmentation from roads disrupts the movement of organisms and flow of ecological processes across the landscape (Marsh et al. 2005, Lindenmayer and Fisher 2006). Roads cause increased runoff, erosion, and sedimentation of waterways (Pitlick 1995, Weaver et al. 1995, Forman and Alexander 1998, Reid and Keppeler 2012). Channel morphology and substrate can be altered from sediment inputs (Beschta 1978), severely degrading native fish habitat. Roads also act as a conduit for invasive species (Gelbard and Harrison 2003).

Fragmentation and land use – Besides direct physical disturbance caused by road building, the creation of roads also leads to habitat fragmentation. Fragmentation occurs for a variety of reasons. One primary reason is the encroachment of housing development throughout much of the coast redwood range. There is pressure for landowners to subdivide second-growth redwood forests for housing, bringing the wildland-urban interface even closer to conservation areas. With homes come invasive weeds, feral cats, more corvid nest predators (a problem for nesting marbled murrelets), motorized recreation, human-caused fire ignition, and altered hydrology with increased erosion. In addition, development limits the tools that can be used in managing wildland fires, such as 'let burn' policies, inhibiting wildfire restoration in many areas.

In addition to housing development, conversion of redwood forests to agricultural lands, primarily for growing wine grapes but also for illegal marijuana production, is an increasing stressor. Past and continuing fragmentation and loss of forest threatens to reduce opportunities for conservation and restoration in the future, when the need for connectivity might become a management priority.

Fire and Fire Management – 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 known to have been frequent. Prior to European settlement, fires in upland redwood forests occurred roughly every 10 to 30 years, with fire frequency depending on distance from the Pacific Ocean and topographic position (Lorimer et al. 2009). There is evidence suggesting that the long-term viability of redwood populations may depend on fire (Lorimer et al. 2009, Ramage et al. 2010). Given the importance of fire to this system, there remains a large degree of uncertainty concerning the historic fire regime (e.g., the degree to which the historic fire regime was driven by Native American management; Norman, 2007) and how this information should be used to guide current management. Through many years of observations and research, scientists know that coast redwoods not only tolerate fire, but even regenerate vigorously after fire.

When fire is suppressed, forest debris can collect on the forest floor and small trees can become dense in second-growth or tree plantations. 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). The 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 et al. 1999, Noss 2000, Brown and Baxter 2003).

Lazzeri-Aerts (2011) found that fires in redwood stands were less severe than fires in other forest types, and that mature forests were more resistant to fire than young stands (Douglas and Bendure 2012). Conserving and restoring mature forest structure to coast redwood stands would be expected to reduce the risk of uncharacteristically severe fire. Thinning in mature coast redwoods was not recommended by conference participants as a tool to reduce fire risk, as canopy gaps in coast redwood stands actually act to increase the production of smaller, fire prone stems and thinning can lead to drier fuels. In contrast thinning was recommended in second-growth in order to promote growth among residual redwood trees and remove overly dense Douglas-fir trees.

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

Sudden Oak Death (SOD), caused by the pathogen *Phytophthora ramorum*, results in mortality of common species in redwood forests. *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 native forests through selective mortality of tanoak (*Lithocarpus densiflorus*), which is particularly susceptible (Metz et al. 2012). The presence of SOD increases the susceptibility of redwood forests to uncharacteristic wildfire (Metz et al. 2013).

Climate Change – The greatest overall stressor to redwood ecosystems is increasingly climate change. Climate change is associated with a whole suite of ongoing and future stressors to redwood ecosystems. A primary impact of climate change is that it exacerbates stressors that are already limiting ecological function and resilience. An emerging threat from climate change is increasing tree mortality and frequency of large-scale forest die-back (van Mantgem et al. 2009, Allen et al. 2010), likely due to warming and water stress (van Mantgem et al. 2009). Redwoods, however, appear to be growing faster in recent decades, perhaps indicating a – potentially transient – positive response to increased insolation (Carroll et al. 2014). Additional risks may arise from the heavy downpours that are already increasing across the nation, and models predict larger, more severe storms for the Southwest region (Melillo et al. 2014), which includes northern California, potentially causing even greater runoff and erosion from roads. Wildfire is expected to increase with climate change (Westerling et al. 2011), increasing the chances of uncharacteristically severe fire that threatens intact redwood stands. With so few old-growth stands remaining, controlling fire near these stands may be increasingly important for retaining some old-growth dependent species (McKenzie et al. 2003). The impacts of fragmentation will also be exacerbated by climate change. Many species require connectivity to disperse to new areas. As climate change progresses, dispersal will be increasingly vital as species are forced to shift to new areas to find suitable climate conditions. Invasive species are expected to benefit from warmer temperatures and less competition with native species. Invasive pathogens like SOD could spread more quickly among trees that are stressed from climate change.

Broad-scale changes in climate are already impacting local conditions across the globe and are expected to accelerate in the coming decades. Potential changes to local conditions include increasing temperatures, changes in the timing and availability of water, decreasing fog, changing wildfire frequency and intensity, and shifts in vegetation and wildlife species distributions.

Temperature and precipitation – Mean temperature in the redwoods region has increased by 0.5° to 1.5° F over the last 50 years (Pierce et al. 2013, Melillo et al. 2014). Projected temperature increases for the far northwestern corner of California are 7-8° F, on average, for 2071-2099, if greenhouse gas emissions continue unabated. Projections for precipitation change are more variable, with different models projecting increases or decreases for the region (Melillo et al. 2014). As temperatures rise, however, drier conditions are expected overall due to evaporation and evapotranspiration, even if precipitation increases on average.

Fog – The distribution and paleoecological history of redwood indicates that redwood is closely associated with summer maritime fog (Johnstone and Dawson 2010). Fog provides water input for redwoods and associated mesic species especially during dry months (Azevedo and Morgan 1974, Dawson 1998, Burgess and Dawson 2004). A recent study assessed changes in the frequency and duration of fog cover over the last century, suggesting a 33% reduction in fog occurrence (Johnstone and Dawson 2010), although this reduction is not apparent in the instrumental record (van Mantgem, personal communication). 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. Summer drought stress is likely even under future scenarios with increasing average precipitation because potential increases in precipitation are expected during winter months.

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, this was based on a single general circulation model (GCM) that was wetter than most others and did not consider changes in fog (Torn et al. 1998, Fried et al. 2004). In contrast, Westerling et al. (2011) projected a 100% to more than 300% increase in large wildfire in much of the northern portion of California based on three different GCMs. Westerling's projections assume that the historical relationship between temperature and wildfire risk is maintained as temperatures rise across California.

Wildfire models can help us predict changes in wildfire frequency and severity over time. Because the last 100 years are associated with both fire suppression and ongoing climate change, however, it is difficult to determine what baseline is appropriate for comparison. Increases in wildfire can be quite beneficial ecologically for systems that have experienced decades of fire suppression and for fire-dependent species. However, overall there remains a large deficit in fire acres and so far a lack of a statistically significant signal in fire severity increases throughout much of the Western U.S. and Canada (Odion et al. 2014). It is unclear how and what changes in fire might occur in redwood forests.

Missing from wildfire projections for the redwood region is the effect of land use on wildfire. Conversion from old-growth coastal wet coniferous forest to second-growth has opened new areas to more fire-prone species such as young Douglas-fir. Young, dense, and highly fragmented forests have replaced fire-resistant old growth throughout much of the redwood range, potentially increasing fire likelihood beyond what the models project.

Range shifts – Two separate investigations using climate envelope model projections indicate that the area with a suitable climate for coast redwood is expected to contract substantially by the end of the century (Strittholt et al. 2010, DellaSala et al. in review). The climate envelope approach includes assessment of current climate conditions throughout the range of redwoods and mapping of where that same set of climate conditions (the "climate envelope") will be found in the future, based on GCM projections (DellaSala et al. in review). This approach has strengths and weaknesses. First, it only incorporates climatic variables, ignoring ecological variables like competition and physical/chemical features such as soil type and acidity.

Also, because redwoods are so long lived, the current climate envelope may not be representative of the conditions that were present when these ancient forests were established. Further, late-seral redwood forests themselves moderate temperature and may act as climate refugia. The sub-canopy of older redwood stands is wetter, cooler, and has low light conditions that favor redwood and other shade tolerant species over other species. Therefore, these older redwood forests will likely persist long after the climate envelope in which they are surrounded has changed.

Strittholt et al. (2010) projected a substantial reduction in the future climatic envelope suitable to support redwoods. In that study, by the 2080's, only two small refuges with similar climate to the present are expected to persist – one immediately south of Eureka, near the Headwaters Forest Reserve, and the other considered an unlikely outlier near Santa Barbara, CA.

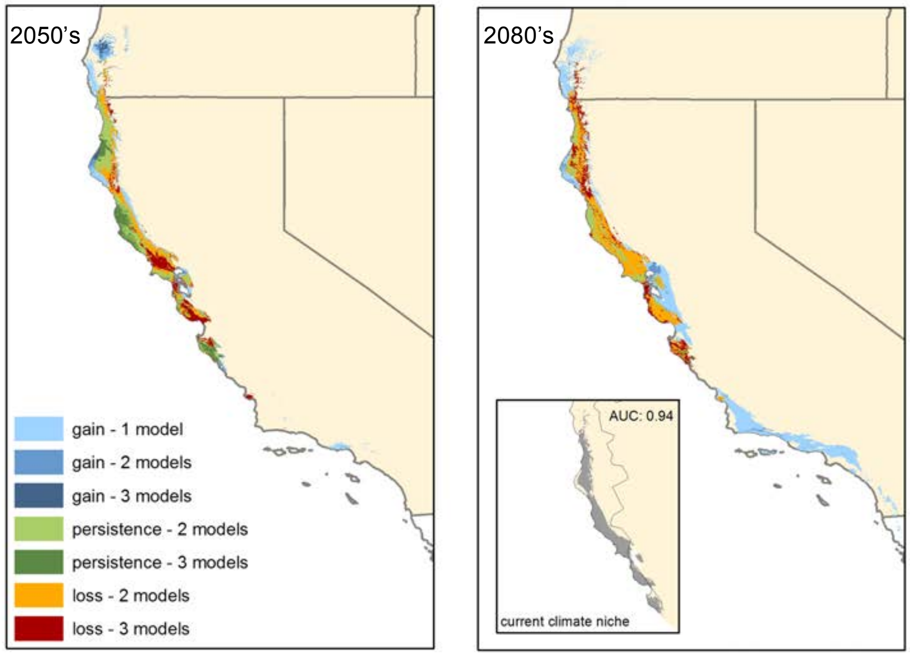

Figure 2. Projected change in redwood climate envelope based on three General Circulation Models, A2A emissions scenario, and two time periods (2050's left; 2080's right).

DellaSala et al. (in review) projected future redwood climate envelope shifts for two time periods – 2050's and 2080's – based on output from three different GCMs (Fig. 2; CCMA-CGCM2, CSIRO-MK2, and HADCM3) and a high emissions (A2A) scenario. Areas of agreement among the three GCMs include extensive range contractions throughout much of the current range of coast redwood (red) and few areas of persistence by the 2080's (dark green). One model of the three indicates potential for expansion of the climate envelope through late century (light blue).

Resilience Strategies for Redwood Ecosystems

In light of management legacies, ongoing stressors, and future climate change impacts that were highlighted during the first half of the workshop, workshop participants talked at length about the need to plan for resistance, resilience, and transition throughout the redwoods ecoregion.

> ***Resistance*** is the ability of a system to withstand impacts without major change in plant and wildlife communities.
>
> ***Resilience*** is the ability of a system to recover after perturbations, such as fire or drought.
>
> ***Transition*** is the change from one type of system to another in response to climate change and/or other factors (Millar et al. 2007).

Most managers and researchers agreed that management strategies for coast redwoods should focus primarily on resilience at this time. Redwoods are very long lived, and redwood ecosystems can potentially persist for hundreds of years, even if reestablishment becomes unsupported by the changing climate. As these forests are impacted by natural disturbance and increasing variability in climate associated with climate change, resilience will become vital for continued persistence.

Resistance approaches can be time and energy intensive and eventually prone to failure as conditions change (Millar et al. 2007). Participants suggested that in certain situations resistance strategies might be called for to protect specific stands. An example from outside the region would be the protection of some of the largest giant sequoias (*Sequoiadendron giganteum*) during 2012 wildfires in California, when sprinklers were used to reduce fire risk in specific stands. Managing for transition was thought to be a strategy to consider in the future, once ecological and climatic trajectories are better understood and new and novel ecosystems can be planned.

Workshop participants recommended four primary approaches to increasing resilience in redwoods ecosystems. These included (1) restoration to conditions and structure resembling those of historic old-growth forests, (2) improving connectivity, (3) reducing stressors, and (4) managing at a range-wide scale. In addition to these four strategies, the group identified and prioritized many other potential strategies (Table 1) for managing this iconic ecosystem. The four primary strategies are summarized below.

(1) Restoration – Increasing efforts to restore degraded and second growth stands to old-growth structure was suggested as a primary strategy to increase the resilience of redwood ecosystems. Yet there is much debate about what structure to aim for as a restoration target. Management targets have typically been based on reconstructions of the era immediately prior to European settlement. This period may not necessarily represent the most stable ecosystem under expected climate regimes, however, and managing for novel ecosystems that provide desired functions may be a more sustainable strategy (Jackson and Hobbs 2009). Rather than aiming for restoration of historic conditions, managers may need to consider "realignment," where managers promote forest composition and functioning that is anticipated to be stable under future conditions (Millar et al. 2007).

Accepting that the future will be different from both the past and the present forces us to manage forests in new ways (Millar et al. 2007). Current old-growth forest structure, based on our best understanding of reference conditions, provides many of the resilience characteristics thought to be needed under a changing climate, as mature redwood forests are highly resilient in the face of fire, pests, and disease. How well current old-growth conditions reflect historic conditions is difficult to determine, as reconstructions of past forest structure are inherently imprecise (Stephenson 1999). The cessation of fire, the introduction of exotic species (including pathogens), and other changes have also likely altered these forests. Limited research suggests at least some *S. sempervirens* populations are demographically stable (Busing and Fujimori 2002, van Mantgem and Stuart 2012). Until a better model for restoration targets is identified, old-growth forests provide our best model for future stands.

Forest thinning – The primary restoration tool used in coast redwood forests is mechanical thinning, where competing vegetation is removed to promote growth of residual trees (Reukema 1975). This method has a long history of success in commercial and noncommercial settings (Wenger 1984, Busing and Garman 2002, Bauhus et al. 2009). While thinning treatments in coastal redwood forests have generally improved at least some aspects of stand conditions (e.g., understory development), thinning has not always improved residual tree growth over the long-term (>10 years following treatment) (Chittick and Keyes 2007, Teraoka and Keyes 2011) or given a clear competitive advantage to redwood over Douglas-fir (Plummer et al. 2012). New methods, such as variable density thinning (O'Hara et al. 2010), are being tested. In some cases it may be possible to thin stands a second time, but in many instances this is difficult due to funding constraints and the removal of roads following restoration treatments (Madej et al. 2013), particularly in parks and protected areas where road densities need to be low in order to maintain desired features. It is still unclear if thinning treatments will confer increased resistance and/or resilience to disturbance (such as drought), but observations from other forest types are promising (Fulé et al. 2012, D'Amato et al. 2013).

Prescribed fire – The cessation of fire in old-growth redwood forests has had unknown consequences for current stand conditions. The purposeful reintroduction of fire to old-growth redwood forests is hindered by concern over its effects on wildlife populations (e.g., Marbled Murrelet). However, prescribed fire is currently being explored as a thinning tool in second-growth redwood forests. Small-scale research burns have recently been conducted at Redwood National Park, although it will be years before the long-term effects are known. Prescribed fire may be an especially attractive management option where logging roads have been removed or where the terrain is otherwise inaccessible.

Wildland fire can be managed for multiple benefits, including long-term stand resilience. The Canoe fire in Humboldt Redwoods State Park, for instance, burned ~10,000 acres in 2003. This fire caused very limited mortality but likely improved stand resilience by reducing understory fuels. Managing natural start fires and allowing more fires to burn, for ecosystem benefits and improved resilience, will be increasingly critical as fire intensity and frequency increase and prescribed fire budgets decrease.

(2) Connectivity – The second primary strategy recommended by workshop participants to increase ecosystem resilience was to build connectivity among restored and intact redwood forest tracts. The capacity for dispersal has been vital to species response to changing climates for millennia. Connectivity is expected to become increasingly important to maintaining ecosystem function as species are forced to shift to new areas with a quickly changing climate (Noss 2001, Hannah et al, 2002).

Because coast redwoods are distributed in three distinct subregions, with locally unique conditions, species compositions, and gene frequencies, connectivity could allow for species or varieties associated with one area to move to others as climatic conditions change. Salamanders are a common component of redwood ecosystems, yet this taxon is known for its poor dispersal abilities and inability to traverse inhospitable areas. The species mix of salamanders in southern redwoods is very different than that found in northern redwoods. Maintaining and improving connectivity, and potentially some level of assisted migration, will be vital for allowing many salamander species to shift over time.

In the northernmost subregion of the coast redwood forest, there is a large gap of protected areas between Redwood National Park and Prairie Creek Redwood State Park. This is private timberland and contains the mouth of the Klamath River. If these lands were managed for restoration, connectivity and natural dispersal of species would likely be enhanced.

Figure 3. Modeled areas of potential future redwood range, including areas of persistence (dark green) and expansion (blue) based on climate envelope model output. Also shown are areas of potentially higher vegetation stability based on MC1 vegetation model output (light green), but not specific to redwoods. Current restoration priority areas for Redwood National Park are inset.

Connectivity is a commonly recommended adaptation strategy for conservation planning, yet it remains difficult to define and monitor. Most evidence for the importance of connectivity comes from behavioral studies and studies of individual species rather than studies of ecosystems. Yet the importance of structural connectivity is becoming more widely understood and measurable with advances in modeling and mapping techniques (Doerr et al. 2010). Current approaches to managing for connectivity in the coast redwoods ecosystem include mapping intact forest patches to identify priority areas for restoration in the fragmented patches, based on the need to restore and connect large tracts of intact redwood forest. Another valuable approach could be to map “land facets” (areas of uniform topography and soils), which allow for movement across common types of terrain that will remain stable, regardless of climatic conditions. These land facets are expected to facilitate movement of associated species today and in the future (Brost and Beier 2012).

Workshop participants suggested that they need additional information on climate change to help prioritize areas for restoration and connectivity. Many forest patches have been prioritized for restoration due to their value in reconnecting mature forest patches that are currently disconnected, but future restoration in areas where the climate is no longer suitable could become problematic. Because restoration benefits are not realized for many decades, it is vital to invest resources into areas and systems that are expected to remain viable over longer time frames. Climate envelope models and dynamic vegetation models (such as the MC1 model) can be useful in informing conservation decisions to maximize their conservation return over many decades. This is in line with the LCC's focus on having climate change science incorporated into ongoing management.

In response to this need, we mapped current National Park Service priority restoration areas (shown in inset on Fig. 3), as well as areas projected to have greater potential vegetation stability, based on two different modeling approaches. The first approach was the climate envelope approach described earlier (DellaSala et al., in review), with potential redwood expansion shown in blue and persistence shown in dark green (Fig. 3). In addition, we also mapped estimated vegetation community stability based on the output from the MC1 Dynamic Vegetation Model (Bachelet et al. 2001). MC1, which was run using two different GCMs (GFDL and PCM) based on a high emissions scenario (A2), provides information on the type of dominant vegetation expected based on GCM output values that are then input into the vegetation model. Figure 3 shows, in light green, where the MC1 Dynamic Vegetation Model predicts dominant vegetation in 2080 to be the same overall type as it was during the historic period (1961), with agreement among at least two out of the three GCMs. Note that the MC1 Dynamic Vegetation Model output shows vegetation stability for all dominant types of vegetation, not specifically redwood. Of interest are areas that are within the range of coast redwood and that show potentially stable dominant vegetation over time.

(3) Reducing stressors – Climate change is already exacerbating stressors to redwood ecosystems, from invasive species to air quality issues. As impacts worsen with climate change, certain thresholds are likely to be passed, beyond which ecosystems or species may be unable to recover. Reducing stressors is expected to lessen the impacts of climate change, thereby forestalling more serious impact and threshold effects. Workshop participants identified a suite of stressors that, if lowered, could increase overall redwood ecosystem resilience.

It is important to note that climate change itself was identified as a key stressor that needs to be reduced. Actions to reduce greenhouse gas emissions and increase long term carbon stores in forests will help to reduce the overall magnitude of climate change. The forestry sector has an untapped potential to contribute to climate change mitigation (Malhi et al. 2002) with improved forest management practices that sequester and store carbon long-term. As redwoods themselves represent great natural potential for removing CO_2 from the atmosphere and storing it for centuries, redwood management that includes carbon storage priorities can help to accomplish numerous goals (Gonzales et al. 2010). Examples of increasing carbon stores include forgoing harvest in mature stands (set-asides) and increasing rotation intervals. Proactive private landowners interested in these practices may take advantage of carbon credits under California's Global Warming Solutions Act (AB32). Landowners are paid for the offsets purchased by companies seeking to offset their greenhouse gas emissions.

(4) Coordinated management across the range of redwoods – Numerous publications call for more integrated management of natural resources across large landscapes, specifically in response to climate change (Hannah et al. 2002, Heller and Zavaleta 2009, Hansen and Hoffman 2011, Stein et al. 2014). Scientists and managers at our workshop also called for increased coordination, information sharing, and cross-jurisdictional planning and management across the range of the coast redwood. Such coordination would allow for better understanding of current forest condition and status; prioritization of conservation areas with the greatest likelihood of long-term persistence; management and monitoring of species range shifts in response to climate change; continued access for Native Americans to important cultural resources; better working relationships among the many entities that currently manage redwood forests; and a clear plan that can be shared with the public.

During the redwoods workshop, experts from very different backgrounds identified increased coordination and regional planning as a high priority need, but for different reasons. Those in the forest products industry desired coordinated regional planning as a way to reduce the uncertainty associated with profits and economic viability, while those in the conservation realm desired coordinated regional planning in order to protect the areas with the greatest conservation value over time. Individual Tribal representatives were interested in coordinated regional planning to ensure continued access to and management of culturally important plants and animals on public lands.

As climate change progresses, many species, sub-species, and varieties of organisms associated with redwood ecosystems are expected to continue to shift their ranges (Walther et al. 2002, Parmesan 2006), requiring managers to communicate and plan across jurisdictional boundaries for viable habitat for those species. Private landowners and forestry lands will become increasingly important in monitoring for change and for managing for conservation in a dynamic manner. For some species (e.g., range restricted endemics), assisted migration will be required for continued persistence, as rapid movement by natural dispersal is unlikely for many taxa (McLachlan et al. 2007). In fact, with assisted migration, the northern California coastal region could become an important refuge for a large proportion of California's floristic diversity as declines occur elsewhere due to climate change (Loarie et al. 2008). A new culture of communication, collaboration, and trust will need to be in place for coordinated conservation and management to occur (West et al. 2009).

Because mature redwood forest ecosystems are slow to develop and reach maximum diversity and function after many centuries (Noss 2000), planning now for future forest condition is vital for forest persistence. Yet climate change creates a moving target and a need for redwood refuges and conservation in areas that may not be ideal now, but are expected to support redwoods at different times in the future. Designating areas as important refuges for future redwoods, even if they are not currently a core portion of the range, will require coordination among numerous federal and state agencies, as well as private landowners, well beyond the current range of this iconic species.

Workshop participant concerns

This workshop brought together many people who are closely involved in charting a path for this important ecosystem in the future. Others will need to be engaged in future outreach and collaborative planning efforts. Participants voiced appreciation for the opportunity to share information and have constructive and low-pressure discussions about legacy conditions, current stressors, economic and ecological viability, and potential future trends.

Overall, most experts and managers recommended focusing on resilience strategies at this time, although resistance strategies (see page 9 for definition) remain worthwhile and will have an important role to play in adaptation. As the ecological response of redwood to climate change becomes more clear over time, transition strategies will increasingly become warranted. Some of the strategies receiving the greatest support were those that speed up the transition from dense, young forest to forest with mature structural components. By moving forests toward late-seral structure and function more quickly, managers are creating increased resilience in the face of drought, disease, invasive species, and fire. Because these strategies can also lead to larger redwoods and faster growth, they are warranted on both conservation lands and timber harvest lands. Both sectors communicated a need for assessment of the most effective restoration techniques and approaches. Participants also communicated a need for information sharing and collaboration across the redwood ecoregion for more cohesive management efforts. Finally, outreach and education on the impacts of climate change and the importance of redwoods conservation in light of climate change was a high priority for workshop participants, in order to build community support (Table 3).

Many participants expressed a need for "no regrets" strategies that increase forest resilience in the face of numerous stressors and different trajectories of change. No regrets strategies are those that are beneficial across a range of potential future conditions, and they often provide both short-term and long-term benefits. Restoration, increased connectivity, reduced stressors, and coordinated management represent no regrets strategies with significant payback regardless of the future trajectory of climate change.

Participants requested future opportunities to continue the discussion and more rigorously develop adaptation strategies. As with most other adaptation planning efforts, adequate funding resources and leadership for strategy development and implementation are lacking (Bierbaum et al. 2013) and will need to be developed. The workshop resulted in a list of information needs (Table 3) that scientists can address in order to bring new information to the next round of collaborative strategizing for the region.

CONCLUSIONS

The redwood region of Northern California has a complex history, with a legacy that will continue to influence future conditions and actions for centuries to come. The complexity and interaction among past management, current stressors, and future climate change exemplify the lesson that while climate change is a global phenomenon, adaptation must be locally specific in order to be effective (Stein et al. 2014). Even with high uncertainty associated with future conditions, leading experts and managers were able to develop strategies that will help ensure continued persistence for coast redwood forests and the diversity of organisms associated with them.

While these efforts are focused on the need for climate change adaptation to ensure redwood viability over the coming century, it is important to note the unique position this species holds in efforts to mitigate climate change. Ancient redwoods store as much or more above ground carbon than any other forest system on earth (Gonzales et al. 2010), and individual trees continue to store increasing amounts of carbon for hundreds and even thousands of years (Sillett et al. 2010). By managing redwoods for climate change adaptation, we are harnessing a powerful tool for use in climate change mitigation efforts as well.

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Photo from Wikimedia

Table 1. Comprehensive list of stressors to coast redwoods ecosystems, as identified by redwoods workshop participants.

- Air pollution impacts
- Air and water temperature increases with climate change
- Black bear damage to trees in some areas
- Cultural species management (or lack of) and declines from climate change
- Economics driving management and conservation
- Fern mats affected by changes in moisture and temperatures
- Fire suppression leading to potentially higher severity wildfire
- Fire mortality increases with drought stress and Sudden Oak Death
- Fog declines affecting tree growth, lichen, tree voles and upper canopy species
- Fragmentation (lack of connectivity) among patches of old growth and restored areas
- High density Douglas-fir regrowth, causing poor growth rates
- Homogeneous stands affected by a lack of disturbance
- Hydrology changes from human use and land use
- Illegal marijuana growing, pesticides, herbicides
- Invasive species, including fungus affecting amphibians, exacerbated by warming
- Management focused on single species and policies that lead to prohibitive complexity
- Management not integrated or collaborative across the region
- Ocean acidification
- Overgrazing
- Pests and pathogens increasing with climate change
- Population growth and land use change pressures
- Predation by corvids increasing (due to changes in habitat), affecting protected species
- Riparian area buffer size not protective enough
- Road erosion and sedimentation of streams increasing with climate change
- Seed availability from different zones shifting with climate change
- Species composition changes with climate change
- Storm severity increases with climate change, causing flooding and windstorms
- Timber harvest management leading to slash, pollution, and soil damage
- Young age classes dominate the region and are more prone to fire and invasive species

Table 2. Strategies recommended by workshop participants are listed in the first column. The number of individuals recommending each strategy for building resilience, increasing resistance, or facilitating transition is shown in columns 2-4.

Strategies	Resilience	Resistance	Transition	Total
Return to historic old-growth structure and condition	2	3		5
a) by increasing use of prescribed fire, especially in old growth	5	5		10
b) by thinning in overly dense young forest	5	4		9
Reduce stressors, including roads, agricultural conversion, fragmentation, harvest practices, invasive species, and others	2	2	1	5
Increase connectivity among intact forest patches (incentives for landowners)	3	1		4
Manage at range-wide scale, across land ownership (regulatory reform, where needed)	1	2	1	4
Retain and protect biological diversity	2	1		3
Increase education and outreach	1	1	1	3
Manage for a different type of old growth than what was previously there	1		2	3
Use adaptive management approach	1	1		2
Apply a variety of different treatments across the landscape	1		1	2
Monitor to determine when to transition			2	2
Plant new species and genotypes			2	2
Protect ecosystem processes	1			1
Protect areas that are intact (especially northern portion of the range)	1			1
Policy change for better management	1			1
Embrace change			1	1

Identify refugia (areas expected to retain redwood and associated species and/or habitats)	1		1
Incorporate climate change into forest planning processes and timeframes	1		1
Paradigm change throughout the region in how people use and manage resources and relate to one another	1		1

Table 3. Information needs identified and prioritized by workshop participants. Those needs in bold received four or more votes as highest priority.

Research

- Modeling to identify areas of higher and lower vulnerability to climate change
- **Science to inform harvest management to increase forest resilience**
- **Research results to inform silvicultural treatments for restoration, including best practices, scale and timeframe**
- Information on expected changes in precipitation and fog
- Information on physiological thresholds and water requirements for plants and animals
- Information on thresholds for when management action is required
- More information on stressor effects and interactions
- Canopy monitoring
- Soil microbe community research

Assessment

- Geospatial analysis (mapping) of current forest distribution and characteristics (forest age, forest ownership, past management, etc.)
- Identification of priority stands and surrounding wetlands and drainages
- Synthesis and assessment of management techniques

Tools

- **Clearinghouse for information pertinent to the region, including current forest status, ownership, who is monitoring what, where**
- Online tools for sharing information and communication across entities

Approach and Collaboration

- Reconciliation of restoration efforts and timber management
- Prioritization strategy and regional plan for funding and effort
- Identify commonalities among neighbors that have different objectives
- More resources (money) for restoration and management
- Ongoing communication and collaboration across land ownerships
- Integrate monitoring efforts

Education

- **Education on opportunities and limitations of carbon credits to fund conservation**
- Information on how to create incentives for restoration

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Appendix 1.

Participants and their affiliations from the redwoods workshop at Humboldt State University, September 6-7, 2013.

Name	Affiliation
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Mary Mahaffy	North Pacific LCC
Jene McCorey	Yurok Tribe
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Kathleen Sloan	Yurok Tribe
Sue Sniado	California Department of Fish and Wildlife
Jason Teraoka	National Park Service
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Philip Van Mantgem	US Geological Survey
Hart Welsh	USDA Forest Service
Mark Wheetley	California Department of Fish and Wildlife
Jon Woessner	Humboldt Redwood Company