Climate Change and the Klamath-Siskiyou Region

Annotated Bibliography

Table of Contents

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(Alphabetical**)**

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Wright, Juanita. 2016 News Release. Southwest Oregon experiencing an increase in drought-related conifer mortality. Pacific Northwest Region Rogue River-Siskiyou National Forest.

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(Organized by Subject Area)

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Streams, Rivers, and Salmon

Asarian, J. Eli and Jeffrey D. Walker. 2016. Long-term trends in streamflow and precipitation in northwest California and southwest Oregon, 1953-2012. Journal of the American Waters Association, 52 (1): 241-261.

Bottom et al. 2009. Reconnecting social and ecological resilience in salmon ecosystems. Ecology and Society 14(1): 5. [online] URL: http://www.ecologyandsociety.org/vol14/iss1/art5/

Study Designs

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Anacker, B.L., Gogol-Prokurat, M., Leidholm, K. and S. Schoenig. 2013. Climate change vulnerability assessment of rare plants in California. Madrono 60(3): 193-210.

- **Study**: We assessed the vulnerability to climate change of 156 rare plant species. The species were selected from the 1625 rare species in California to comprise eight rarity types, classified according to range size, population size, and habitat specificity. For each of the 156 species, we first assigned a climate change vulnerability score using life history attributes and species distribution models, as specified by the Climate Change Vulnerability Index (CCVI) of NatureServe. The resulting CCVI scores were extremely vulnerable (n 5 2), highly vulnerable (n 5 40), moderately vulnerable (n 5 57), presumed stable (n 5 32), increase likely (n 5 16), and insufficient evidence (n 5 9).**Background**: topographically complex landscapes may provide refugia or paths for movement to more suitable areas under changing temperature and moisture regimes (Hunter et al. 1988; Beier and Brost 2010).

Asarian, J. Eli and Jeffrey D. Walker. 2016. Long-term trends in streamflow and precipitation in northwest California and southwest Oregon, 1953-2012. Journal of the American Waters Association, 52 (1): 241-261.

- **Study**: assessed long-term (1953-2012) trends in streamflow and precipitation in northern California and southern Oregon at 26 sites regulated by dams and at 41 “unregulated” sites (see map on right).
- **Study**: The study area was chosen to coincide with the range of the Southern Oregon/Northern California Coast Evolutionary Significant Unit of coho salmon.

Batabyal, Amitrajeet A. 1998. On some aspects of ecological resilience and the conservation of species. Journal of Environmental Management 52: 373-378.

Bottom et al. 2009. Reconnecting social and ecological resilience in salmon ecosystems. Ecology and Society 14(1): 5. [online] URL: http://www.ecologyandsociety.org/vol14/iss1/art5/

- **Study**: In this special feature introduction, we explore several key attributes of ecosystem resilience that have been overlooked by traditional salmon management approaches.

Breining, Greg. 2016. What’s a National Park to do about climate change? Ensia Magazine. http://ensia.com/features/whats-a-national-park-to-do-about-climate-change/

Cahall, Rebecca E. and John P. Hayes. 2009. Influences of postfire salvage logging on forest birds in the Eastern Cascades, Oregon, USA. Forest Ecology and Management 257: 1119-1128.

- **Study**: We compared densities and relative abundances of forest birds after fire in unsalvaged stands and stands subjected to one of two intensities of salvage logging (moderate, 30 snags retained per ha and heavy, 5–6 snags retained per ha) in mixed-conifer forests in central Oregon.
- **Study**: We evaluated three hypotheses concerning the influence of different intensities of salvage on densities or relative abundances of sixteen species of birds, and two hypotheses

concerning the influence of time since salvage logging on relative abundances or densities of birds.

- Study: We also examined the relationship between vegetation and abundances of each bird species.

Campbell, John L., Mark E. Harmon, and Stephen R. Mitchell. 2011. Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? Frontiers in Ecology and the Environment 10.2: 83-90.

- Study: In this paper, we combine empirical data from various fire-prone, semiarid conifer forests of the western US (where issues of wildfire and fuel management are most relevant) with basic principles of forest growth, mortality, decomposition, and combustion. Our goal is to provide a complete picture of how fuel treatments and wildfires affect aboveground forest C stocks by examining these disturbance events (1) for a single forest patch, (2) across an entire forest landscape, (3) after a single disturbance, and (4) over multiple disturbances.
- Study: The empirical data used in this paper derive from semiarid, fire-prone conifer forests of the western US, which are largely composed of pine, true fir (Abies spp), and Douglas fir. These are the forests where management agencies are weighing the costs and benefits of up-scaling fuel-reduction treatments.

Chmura et al. 2011. Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. Forest Ecology and Management 261: 1121-1142.

- Study: Review study containing lots and lots of minutiae around how plants respond physiologically to increases in temperature, CO2, etc.
- Study: A premise of this review is that the persistence and integrity of forests depend on the acclimation and adaptation of forest trees to future climates. In this review, we identify critical processes, traits and attributes that will underpin this adaptation. Specifically, we (1) review the ecophysiological foundations of forest growth, reproduction and mortality in relation to elevated [CO2], warmer temperatures, changes in precipitation, and droughts; emphasizing interactions among these factors, and how they interact with disturbances, such as fire, insects and diseases; and (2) identify key adaptations and processes underpinning tree tolerance and resistanceto anticipated stresses. It will be important to consider these adaptations when managers design strategies to help forests to adapt to future climates. We center our attention on forests of the NW – the states of Washington, Oregon, Idaho, the northern parts of California, and western parts of Montana.

Climate Leadership Initiative, National Center for Conservation Science and Policy, Pacific Northwest Research Station. 2008. Preparing for Climate Change in the Rogue River Basin of Southwest Oregon.

Damschen, E.I., Harrison, S., Ackerly, D.D., Fernandez-Going, B.M. and B.L. Anacker. 2012. Endemic plant communities on special soils: early victims or hardy survivors of climate change? Journal of Ecology 100: 1122-1130.

- Study: Here, we ask how plant communities on serpentine (ultramafic) soils will be affected by climate change, relative to those on less extreme soils

De Frenne et al. 2013

- **Study**: Here we compiled plant occurrence data (1,032 species in total) from 1,409 resurveyed vegetation plots in temperate deciduous forests. The plots were distributed across 29 regions of temperate Europe and North America (Fig. 1 A and B) with an average interval of 34.5 y (range: 12–67 y) between the original and repeated vegetation surveys (Table S1). From these plots, we tested for plant community responses to recent macroclimate warming and assessed the potential role of changes in forest canopy cover in modulating such responses.

DellaSala et al. 2010. Climate-adapted conservation planning. Powerpoint presentation.

DellaSala, D.A., Baker, R., Heiken, D., Frissell, C.A., Karr, J.R., Nelson, S.K., Noon, B.R., Olson, D. and J. Strittholt., 2015. Building on Two Decades of Ecosystem Management and Biodiversity Conservation under the Northwest Forest Plan, USA. Forests, 6(9), pp.3326-3352.

- **Study**: This paper (1) showcases the fundamental conservation biology and ecosystem management principles underpinning the Northwest Forest Plan as a case study for managers interested in large-landscape conservation; and (2) recommends improvements to the plan's strategy in response to unprecedented climate change and land-use threats.

DellaSala, Dominick A. 2016 White Paper. Do mountain pine beetle outbreaks increase the risk of high-severity fires in Western forests: a summary of recent field studies. Geos Institute.

- **Study**: This paper summarizes results from dozens of recent field studies from multiple regions (Pacific Northwest, Pacific Southwest, Rockies) and forest types (mixed conifer, mixed evergreen, subalpine, lodgepole pine, spruce-fir) on effects of mountain pine beetle tree kill on fire severity.

DellaSala et al. 2016. In Review. (To be added…)

Dobrowski. 2011

- **Study**: Here I examine the climatic basis for microrefugia and assert that the interaction between regional advective influences and local terrain influences will define the distribution and nature of microrefugia. I review the climatic processes that can support their subsistence and from this climatic basis: (1) infer traits of the spatial distribution of microrefugia and how this may change through time; (2) review assertions about their landscape position and what it can tell us about regional climates; and (3) demonstrate an approach to forecasting where microrefugia may occur in the future.

Dugger et al. 2016. The effects of habitat, climate, and Barred Owls on long-term demography of Northern Spotted Owls. The Condor 118: 57-116.

- **Study**: We used mark–recapture, reproductive output, and territory occupancy data collected during 1985–2013 to evaluate population processes of Northern Spotted Owls (Strix occidentalis caurina) in 11 study areas in Washington, Oregon, and northern California, USA. We estimated apparent survival, fecundity, recruitment, rate of population change, and local extinction and colonization rates, and investigated relationships between these parameters and the amount of suitable habitat, local and regional variation in meteorological conditions, and competition with Barred Owls (Strix varia).

Dunk, J.R., Zielinski, W.J. and H.H. Welsh, Jr. 2006. Evaluating reserves for species richness and representation in northern California. Diversity and Distributions 12: 434-442.

- **Study**: we used field data from a random sampling design to map the distribution of local and regional richness of terrestrial molluscs and salamanders within northern California's portion of the Klamath-Siskiyou region
- **Study**: We also evaluated the protection afforded by reserves to hotspots of species richness and species representation of these taxa.
- **Study**: Roberge & Angelstam (2004) noted that the greatest challenge to evaluating the umbrella species concept was data from actual, not hypothetical, reserves designed around umbrella species. Herein, we provide such an evaluation for a conservation plan designed largely around the northern spotted owl (Strix occidentalis caurina ; Merriam, 1898).
- **Study**: We evaluated the distribution of terrestrial mollusc and salamander species richness and the protection afforded by two reserve types and non-reserved lands to hotspots of species richness and to species representation. We also evaluated the concordance of richness patterns of terrestrial molluscs and salamanders.
- **Study**: We had three goals.
    - Our first goal was to identify hotspots of local and regional richness for each taxon (molluscs and salamanders). Local richness is ultimately limited by the regional richness surrounding a local site. However, due to the varying histories of impacts (e.g. timber harvest, fire) across our study area, we could conceive of several factors that could 'uncouple' a strong correlation between local and regional richness, such that hotspots of local richness could be found outside of hotspots of regional richness.
    - Our second goal was to evaluate the concordance of local and regional distributional patterns between these disparate taxa to determine whether either taxon would be a good surrogate for the diversity of the other (e.g. Moritz et al ., 2001).
        - Although not closely related taxonomically, terrestrial molluscs and terrestrial salamanders share two key features: (1) both have low vagility and (2) both appear to need microclimates that provide abundant moisture during, at least, a part of the year, and thus one might expect them to show similar geographical patterns of diversity.
    - Our third goal was to compare how the pre- and Northwest Forest Plan reserves protect hotspots of species richness, and represent species composition, within these taxa, even though these were not explicitly considered when either reserve type was established.
        - Conservation of hotspots alone may neglect other important and valued attributes of an area's biota (Kareiva & Marvier, 2003), including protection of rare (Lennon et al ., 2004) or endemic (Orme et al ., 2005; Stohlgren et al ., 2005) species; as well as species representation and persistence (Margules & Pressey, 2000).
        - Hence, we also evaluated the degree to which regional hotspots for each taxon sheltered the rarest species within each taxon.
        - Our analyses can be considered an evaluation of the protections the spotted owl provides as an umbrella for hotspots of mollusc and salamander richness and species representation within each taxon.

Fontaine, J.B., Donato, D.C., Robinson, W.D., Law, B.E. and J.B. Kauffman. 2009. Bird communities following high-severity fire: response to single and repeat fires in a mixed-evergreen forest, Oregon, USA. Forest Ecology and Management 257: 1496-1504.

- **Study**: We studied bird communities using point counting in the Klamath-Siskiyou ecoregion of Oregon, USA at various points in time after one or two high-severity fires. Time points included 2 and 3 years after a single fire, 17 and 18 years after a single fire, 2 and 3 years after a repeat fire (15 year interval between fires), and >100 years since stand-replacement fire (mature/oldgrowth forest).
- **Study**: We conducted our study in the Klamath-Siskiyou region in northwestern North America that is characterized by a wet Mediterranean climate and a mixed severity fire regime in which fires burn every 5–75 years (Agee, 1993; Taylor and Skinner, 1998).
- **Study**: Our objectives were to compare bird communities at different times since stand-replacement fire and use the unique opportunity afforded by the 200,000 ha Biscuit Fire – which reburned a preexisting 15-year old fire – to assess the effect of short-interval repeated high-severity fire on bird communities.
- **Study**: We used community-level (species richness, total density, ordination) and species-level (indicator species) metrics to identify bird communities and species associated with fire-based disturbance as well as the predominant environmental gradients associated with those communities.
- **Study**: In July 2002, at least two separate lightning strikes ignited fires in southwestern Oregon which became the 200,000 ha Biscuit Fire. The Biscuit Fire completely reburned the 38,000 ha 1987 Silver Fire while the nearby 8000 ha 1987 Galice Fire remained outside the Biscuit Fire perimeter (Fig. 1). All three fires burned for extended periods (weeks to months), generating a complex mosaic pattern of fire severities.
- **Study**: Forest types in the study area are typical of the upper mixed-evergreen zone, trending into the white fir zone (Franklin and Dyrness, 1973), dominated by conifer species such as Douglas-fir (Pseudotsuga menziesii), sugar pine (Pinus lambertiana), and white fir (Abies concolor). Typical evergreen hardwoods include Pacific madrone (Arbutus menziesii), tanoak (Lithocarpus densiflorus), and canyon live-oak (Quercus chrysolepis) and shrubs such as manzanita (Arctostaphylos sp.) and ceanothus (Ceanothus sp.). Elevations spanned 400–1400 m on a full range of aspects, primarily on slopes >20%.
- **Study**: Avian point counts were conducted during days with no precipitation and light to no wind from mid-May to early July.
- **Study**: The results presented in this paper are from patches that experienced stand-replacement fire and postfire salvage logging 1–3 years after the initial fire event. High-severity fire in this study constituted >95% overstory mortality while postfire salvage logging represented partial removal of fire-killed trees. Salvage logging intensities were somewhat higher in the two 1987 fires than the 2002 Biscuit Fire due to changes in management practices.
    - In 1987 fires, snag retention ranged from 7 to 18 snags ha——————————————1 while Biscuit Fire snag retention levels were 3–29 large (>41 cm) snags per hectare, and variable retention of smaller (<41 cm) snags depending on merchantability (USDA, 2004, see Section 3).
- **Study**: Despite the confounding of fire and post-fire salvage in our study, we believe that the amplitude of short-term ecological change resulting from high-severity fire is much greater than that of post-fire salvage logging and that the results presented are correctly attributed to gross changes in seral stage due to fire.

Frey et al. 2016. Spatial models reveal the microclimatic buffering capacity of old-growth forests. Sci. Adv. 2016; 2:e1501392 22 April 2016.

- **Study**: Here, we examine whether the structural characteristics present in old-growth forests (for example, heterogeneous canopies, high biomass, and complex vertical structure) increase site-scale thermal buffering capacity over more structurally simple, yet mature plantation forest stands.
- **Study Site**: H J Andrews Experimental Forest, in southern Cascades east of Eugene

Grant, Evan H. Campbell and David A. W. Miller, Benedikt R. Schmidt, Michael J. Adams, Staci M. Amburgey, Thierry Chambert, Sam S. Cruickshank, Robert N. Fisher, David M. Green, Blake R. Hossack, Pieter T. J. Johnson, Maxwell B. Joseph, Tracy A. G. Rittenhouse, Maureen E. Ryan, J. Hardin Waddle, Susan C. Walls, Larissa L. Bailey, Gary M. Fellers, Thomas A. Gorman, Andrew M. Ray, David S. Pilliod, Steven J. Price, Daniel Saenz, Walt Sadinski & Erin Muths. Quantitative evidence for the effects of multiple drivers on continental-scale amphibian declines. Scientific Reports, 2016 DOI: 10.1038/srep25625

  - **Study**: "We combined nearly half a million actual observations of 84 species across 61 study areas to answer questions about the causes of wide-scale amphibian declines."

Gunderson, Lance H. 2000. Ecological resilience—in theory and application. Annual Review of Ecology and Systematics 31: 425-439.

- **Study:** This review is divided into three parts.
  - The first section reviews concepts and multiple meanings of resilience as they have appeared in the literature. That section reviews examples of modeling and field experiments that enrich our understanding of ecological change.
  - The second section includes an assessment of how resilience is related to other key ecosystem properties.
  - The review concludes with a section on how ecological resilience is key to management of complex systems of people and nature.

Halofsky et al. 2011. Mixed-severity fire regimes: lessons and hypotheses from the Klamath-Siskiyou Ecoregion. Ecosphere 2(4): 1-19.

- **Study**: Since 2002, we have engaged in studies of early ecosystem response to 15 of these fires, ranging from determinants of fire effects to responses of vegetation, wildlife, and biogeochemistry. We present here some of our important early findings regarding mixed-severity fire, thereby updating the state of the science on mixed-severity fire regimes and highlighting questions and hypotheses to be tested in future studies on mixed-severity fire regimes.
- **Study**: Since 2002, we have engaged in studies of early ecosystem response to the fires, ranging from determinants of fire effects to responses of vegetation, wildlife, and biogeochemical dynamics. Here we synthesize results of our various studies, which focus on 15 fires that have occurred over the last twenty years in the Klamath-Siskiyou region. Our purpose is to highlight some important early discoveries from a model M-S fire region, and use these findings as a platform to develop hypotheses and research directions that may be explored in other systems influenced by M-S fires.

Harrison, S., Damschen, E.I. and J.B. Grace. 2010. Ecological contingency in the effects of climate warming on forest herb communities. www.pnas.org/lookup/suppl/doi:10.1073/pnas.1006823107/-/DCSupplemental.

- **Study**: We analyzed change in understory herb communities over a 60-y period (1949/1951–2007/2009) in a complex montane landscape (the Siskiyou Mountains, Oregon) where mean temperatures have increased 2 °C since 1948.
- **Study**: Our 185 sites included primary and secondary-growth lower montane forests (500–1.200 m above sea level) and primary upper montane to subalpine forests (1,500–2,100 m above sea level).
    - Our study sites were not grazed by livestock and have not burned since Whittaker's time, and exotic species were too sparse to be detectable in our sampling. In the sites that were not clear-cut in the 1960s through the 1980s, there have been no other large-scale human disturbances.
- **Study**: Our analyses are based on the 181 herb species, all perennial, for which either we in 2007–2009 or Whittaker in 1949–1951 found >0% cover in at least one of the 185 plots. All these 181 species were native to the region, because neither we nor Whittaker found any exotic species common enough to register a cover value of >0%.

Harrison et al. 2015. Plant communities on infertile soils are less sensitive to climate change. Annals of Botany 116: 1017-1022.

- **Study**: Much evidence suggests that plant communities on infertile soils are relatively insensitive to increased water deficit caused by increasing temperature and/or decreasing precipitation. However, a multidecadal study of community change in the western USA does not support this conclusion. This paper tests explanations related to macroclimatic differences, overstorey effects on microclimate, variation in soil texture and plant functional traits.
- **Study**: A re-analysis was undertaken of the changes in the multi-decadal study, which concerned forest understorey communities on infertile (serpentine) and fertile soils in an aridifying climate (southern Oregan) from 1949–1951 to 2007–2008.
    - Macroclimatic variables, overstorey cover and soil texture were used as new covariates. As an alternative measure of climate-related change, the community mean value of specific leaf area was used, a functional trait measuring drought tolerance.
    - We investigated whether these revised analyses supported the prediction of lesser sensitivity to climate change in understorey communities on infertile serpentine soils.

Lienard, J., Harrison, J. and N. Strigul. 2016. US forest response to climate-related stress: a tolerance perspective. Global Change Biology, doi: 10.1111/gcb.13291

- **Study**: Here, we develop and apply an intermediate approach wherein we use stand-level tolerances of environmental stressors to understand forest distributions and vulnerabilities to anticipated climate change throughout the USA.
    - In contrast to other existing models, this approach can be applied at a continental scale while maintaining a direct link to ecologically relevant, climate-related stressors.
    - We first demonstrate that shade, drought, and waterlogging tolerances of forest stands are strongly correlated with climate and edaphic conditions in the conterminous United States. This discovery allows the development of a tolerance distribution model (TDM), a novel quantitative tool to assess landscape level impacts of climate change. We then focus on evaluating the implications of the drought TDM.
- **Study**: In our Tolerance Distribution Model (TDM), we determine relationships between tolerance traits and climate variables and use the resulting best model to identify regions that are vulnerable to anticipated climate change.

  - We first employ species-level rankings of shade, drought, and waterlogging tolerance developed by foresters (Niinemets & Valladares, 2006; Valladares & Niinemets, 2008; Lienard et al., 2015) to examine whether and how major climate and edaphic factors in the conterminous United States affect tree species distributions.

Morelli et al. 2016

- Study: Our goals are to: (1) build on recent literature to elaborate the value of climate change refugia as a short- to medium-term management strategy; (2) aid identification of climate change refugia by describing the processes that create them; and (3) introduce a framework for operationalizing the concept of refugia for climate adaptation.
- Study: We briefly review the theoretical framework for refugia, based in the Quaternary literature but with application to conservation (also see [7, 8, 9]).
- Study: We delineate seven steps for managing refugia (Fig 3, Table 1).
- Study: We have outlined the opportunities and challenges for effective implementation of the climate change refugia concept.

Mote et al. 2003. Preparing for climate change: the water, salmon, and forests of the Pacific Northwest. Climate Change 61: 45-88.

- Study: This paper examines the influence of past climatic variability and likely future climatic change (20-50 year time scenarios) on three key climate-sensitive resources in the Pacific Northwest (PNW), namely, water, salmon, and forests. Undergirding the work is a retrospective analysis of connections between climatic variations and each resource.

Myer, G. 2013. The Rogue Basin Action Plan for Resilient Watersheds and Forests in a Changing Climate. Thaler, T., Griffith, G., Perry, A., Crossett, T., Rasker, R. (Eds). Model Forest Policy Program in association with the Southern Oregon Forest Restoration Collaborative, the Cumberland River Compact and Headwaters Economics; Sagle, ID. December, 2013.

- Study: It is our hope that the science and recommendations put together by the Climate Action Planning team and partners will lead to an all lands approach to forest management to increase resilience to climate change in the Rogue River Basin.
- Study: This planning process included an assessment of the risks and opportunities related to the economy, forest, and water of the Rogue Basin. A variety of stakeholders and experts provided their input. After gathering data and information to assess the past, current, and projected future conditions of the Rogue Basin, a list of risks and stressors was created. From that list, relative risk values were assigned to the emergent risks (high, medium, low), as well as priority values and the capacity to respond. From that exercise, goals, objectives, and specific, on-the-ground strategies were developed. This plan calls for identifying restoration need, management that plans for projected changes in the climate, and economic opportunity. It gives equal weighting on economic, ecological and social goals for forest management consistent with the Productive Harmony Guidelines of the Southern Oregon Forest Restoration Collaborative. The plan explicitly integrates climate change projections, habitat protection, riparian and forest restoration, fire safety, ecosystem services, and economic activity.

Noss, Reed F. 2001. Beyond Kyoto: forest management in a time of rapid climate change. Conservation Biology 15(3): 578-590.

- **Study**: I review properties of forest ecosystems and management options for enhancing the resistance and resilience of forests to climate change.
- **Study**: In particular, I ask what inherent properties of forest ecosystems and what kinds of management are likely to enhance the resistance and resilience of forests.

Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T. and P.B. Moyle. 2006. Managing fire-prone forests in the western United States. Frontiers in Ecology and Environment 4(9): 481-487.

- **Study**: We review the ecological science relevant to developing and implementing fire and fuel management policies for forests before, during, and after wildfires.
- **Study**: For this paper we evaluated the scientific literature that is relevant to conservation, restoration, and management of forests in the western US (excluding Alaska). Our review addresses ecological science relevant to developing and implementing fire and fuel management policies, including activities conducted before, during, and after wildfires. Our focus is primarily on wildlands, rather than the wildland-urban interface, where ecological values may be secondary to fire-risk mitigation to protect people and homes (DellaSala et al. 2004). In wildlands especially, sustainable forest management must be based on well-grounded ecological principles.

Odion, D.C., Frost, E.J., Strittholt, J.R., Jiang, H., DellaSala, D. and M.A. Moritz. 2004. Patterns of fire severity and forest conditions in the western Klamath Mountains, California. Conservation Biology 18: 927-936.

- **Study**: We tested for modern human impacts on the fire regime by analyzing temporal patterns in fire extent and spatial patterns of fire severity in relation to vegetation structure, past fire occurrence, roads, and timber management in a 98,814-ha area burned in 1987.
- **Study**: Extensive fires burned in the Klamath-Siskiyou region in 1987, creating a landscape well suited to test the following hypotheses: (1) within the same vegetation types, fire severity is greater where previous fire has been long absent, and (2) exclusive of where plantations are, the proportion of high-severity (crown) fire is lower in previously roaded and managed portions of the burned land- scape.

Odion, D.C., Moritz, M.A. and D.A. DellaSala. 2010. Alternative community states maintained by fire in the Klamath Mountains, USA. Journal of Ecology 98: 96-105.

- **Study**: We hypothesized that alternative community states occur in a largely forested landscape in the Klamath Mountains, north-western California, USA, where shrub-dominated sclerophyllous vegetation establishes after fire that is lethal to forests. Forests redevelop if succession is not arrested by fire. Our hypothesis would require that sclerophyll and forest vegetation states each be maintained by different self-reinforcing relationships with fire.
- **Study**: In a recent study, we investigated spatial patterns of wildfire severity in relation to management in a landscape in northwestern California and hypothesized that coexisting forest and sclerophyll vegetation are naturally occurring alternative states maintained by fire (Odion et al. 2004). Our goal here is to test this hypothesis systematically taking into account spatial autocorrelation, time-since-fire (TSF) as affected by fire exclusion and the potential for vegetation to persist for multiple generations. Our hypothesis would require that co-occurring vegetation states be maintained by different, self-reinforcing relationships with fire. Therefore, sclerophyll vegetation where TSF is relatively short should be especially pyrogenic, and forests where TSF is long should be especially non-pyrogenic.

Olson et al. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou Ecoregion. Nature Areas Journal 31: 65-74.

Peterson, G., Allen, C.R. and C.S. Holling. 1998. Ecological resilience, biodiversity, and scale. Ecosystems 1: 6-18.

- Study: We describe existing models of the relationship between species diversity and ecological function
- Study: We propose a conceptual model that relates species richness, ecological resilience, and scale.
- Study: Our model expands theory relating biodiversity to ecological resilience by incorporating scale.

Sarr, D.A., Hibbs, D.E., Shatford, J.P.A. and R. Momsen. 2011. Influences of life history, environmental gradients, and disturbance on riparian tree regeneration in Western Oregon. Forest Ecology and Management 261: 1241-1253.

- Study: In two related field studies: (1) a multiscale riparian forest inventory and (2) a comparative study of natural forest gap and nongap environments, we explored regeneration patterns of native riparian trees in relation to large- and small-scale ecological drivers in four western Oregon watersheds spanning a climatic gradient from dry to wet.
- Study: In this study, we explored relationships between environmental conditions and regeneration patterns for nearly two dozen native tree species that occur in mountain riparian forests across western Oregon. Our objectives were to: (1) analyze the regeneration behavior of a broad suite of native riparian trees and (2) report how regeneration behavior of native species responds to natural variation in the regeneration environment.
- Study: It is important to acknowledge that the spatial patterns in seedling abundances we observed tell only a partial story of the forest regeneration process. A comprehensive understanding will await more long-term studies of temporal dynamics of disturbance, establishment, and forest development.

Skinner, C.N., Taylor, A.H. and J.K. Agee. 2006. Chapter 9: Klamath Mountains Bioregion; In: Fire in California's Bioregions.

Spittlehouse and Stewart. 2003.

- Study: The objective of this paper is to encourage the forestry community to evaluate the long-term impacts of climate change and determine what the community might do now and in the future to respond to this threat.
- Study: We focus here on a framework for planning adaptive actions.

Stralberg, D., Jongsomjit, D., Howell, C.A., Snyder, M.A., Alexander, J.D., Wiens, J.A. and T.L. Root. 2009. Re-shuffling of species with climate disruption: a no-analog future for California birds? PLoS ONE 4(9): e6825. doi:10.1371/journal.pone.0006825

- Study: We used a multivariate approach borrowed from paleoecology to quantify the potential change in California terrestrial breeding bird communities based on current and future species-distribution models for 60 focal species.
- Study: We used a representative subset of terrestrial breeding birds to evaluate the potential for no-analog assemblages as a result of projected climate disruption. We chose birds for this

analysis due to their high trophic position, relatively high visibility and detectability during the breeding season, and high mobility, which we assume allow them to track environmental change rapidly [25,26]. We used high-quality, breeding-season datasets from multiple sources to develop intermediate-scale (800-m pixel resolution) spatial models to predict current and future probabilities of occurrence for each of 60 focal species selected to represent avian communities of five major habitat types: oak woodland, coniferous forest, chaparral/scrub, grassland, and riparian [27].

- **Study**: Our analysis assumes that species interactions do not constrain current or future species distributions. This is one of the chief limitations of an empirical SDM approach, which necessarily models the realized, rather than fundamental niche of a species

Strittholt, J.R. and D.A. DellaSala. 2001. Importance of roadless areas in biodiversity conservation in forested ecosystems: case study of the Klamath-Siskiyou Ecoregion of the United States. Conservation Biology 15(6): 1742-1754.

- **Study**: We examined the ecological attributes of mapped roadless areas for the Klamath-Siskiyou ecoregion of northwestern California and southwestern Oregon (U.S.A.).
  - Attributes examined include
    - special elements (such as natural heritage, serpentine geology, late-seral forests, Port Orford cedar [Chamaecyparis lawsonianal),
    - key watersheds;
    - elevation and habitat representation;
    - overall landscape connectivity.
- **Study**: We compared designated wilderness to roadless areas, giving special attention to the relative importance of small roadless areas (405-2024 ha). We mapped nearly 500 roadless areas of >405 ha.
- **Study**: we sought to evaluate the ecological attributes of existing roadless areas in a forest ecoregion, the Klamath- Siskiyou. The ecological attributes we examined included five special elements of conservation concern, two representation evaluations, and regional landscape connectivity.

Strittholt, J.R., DellaSala, D.A. and H. Jiang. 2006. Status of Mature and Old-Growth Forests in the Pacific Northwest. Conservation Biology 20(2): 363-374.

- **Study**: Our objectives were to (1) determine the areal extent of old (>150 years) and mature (50–150 years) conifer forests based on 2000 Landsat 7 ETM+ imagery, (2) examine levels of protection, (3) determine the degree of additional protection afforded to old and mature conifer forests if late-successional reserves (LSRs) and inventoried roadless areas (IRAs) were fully protected, and (4) review management options to achieve greater protection of older forests.

Taylor and Skinner 2003.

- **Study**: The goal of this study is to better understand the spatial and temporal patterns of, and controls on, fire regimes and forest structure in mixed conifer forests of the Klamath Mountains.
- **Study**: Our study was conducted in a 2325-ha area of two small watersheds in the Shasta-Trinity National For- ests, 8 km west of Hayfork, California in the south- central Klamath Mountains (Fig. 1). Elevations range from 640 to 1360 m. The climate is characterized by warm, dry summers and cool, wet winters.

Welsh, Jr., H.H. and A.J. Lind. 2002. Multiscale habitat relationships of stream amphibians in the Klamath-Siskiyou Region of California and Oregon. Journal of Wildlife Management 66(3): 581-602.

- **Study**: We sampled amphibians in 39 second- and third-order streams in the conifer-hardwood forests of northwestern California and southwestern Oregon, USA (the Klamath-Siskiyou Region) during 1984 and 1985. We concurrently measured spatial, structural, compositional, and climatic attributes of the forest and stream environment-attributes representing landscape, macroenvironment, and microenvironment scales-to determine key habitat relationships.
- **Study**: forest sites were systematically selected to represent both the range of geographic variation across the mixed Douglas-fir-hardwood forests of the KS Region and the seral continuum from young to old-growth forest.

Wright, Juanita. 2016 News Release. Southwest Oregon experiencing an increase in drought-related conifer mortality. Pacific Northwest Region Rogue River-Siskiyou National Forest.

Ecological Resilience

Batabyal, Amitrajeet A. 1998. On some aspects of ecological resilience and the conservation of species. Journal of Environmental Management 52: 373-378.

- Background: The resilience of ecological functions in ecosystems is generally an increasing function of the number of substitute species that can perform those functions.

Bottom et al. 2009. Reconnecting social and ecological resilience in salmon ecosystems. Ecology and Society 14(1): 5. [online] URL: http://www.ecologyandsociety.org/vol14/iss1/art5/

- **Background**: The resilience of ecosystem services has been linked to the diversity of species within functional groups —i.e., sets of organisms that support similar ecosystem processes (Walker et al. 1999, Carpenter et al. 2006)—and to the diversity within species and populations (Luck et al. 2003).
- **Background**: We define resilience as the amount of disturbance that an ecosystem can accommodate without shifting to a different regime or stability domain as characterized by a fundamentally different structure, function, and feedback mechanisms (Walker et al. 2004).
- **Background**: Regime shifts often are attributed to human actions that have undermined ecosystem resilience (Folke et al. 2004).

Gunderson, Lance H. 2000. Ecological resilience—in theory and application. Annual Review of Ecology and Systematics 31: 425-439.

- **Background**: Ecological resilience was defined, in 1973 by C.S. Holling, as the amount of disturbance that an ecosystem could withstand without changing self-organized processes and structures (defined as alternative stable states)
- **Background**: Example of ecosystem changing from one stable state to another
    - Zimbabwe and Australia: from grassland to woody semi-arid rangeland
        - Alternative stable states are defined by dominant plant form
        - Disturbance is grazing pressure
    - From clear lake to turbid lake
        - Alternative stable states are defined by primary produces in water (micro-producers in water column versus rooted macrophytes)
        - Disturbance is amount of fertilizer in water
    - The Everglades: from sawgrass or wet prairie communities to cattail
        - Increased phosphorus concentration in the soils allow cattails to dominate
- **Background**: Walker (58) developed a driver and passengers analogy. Walker proposed that functional groups of species can be divided into 'drivers' and 'passengers.' Drivers are keystone species that control the future of an ecosystem, while the passengers live in but do not alter significantly this ecosystem. However, as conditions change, endogenously or exogenously, species shift roles. In this model, removing passengers has little effect, but removing drivers can have a large impact. Ecological resilience resides both in the diversity of the drivers, and in the number of passengers who are potential drivers.
- **Background**: Walker has more recently shown how the diversity of functional groups also maintains the resilience of ecosystem structure and function (56). Such diversity provides robustness to ecosystem functions and resilience to the system behavior. Moreover, this seems the way many biological processes are regulated-overlapping influences by multiple processes, each one of which is inefficient in its individual effect but together operating in a robust manner.

- **Background**: Species combine to form an overlapping set of reinforcing influences that help spread risks and benefits widely to retain overall consistency in performance independent of wide fluctuations in the individual species. Because of the robustness of this redundancy within functional groups, and the non-linear way behavior suddenly flips from one pattern to another and one set of controls to another, gradual loss of species involved in controlling structure initially would have little perceived effect over a wide range of loss of species. As loss of those species continued, different behavior would emerge more and more frequently in more and more places. To the observer, it would appear as if only the few remaining species were critical when in fact all add to the resilience.

Noss, Reed F. 2001. Beyond Kyoto: forest management in a time of rapid climate change. Conservation Biology 15(3): 578-590.

- **Background**: Stability has been defined in many ways, representing three general concepts: (1) the ability to maintain a relatively constant state in the face of disturbance and stress; (2) the ability to recover quickly after a disturbance; and (3) a combination of these two abilities. The first concept is often referred to as resistance. The second concept is usually referred to as resilience (Pimm 1984, 1991), although other meanings of resilience can be found in the literature (Table 1).
- **Background**: Whitford et al. (1999) found that both the resistance and resilience of vegetation to drought are reduced in intensely stressed ecosystems (in this case, desert grasslands grazed by domestic livestock) compared with lightly stressed ecosystems.
- **Background**: What properties of a forest ecosystem contribute to resistance and resilience? Some studies have demonstrated increased tolerance to environmental extremes and greater temporal stability and recovery potential as species richness increases (McNaughton 1993; Tilman & Downing 1994; Tilman 1996, 1999). The most compelling explanation for how species richness enhances stability is the redundancy provided by multispecies membership in critical functional groups (Walker 1992, 1995; Peterson et al. 1998).
- **Background**: Diversity of functional groups, in addition to diversity of species within groups, appears to encourage ecological resistance.
- **Background**: A test of the effects of functional group richness on the invasibility of grasslands showed that invasion success was negatively related to functional group richness (Symstad 2000).
    - Three lessons emerge from these findings:
    - (1) a diversity of functional groups should be maintained;
    - (2) species richness and redundancy should be maintained within functional groups;
    - (3) keystone species must be identified and kept in ecologically optimal, not just minimally viable, populations.
- **Background**: Adaptive evolution ultimately depends on adequate levels of genetic variation within and among populations, although this variation can be expected to decline in response to the directional selection imposed by changing climate.

Peterson, G., Allen, C.R. and C.S. Holling. 1998. Ecological resilience, biodiversity, and scale. Ecosystems 1: 6-18.

- **Background**: One of the central questions in ecology is how biological diversity relates to ecological function. Maintaining the ecological services that support humanity, and other life, during this period of extensive and rapid global change and ecological reorganization requires understanding how ecological interactions among species produce resilient ecosystems.

- **Background**: Species perform diverse ecological functions. A species may regulate biogeochemical cycles (Vitousek 1990; Zimov and others 1995), alter disturbance regimes (Dublin and others 1990; D’Antonio and Vitousek 1992), or modify the physical environment (Jones and others 1994; Naiman and others 1994). Other species regulate ecological processes indirectly, through trophic interactions such as predation or parasitism (Kitchell and Carpenter 1993; Prins and Van der Jeud 1993), or functional interactions such as pollination (Fleming and Sosa 1994) and seed dispersal (Brown and Heske 1990). The variety of functions that a species can perform is limited, and consequently ecologists frequently have proposed that an increase in species richness also increases functional diversity, producing an increase in ecological stability (Tilman and others 1996).
- **Background**: Many competing models attempt to describe how an increase in species richness increases stability. Following previous authors, we divide these models into four classes: ‘‘species richness–diversity’’ (MacArthur 1955), ‘‘idiosyncratic’’ (Lawton 1994), ‘‘rivet’’ (Ehrlich and Ehrlich 1981), and ‘‘drivers and passengers’’ (Walker 1992). These models all explicitly or implicitly assume that a species has ecological function, and that the function of a species can be represented as occupying an area of multidimensional ecological function space (Grinnell 1917; Hutchinson 1957; Sugihara 1980).
- **Background**: Ehrlich and Ehrlich’s (1981) rivet hypothesis, which is similar to Frost and colleagues’ (1995) model of compensating complementarity, likens the ecological function of species to the rivets that attach a wing to a plane. Several rivets can be lost before the wing falls off. This model proposes that the ecological functions of different species overlap, so that even if a species is removed, ecological function may persist because of the compensation of other species with similar functions (Figure 3). In the rivet model, an ecological function will not disappear until all the species performing that function are removed from an ecosystem. Overlap of ecological function enables an ecosystem to persist. Compensation masks ecosystem degradation, because while a degraded system may function similarly to an intact system, the loss of redundancy decreases the system’s ability to withstand disturbance or further species removal.
- **Background**: Walker’s ‘‘drivers and passengers’’ hypothesis accepts the notion of species complementarity and extends it by proposing that ecological function resides in ‘‘driver’’ species or in functional groups of such species (Walker 1992, 1995). It is similar to Holling’s (1992) ‘‘extended keystone hypothesis.’’ Walker defines a driver as a species that has a strong ecological function. Such species significantly structure the ecosystems in which they and passenger species exist. Passenger species are those that have minor ecological impact. Driver species can take many forms. They may be ‘‘ecological engineers’’ (Jones and others 1994), such as beavers (Naiman and others 1994), or gopher tortoises (Diemer 1986), which physically structure their environments. Or drivers may be ‘‘keystone species’’ (Paine 1969), such as sea otters (Estes and Duggins 1995) or asynchronously fruiting trees (Terborgh 1986), that have strong interactions with other species (Power and others 1996).Walker (1995) proposes that since most ecological function resides in the strong influence of driver species, it is their presence or absence that determines the stability of an ecosystem’s ecological function (Figure 4).
- **Background**: Tilman, for example, demonstrated that more diverse plots (4 3 4m) have greater plant cover and more efficiently utilize nitrogen (Tilman 1996). Tilman and colleagues demonstrated that ecological function was more stable in diverse communities despite, or perhaps because of, large fluctuations in populations of species (Tilman and others 1996). These results echo those of Frank and McNaughton (1991), who demonstrated that more diverse natural grass communities recovered faster than less diverse communities following drought.

- **Background**: In a series of experiments, Ewel and coworkers constructed a set of tropical ecosystems with different levels of species richness and compared their functioning to adjacent rainforest. They demonstrated that relatively few species, if drawn from different functional groups, can duplicate the ecological flows of a diverse rainforest (Ewel and others 1991). Herbivory per leaf area was lower and less variable in species-rich plots (Brown and Ewel 1987). They also demonstrated that a variety of ecosystem variables, such as soil organic matter, increase rapidly as one adds different functional types to a plot (Ewel and Bigelow 1996), and that simple agroecosystems function quite similarly to much more species-rich rainforests, at least in areas of about 1⁄3 ha (80 3 40 m) for 5 years (Ewel and others 1991).
- **Background**: Naeem and coworkers (1994) assembled replicate artificial ecosystems at a number of levels of species richness. They demonstrated that carbon dioxide consumption, vegetative cover, and productivity increased with species richness. These increases were greater between 9 and 15 species than between 15 and 31 species, providing support for the hypothesis that an increase in species richness increases ecological redundancy. Water and nutrient retention did not vary with species richness.
- **Background**: Frost and coworkers (1995) demonstrated that ecological function is preserved if population declines of zooplankton species are compensated for by population increases in other species with similar ecological functions. Their results suggest that lakes with fewer species in a functional group would exhibit decreased ability to compensate for population declines in other species.
    - Similarly, Schindler (1990) observed that the largest changes in ecological processes and food-web organization occurred when species that were the only remaining member of a functional group were eliminated.
- **Background**: When a system can reorganize (that is, shift from one stability domain to another), a more relevant measure of ecosystem dynamics is ecological resilience (Holling 1973). Ecological resilience is a measure of the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures.
- **Background**: Ecological resilience assumes that an ecosystem can exist in alternative self-organized or ‘‘stable’’ states. It measures the change required to move the ecosystem from being organized around one set of mutually reinforcing structures and processes to another.
- **Background**: Ecological and engineering resilience reflect different properties. Ecological resilience concentrates on the ability of a set of mutually reinforcing structures and processes to persist. It allows ecologists or managers to focus upon transitions between definable states, defined by sets of organizing processes and structures, and the likelihood of such occurrence. Engineering resilience, on the other hand, concentrates on conditions near a steady state where transient measurements of rate of return are made following small disturbances.
- **Background**: Ecosystems are resilient when ecological interactions reinforce one another and dampen disruptions. Such situations may arise due to compensation when a species with an ecological function similar to another species increases in abundance as the other declines (Holling 1996), or as one species reduces the impact of a disruption on other species.
- **Background**: At the largest landscape scales, climate, geomorphological, and biogeographical processes alter ecological structure and dynamics across hundreds of kilometers and over millennia (Figure 8).
- **Background**: Species can be divided into functional groups based upon their ecological roles (Clark 1954; Ko¨rner 1996). Species can be also be divided into groups based upon the specific scales that they exploit. The ecological scales at which species operate often strongly

correspond with average species body mass, making this measure a useful proxy variable for determining the scales of an animal's perception

- **Finding**: We suggest that species interact with scale-dependent sets of ecological structures and processes that determine functional opportunities. We propose that ecological resilience is generated by diverse, but overlapping, function within a scale and by apparently redundant species that operate at different scales, thereby reinforcing function across scales. The distribution of functional diversity within and across scales enables regeneration and renewal to occur following ecological disruption over a wide range of scales.
- **Finding**: These studies demonstrate that the stability of many, but not all, ecological processes increases with species richness. They also suggest that the ecological stability is generated more by a diversity of functional groups than by species richness.
- **Finding**: The model that best describes an ecosystem appears to depend upon the variety of functional roles that are occupied in that system, and the evenness of the distribution of ecological function among species. An ecosystem consisting of species that each performs different ecological functions will be less redundant than an ecosystem consisting of the same number of species that each perform a wide variety of ecological functions.
- **Finding**: The experimental results just discussed suggest ecosystems possess considerable functional redundancy. Indeed, it is difficult to envision how ecosystems without redundancy could continue to persist in the face of disturbance. We assume that since no species are identical, redundancy does not reside in groups of species, but rather it emerges from the interactions of species. Therefore, it is not possible to substitute species for one another; rather, there are many possible combinations and organizations of species that can produce similar ecological functions.
- **Finding**: We propose that the resilience of ecological processes, and therefore of the ecosystems they maintain, depends upon the distribution of functional groups within and across scales.
- **Finding**: We hypothesize that if species in a functional group operate at different scales, they provide mutual reinforcement that contributes to the resilience of a function, while at the same time minimizing competition among species within the functional group (Figure 9).
    - This cross-scale resilience complements a within-scale resilience produced by overlap of ecological function among species of different functional groups that operate at the same scales.
    - Competition among members of a multitaxa functional group may be minimized if group members that use similar resources exploit different ecological scales.
    - Ecological resilience does not derive from redundancy in the traditional engineering sense; rather, it derives from overlapping function within scales and reinforcement of function across scales.
- **Finding**: Members of functional groups maintain and therefore determine the resilience of ecosystems by spreading their influence over a range of scales. When a functional group consists of species that operate at different scales, that group provides cross-scale functional reinforcement that greatly increases the resilience of its function. This interpretation of the partitioning of ecological function suggests that what is often defined as redundancy, is not. The apparent redundancy of similar function replicated at different scales adds resilience to an ecosystem: because disturbances are limited to specific scales, functions that operate at other scales are able to persist.
- **Finding**: An indirect consequence of species loss is that it limits the potential number of ways a system can reorganize. Especially troubling is the possibility that the loss of large species, such

as moose (Pastor and others 1993) or elephants (Dublin and others 1990), that generate mesoscale ecological structure may also eliminate forms of ecological organization.

- **Finding**: We propose that ecological resilience is generated by diverse, but overlapping, function within a scale and by apparently redundant species that operate at different scales.

Connectivity

Ayram et al. 2016. Habitat connectivity in biodiversity conservation: A review of recent studies and applications. Progress in Physical Geography 40(1): 7-37.

- **Study**: This paper presents a review of the literature based on 162 publications from 2000 to 2013, in which we evaluated the current state and recent advances in the integration of landscape connectivity in the identification and planning of conservation areas.
- **Study**: The literature review and data analysis were based on a database organized into five categories: General information, study areas, research objectives, research methods in connectivity studies, and integration of connectivity with conservation.
- **Background**: The study of landscape connectivity in conservation has increased considerably since the early part of the 21st century. While the implications of landscape connectivity are self-evident for conservation, they are also important for physical geography since a proper understanding of landscape patterns and processes allows for better landscape management practices, which are at the core of geography.
- **Background**: Connectivity is a key factor in indicating the ecological effects of environmental change. For example, protected areas cannot meet their conservation goals if they do not have functional linkages between them that allow ecological processes like gene flow, migration, re-colonization of areas with threatened populations, and, most importantly, the possibility by individuals and populations to adapt to climate change (Rudnick et al., 2012).
- **Background**: The definition of landscape connectivity includes two fundamental concepts: a) structural connectivity, corresponding to spatial relationships (continuity and adjacency) between the structural elements of the landscape (e.g. Forest patches), which is independent on the ecological characteristics of the species (Taylor et al., 2006; Tischendorf and Fahrig, 2000), and b) functional connectivity, which refers to landscape features that facilitate or impede the movement of species between habitat patches (Taylor, 1993; Taylor et al., 2006).
- **Finding**: We found a substantial increase in the number of publications relating to connectivity and conservation from 2008 to 2013. Least cost analysis was the method most commonly applied.
- **Finding**: We found no implementation of landscape connectivity proposals generated by the studies (e.g. potential corridors) into real landscape elements to ensure the permanence and functionality of ecosystems.
- **Finding**: The last decade showed a notable increase in the number of publications that incorporate habitat connectivity in conservation analyses, indicating that there is an expanding research interest in this topic.
- **Finding**: Least cost analysis was the most utilized method in connectivity analyses (see Figure 7). This approach assumes that the ability of focal species to disperse results from the characteristics of the landscape matrix facilitating or impeding their mobility between patches (Adriaensen et al., 2003).

Cushman et al. 2013. Biological corridors and connectivity. Chapter 21 in "Key Topics in Conservation Biology 2." Edited by David W. Macdonald and Katherine J. Willis. John Wiley & Sons, Lmtd.

- **Study**: The goal of this chapter is to describe the state of the art in quantitative corridor and connectivity modelling. We will review several critical issues in modelling, and provide expert guidance and examples to help practitioners implement effective programmes to preserve, enhance or create connectivity among wildlife populations.

- **Background**: The ability of individual animals to move across complex landscapes is critical for maintaining regional populations in the short term (Fahrig 2003; Cushman 2006), and for species to shift their geographic range in response to climate change (Heller & Zavaleta 2009).
- **Background**: Habitat fragmentation decreases dispersal success (Gibbs 1998), increases mortality (Fahrig et al. 1995) and reduces genetic diversity (Reh & Seitz 1990; Wilson & Provan 2003). Local populations may decline if immigration is prevented (Brown & Kodric-Brown 1977; Harrison 1991) and may prevent recolonization following local extinction (Semlitsch & Bodie 1998).

Hodgson et al. 2009. Climate change, connectivity and conservation decision making: back to basics. Journal of Applied Ecology 46: 964-969.

- **Study**: In this study, we revisit the principles of spatial ecology and conservation planning. We summarize how connectivity emerges as a complicated function of habitat area, habitat quality, the spatial arrangement of habitat and species-specific dispersal. We argue that uncertainty associated with connectivity is generally higher than uncertainty about habitat area and quality, and threatening processes such habitat destruction.
- **Background**: Increasing ‘connectivity’ has emerged as the most favored option for conservation in the face of climate change.
- **Finding**: We argue that the importance of connectivity is being overemphasized: quantifying the benefits of connectivity per se is plagued with uncertainty, and connectivity can be co-incidentally improved by targeting more concrete metrics: habitat area and habitat quality.
- **Finding**: As uncertainties about connectivity tend to be high, and increases in habitat quantity and quality coincidentally improve connectivity, we conclude one should generally provide higher weight in decision-making to actions that increase area and quality. Theoretically, we know that populations will sometimes benefit more from a small, well-connected piece of habitat than a larger, more isolated one, but the relative uncertainties and the probability of worse-than-expected outcomes should also affect our decision making.
- **Finding**: renewed effort and additional funding to conserve extra land is warranted. Locations that have low human impacts should remain good for many species, even if the identities of those species change.
- **Finding**: Thirdly, the majority of small-range terrestrial species are clustered into a small percentage of the land surface (centres of endemism ⁄ areas of high irreplaceability, cf. Wilson, Carwardine & Possingham 2009), many of which are mountain ranges.Ahigh percentage of the species threatened with extinction from climate change are found in such locations: they are expected to show range retractions within the regions where they currently occur, and are unlikely to achieve long distance colonization of other parts of the world (Midgley et al. 2002; Williams, Bolitho, & Fox 2003; Thomas et al. 2004; Malcolm et al. 2006;Ohlemu¨ ller et al. 2008). So, our thirdmessage is that concentration of conservation effort in centres of endemism remains a valid strategy.
- **Finding**: Fourthly, almost all threatened species are negatively impacted by multiple factors. In some instances, mitigating known threats other than climate change may be sufficient to permit a population to persist, even if the local climate has deteriorated. When this strategy cannot ensure persistence in its own right, mitigating known threats should be regarded as an essential first step in making populations robust to climate change. We recommend dealing with known

(stoppable) threats for which there are known solutions before addressing uncertain and ⁄ or unstoppable threats with less certain or less feasible solutions (Pressey et al. 2007; Wilson et al. 2007).

- **Finding**: These four principles, increasing protected area, maintaining and in some cases increasing environmental heterogeneity, concentrating efforts in centers of endemism, and reducing other pressures are likely to be beneficial and robust, with or without climate change.
- **Finding**: Land conversion and land-use change leading to habitat loss is still the most cited threat to currently endangered species, and the most straightforward way to tackle this is to maintain and restore larger areas of natural habitat. Species will not be able to survive where they are or shift their distributions to new climatically suitable areas unless there are sufficient habitats for them, and it should be remembered that increasing habitat area is an effective way of increasing 'connectivity'.
- **Finding**: Furthermore, conserving habitats will be beneficial even if the particular species found in an area are gradually replaced by others as the climate changes. The conservation of high quality existing habitats should therefore remain the primary focus of conservation efforts to maintain biodiversity.

Honnay et al. 2002. Possible effects of habitat fragmentation and climate change on the range of forest plant species. Ecology Letters 5: 525-530.

- **Study**: We report the results of two forest plant colonization studies in two fragmented landscapes in central Belgium.
- **Background**: The associated changes in the ratio of extinctions and colonizations at the boundaries of species ranges are expected to result in northward range shifts for a lot of species. However, net species colonization at northern boundary ranges, necessary for a northward shift and for range conservation, may be hampered because of habitat fragmentation.
- **Climate Impacts**: Global circulation models predict an increase in mean annual temperature between 2.1 and 4.6 C by 2080 in the northern temperate zone.
- **Finding**: Almost all forest plant species (85%) had an extremely low success of colonizing spatially segregated new suitable forest habitats after c. 40 years. In a landscape with higher forest connectivity, colonization success was higher but still insufficient to ensure large-scale colonization. Under the hypothesis of net extinction at southern range boundaries, forest plant species dispersal limitation will prevent net colonization at northern range boundaries required for range conservation.

Klamath Siskiyou Region – General Ecological Info

Chmura et al. 2011. Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. Forest Ecology and Management 261: 1121-1142.

- **Background**: Forests in the northwestern U.S. (NW) are distinct among the Northern Hemisphere temperate forests in their species composition and high productivity (Waring and Franklin, 1979). Composed mostly of conifers, these forests are adapted to the wet/mild winters and warm-dry summers typical of the region (Franklin and Halpern, 2000). There are steep climatic gradients associated with elevation, latitude, distance from the ocean, and proximity to the mostly north–south mountain ranges. Complex topography contributes to substantial climatic variability at a fine scale, often resulting in mosaics of vegetation types within small geographic areas.

Climate Leadership Initiative, National Center for Conservation Science and Policy, Pacific Northwest Research Station. 2008. Preparing for Climate Change in the Rogue River Basin of Southwest Oregon.

- Ecological Considerations: valuable species at risk to fire: Port Orford Cedar, Brewer's Oak, Marbled Murrelet, northern spotted owl, fisher.
- Ecological Considerations for aquatic and terrestrial species in Rogue Basin:
  - Threats to terrestrial vegetation
    - Drought-stressed vegetation could be more susceptible to insect outbreaks and disease
    - Stressed and dying vegetation will allow larger and more frequent fires
    - Rapid climate shifts in concert with existing habitat fragmentation will make it difficult for some native vegetation to adjust and disperse
  - Threats to terrestrial animals
    - Rapid climate shifts in concert with existing habitat fragmentation will make it difficult for some native animals to adjust and disperse
  - Threats to long-distance avian migrants
    - Changes to timing of flowering and insect emergences could result in lowered access to primary foods
  - Threats to amphibians
    - Increased drying of the environment combined with low mobility of many amphibians could cause amphibian populations to decrease
  - Threats to high elevation wildlife and plants
    - Available habitat may become reduced leading to population reductions
  - Threats to all wildlife
    - Diseases and disease vectors are expected to increase with warmer temperatures
    - Wildlife under stress from climate change and/or other stressors will be more susceptible to disease
    - Conditions may become more favorable for some exotic, invasive species

DellaSala et al. 1999.

- **Study**: We reviewed the conservation importance and status of the Klamath-Siskiyou Ecoregion relative to that of 30 temperate coniferous forest ecoregions in the United States and Canada and also compared the results to a related global comparison of diverse forest ecoregions.
- **Finding**: Based on comparisons of species richness, endemism, unique evolutionary and ecological phenomenona (e.g., species migrations, adaptive radiations), and global rarity of habitat types, we ranked the biodiversity of the Klamath-Siskiyou Ecoregion among the world's most outstanding temperate coniferous forests.
- **Finding**: We identified a total of 2,377 species for six terrestrial taxa that we analyzed: native plants (78%, n=1,859), birds (9%, n=222), butterflies (6%, n=141), mammals (3%, n=69), land snails (2%, n=54), and reptiles and amphibians (1%, n=32). Of this total, 168 species (7%) occur nowhere else in the world.
- **Finding**: The ecoregion supports a continental maximum of conifers (30 species); up to 17 species have been recorded in an area of 2.6 km(2). The combined freshwater habitats of the region support exceptionally high levels of endemism: 14 of 33 (42%) fish and 142 of 235 (60%) mollusk taxa are endemic to the region.
- **Finding**: We ranked the status of the region's terrestrial biodiversity as endangered. Approximately 25% of forests are intact and 10.5% are legally protected (e.g., as congressionally designated wilderness) from logging.
- **Finding**: We identified 24 stand types and plant series considered distinctive by the California Native Plant Society, 2 forest ecosystem types told-growth and mature, riparian forest) considered threatened or endangered by the National Biological Survey, and 10 plant communities listed as critically globally imperiled (G1) or globally imperiled (G2) by The Nature Conservancy.
- **Finding**: We documented 138 terrestrial and 16 freshwater taxa with state or federal listing status, 5 terrestrial species extirpated from the region.
- **Finding**: More than half of the listed terrestrial taxa were restricted geographically to the region (i.e., endemics) or were limited to elevations less than or equal to 1,524 m where few protected areas occurred.
- **Finding**: Most mollusk populations have declined dramatically (>90% historic range contractions) throughout the region, and 11 fish taxa (especially anadromous salmonids) have a special status designation due to extensive habitat degradation and changes in hydrology and water quality.

DellaSala et al. 2010. Climate-adapted conservation planning. Powerpoint presentation.

- Ecological Considerations
  - Greater than 10% of all mesic species (lichens, bryophytes, salamanders, mollusks, insects) may disappear from region
  - Hundreds to thousands of species at risk
  - Coastal areas at highest risk
  - Bird communities may shift with conditions
    - More grassland species
    - Fewer shrub species
    - Fewer forest species

DellaSala, D.A., Baker, R., Heiken, D., Frissell, C.A., Karr, J.R., Nelson, S.K., Noon, B.R., Olson, D. and Strittholt, J., 2015. Building on Two Decades of Ecosystem Management and Biodiversity Conservation under the Northwest Forest Plan, USA. Forests, 6(9), pp.3326-3352.

- **Background**: The 1994 Northwest Forest Plan (NWFP) shifted federal lands management from a focus on timber production to ecosystem management and biodiversity conservation. The plan established a network of conservation reserves and an ecosystem management strategy on ~10 million hectares from northern California to Washington State, USA, within the range of the federally threatened northern spotted owl (Strix occidentalis caurina).
  - Twenty years into plan implementation, however, the U.S. Forest Service and Bureau of Land Management, under pressure for increased timber harvest, are retreating from conservation measures. We believe that federal agencies should instead build on the NWFP to ensure continuing success in the Pacific Northwest.
- **Background**: The NWFP amended resource management plans for 19 national forests and seven BLM planning districts with 80% of those lands dedicated to some form of conservation (Figure 1). This increased level of protection and improved management standards were necessary because for many decades federal lands were managed without proper regard for water quality, fish and wildlife viability, and ecosystem integrity. Overcutting of older forests and rapid road expansion were the main factors responsible for the 1990 threatened species listing of the northern spotted owl, 1992 threatened listing of the marbled murrelet (Brachyramphus marmoratus), multiple listings of Evolutionary Significant Units (ESUs) of salmonids (Oncorhynchus spp.), and pervasive and mounting water quality problems.
- **Background**: Older forests in the Pacific Northwest are a conservation priority because they harbor exceptional levels of forest biodiversity (e.g., >1000 species have been recognized) and numerous at-risk species [2]. Historically, such forests widely dominated much of the Pacific Northwest landscape, especially in wet areas (coastal) where the intervals between successive fires were centuries long [5].
- **Background**: Most forest types in this region generally begin acquiring older forest characteristics at 80 years, depending on site productivity and disturbance history, with full expression of structural diversity at 400+ years [7]. Upper elevation subalpine fir (Abies lasiocarpa) and Pacific silver fir are not considered old growth until they are 260–360 years old [8]. Notably, researchers have recently developed an old-growth structure index (OGSI) to represent a successional continuum from young to older forests. The OGSI is a continuous value of 0–100 used to delineate older forests based on four features: (1) large live tree density; (2) large snag density; (3) down wood cover; and (4) tree size diversity at the stand level [9].
- **Background**: Young forests <80 years old that originate from natural disturbance in older forests, known as complex early seral forest, also have high levels of structural complexity (e.g., snags and downed logs) and species richness (especially forbs, shrubs; [10,11]). These younger forests have only recently been recognized as a conservation priority and like old growth have been replaced by structurally simplistic tree plantations [10].
- **Background**: The Marbled Murrelet nests in older-aged forests usually within 80-km of the coast from northern California to Alaska. The murrelet was listed as threatened in the Pacific Northwest due to habitat fragmentation from roads and clearcuts that expose murrelets to increased levels of nest predation [57–59]. Murrelet distribution and population trends are determined by the amount of suitable nesting habitat within five coastal “conservation zones” from Washington to California [60]. In general, as nesting habitat decreases murrelet abundance goes down, although abundance is also related to near-shore marine conditions (e.g., fish-prey abundance). Over the NWFP area, the trend estimate for the 2001–2013 period was slightly negative (~1.2%) (confidence intervals overlapped with zero [60]).
- **Background**: About 1 million ha of potential suitable nesting habitat for murrelets remained on all lands within the range of the murrelet at the start of the NWFP (estimate based on satellite

imagery [60]). Of this, only ~186,000 ha was estimated as high quality nesting habitat based on murrelet nest site locations. Over the NWFP baseline (1993–2012), net loss of potential nesting habitat was 2% and 27% on federal and nonfederal lands, respectively [60]. Losses on federal lands were mostly due to fire (66%) and logging (16%); on nonfederal lands logging (98%) was the primary cause of habitat loss [60].

- **Background**: Unfortunately, attempts to revise the Northwest Forest Plan have been bogged down by ongoing controversy over timber vs. biodiversity values that has led to a perpetual tug-of-war between decision makers that either support or seek to dismantle the NWFP. If this trend continues, federal land management may regress and recreate many of the problems the NWFP was implemented to correct, including re-inflamed social conflict, a cascade of endangered species listings, permanently increased conservation burdens on private landowners due to additional endangered species listings, and loss of ecological integrity that underpins the region's ecosystem services and their adaptive capacity to climate change.

DellaSala, Dominick A. 2016 White Paper. Do mountain pine beetle outbreaks increase the risk of high-severity fires in Western forests: a summary of recent field studies. Geos Institute.

- **Background**: Mountain pine beetle outbreaks are primarily the result of a warming climate that has allowed more beetles to survive and to have multiple broods within a breeding season.
- **Background**: Since the mid 1990s, mountain pine beetles have killed pine trees across some 27,413 square miles1, an area larger than the state of West Virginia. Such outbreaks have led to widespread concerns that the dead trees left behind by these outbreaks increase the risk of high-severity fire. Recent field studies in western forests have consistently shown that outbreaks actually do little to increase fire severity[2,3].
- **Background**: Bark beetle outbreaks do not destroy the forest as forests are quite resilient to them, rebounding soon after the outbreak with vigorous plant growth. Bark beetle-caused tree mortality also increases the diversity of plant species by creating gaps in the forest canopy that provide increased sunlight and nutrients for plant growth. Dead trees (snags) caused by outbreaks are the most ecologically valuable structures of a forest, used by numerous woodpeckers, owls, hawks, songbirds, bats, squirrels, and martens. The ensuing "complex early seral forest" (snag forest) is one of the most biologically diverse and rarest forest types in western North America because salvage logging nearly always destroys these forests8,9.
- **Background**: Beetle-killed trees also contribute to recruitment of large coarse woody debris into riparian areas and streams, which exerts important beneficial influences on storage of sediment and organic matter and river and floodplain habitat for wildlife, including trout. In comparison to logging that can remove all riparian wood and severely deplete instream wood recruitment, beetle outbreaks provide a source of instream wood for decades.

Dugger et al. 2016. The effects of habitat, climate, and Barred Owls on long-term demography of Northern Spotted Owls. The Condor 118: 57-116.

- **Background**: The harvesting of old-growth forest habitat suitable for Spotted Owls and other dependent species (e.g., Marbled Murrelet [Brachyramphus marmoratus], red tree vole [Arborimus longicaudus]) on federal lands has declined since the adoption of the NWFP. However, low rates of loss continue on all lands within the NWFP area (~3% since 1993), although on federal lands this loss has been primarily attributed to large wildfires (Davis et al. 2011, 2015).
- **Ecological Consideration**: The Barred Owl is a medium-sized, congeneric owl species that was historically restricted to the forests of eastern North America, but has now invaded the entire

range of the Northern Spotted Owl (Bent 1938, Livezy 2009). The cause of this range expansion is unclear, but there is mounting evidence that the species is having a negative effect on the Spotted Owl (e.g., Dugger et al. 2011, Forsman et al. 2011, Yackulic et al. 2014), most likely through competition for resources. Recent studies have confirmed high overlap in resource use between the 2 species (Hamer et al. 2001, 2007, Livezy 2007, Singleton et al. 2010,Wiens et al. 2014)

Dunk, J.R., Zielinski, W.J. and H.H. Welsh, Jr. 2006. Evaluating reserves for species richness and representation in northern California. Diversity and Distributions 12: 434-442.

- **Background**: No existing reserves in the KS region were created specifically for molluscs and salamanders, yet it was assumed that reserves established largely around considerations for the northern spotted owl (Strix occidentalis caurina) would afford adequate protection for many lesser-known species.
- **Background**: Species of terrestrial molluscs and salamanders share two general features: (1) they have extremely low vagility, and (2) they are often associated with moist, cool microclimates.
- **Background**: In the Pacific Northwest of the USA, the Northwest Forest Plan (hereafter NFP; USDA/USDI, 1994) was developed as a large-scale (c . 10 million ha) ecosystem management plan; striving to provide a predictable and sustainable timber supply and to adequately protect species.
- **Background**: More recently, through the Northwest Forest Plan, the US government created a network of ‘late successional reserves’ and ‘riparian reserves’ (USDA/USDI, 1994). The late successional reserve network was designed, largely, based on quantitative information and conservation considerations of the northern spotted owl as well as, generally, qualitative, expert-based considerations of > 1000 other species; including some terrestrial molluscs and salamanders.
- **Background**: Land management activities within NFP reserves must generally be consistent with the goal of facilitating late-successional forest conditions more rapidly than would otherwise occur.
- **Background**: The Klamath-Siskiyou region is considered extremely ecologically diverse (DellaSala et al., 1999; Ricketts et al., 1999), primarily because of its geological and climatic history. For example, regarding the Klamath-Siskiyou region’s flora, Coleman & Kruckeberg (1999) stated ‘following the increased aridity of the Miocene, the KS [Klamath-Siskiyou] region, with its benign climate, became the refuge for elements of a shrinking warmtemperate flora in the Far West. Second, the spatial isolation, coupled with a long-persisting high level of habitat diversity, created a multiplicity of settings for both the genesis of new species and the persistence of relictual species.’
- **Ecological Considerations**: Due to the limited dispersal ability of land molluscs and salamanders, areas containing the highest local species richness are of conservation importance.
- **Finding**: Existing reserves disproportionately included areas of hotspots of species richness for both taxa, when hotspots included the richest c . 25% of the area, whereas non-reserved lands contained greater than expected areas with lower species richness.
    - However, when a more strict definition of hotspot was used (i.e. the richest c .10% of areas), local hotspots for both taxa were not disproportionately found in reserves.
- **Finding**: Reserves set aside largely for human aesthetics and recreation and those set aside for biodiversity both contributed to the protection of areas with high (greatest 25%) species richness.

- **Finding**: Existing biodiversity reserves represented 68% of mollusc species and 73% of salamander species, corresponding to the 99th and 93rd percentiles, respectively, of species representation achieved by simulating a random distribution of the same total area of reservation.
    - Cumulatively, however, reserves set aside for inspiration and biodiversity represented 83% of mollusc species and 91% of salamander species.
    - The existing reserves provide conservation value for terrestrial molluscs and salamanders.
    - This reserve network, however, should not be considered optimal for either taxa.
- **Finding**: A total of 47 mollusc species and 11 salamander species were detected. Mean local richness for molluscs per survey plot was 1.15 (SD = 1.19) and ranged from 0 to 6 (Fig. 1). Mean local richness for salamanders was 0.48 (SD = 0.74) and ranged from 0 to 3 species (Fig. 1).
- **Finding**: The local richness hotspots 90 and hotspots 75 for molluscs were those 14 plots (4.5% of all plots), where ≥ 4 species were detected, and 103 plots (33.6% of all plots), where ≥ 2 species were detected, respectively (Fig. 2a).
- **Finding**: The local richness hotspots 90 and hotspots 75 for salamanders were those 22 plots (9.4% of all plots) where ≥ 2 species were detected and those 85 plots (36.3% of all plots) where ≥ 1 species was detected, respectively (Fig. 2b).
- **Finding**: Mollusc hotspots had more reserved land than expected and less non-reserved land. Salamander hotspots had much more reserved land than expected and much less non-reserved.
- **Finding**: Local richness of salamanders and molluscs was significantly, though extremely weakly, correlated (F = 7.135, P = 0.008, r 2 = 0.029).
- **Finding**: The 100 simulations of reserve locations resulted in 17–35 mollusc species and two to nine salamander species being represented within the reserves. The actual NFP reserves contained 32 mollusc species and eight salamander species; with only one and seven simulated reserves ranking higher than the actual reserve system's representation of mollusc species and salamander species, respectively.
    - Although both taxa had species represented much greater than would be expected by chance, only 68% and 73% of all mollusc and salamander species were detected in reserves, respectively. However, when including pre-NFP reserves, reserved lands contained 39 mollusc species (83% of all mollusc species) and 10 salamander species (91% of all salamander species).
- **Finding**: For terrestrial molluscs and salamanders, the most species-rich areas were discovered in the western/northwestern portion of our study area (Figs 2 and 3), an area that overlaps the area Stebbins & Major (1965; see their Fig. 2) identified as having a high frequency of relictual plant species.
- **Finding**: Our finding that the regional mollusc hotspots75 encompassed 61% of the regional salamander hotspots75, but only 45% overlap vice versa provides equivocal support to our contention that both taxa may have responded similarly to historical, and perhaps contemporary, factors.
- **Finding**: Our analyses, however, showed that the reserves they delineated, together with pre-existing reserves, disproportionately protected hotspots of local and regional richness for both taxa. Hotspots of both taxa at the local and regional scale, and hotspots of both taxa at the regional scale were represented by reserves more than non-reserved lands. Although regional richness hotspots of both taxa were disproportionately associated with reserved lands, those locations where local richness was greatest (local hotspots) were not disproportionately associated with reserved lands.

    - Therefore, our sample suggests that the current reserve network does not provide disproportionate protection to those local areas richest in species of terrestrial molluscs and salamanders
- **Finding**: Both mollusc and salamander species representation was much greater in Northwest Forest Plan reserves than would be expected by chance.
- **Finding**: Rare molluscs were disproportionately (nearly twice the number expected) found in regional hotspots and local hotspots. Even so, 12 of the 26 rare mollusc species were not found within the mollusc regional hotspots. Similarly, only two of the four rare salamanders were found in regional salamander hotspots75, and none in the regional salamander hotspots90.
    - Thus, a large proportion of the rare species within each taxon would go unprotected with conservation plans developed only around such hotspots (see Lennon et al., 2004).
- **Finding**: If the Northwest Forest Plan reserves represent a large-scale plan largely for the northern spotted owl, as well as other organisms having smaller spatial requirements than the owl, our findings suggest that owl conservation provides some umbrella protection for areas with high species richness of Richness, representation, and reserves terrestrial molluscs and salamanders in national forests in northern California. In terms of species representation, NFP reserves (and thus the northern spotted owl as a focal species for conservation) do fairly well; but taken together with pre-NFP reserves represent a large percentage (> 80%) of terrestrial mollusc and salamander species.

Frey et al. 2016. Spatial models reveal the microclimatic buffering capacity of old-growth forests. Sci. Adv. 2016; 2:e1501392 22 April 2016.

- **Background**: In forested montane regions, microclimate is thought to be influenced by elevation, microtopography, and vegetation.
- **Background**: the impacts of climate change on biodiversity are expected to be particularly substantial in mountainous regions
    - **Source**: Mountain Research Initiative EDW Working Group, Elevation-dependent warming in mountain regions of the world. Nat. Clim. Change 5, 424–430 (2015).

Grant, Evan H. Campbell and David A. W. Miller, Benedikt R. Schmidt, Michael J. Adams, Staci M. Amburgey, Thierry Chambert, Sam S. Cruickshank, Robert N. Fisher, David M. Green, Blake R. Hossack, Pieter T. J. Johnson, Maxwell B. Joseph, Tracy A. G. Rittenhouse, Maureen E. Ryan, J. Hardin Waddle, Susan C. Walls, Larissa L. Bailey, Gary M. Fellers, Thomas A. Gorman, Andrew M. Ray, David S. Pilliod, Steven J. Price, Daniel Saenz, Walt Sadinski & Erin Muths. Quantitative evidence for the effects of multiple drivers on continental-scale amphibian declines. Scientific Reports, 2016 DOI: 10.1038/srep25625

- **Background**: Amphibian declines are a global phenomenon and declines in the USA have continued unabated since at least the late 1960s, occurring even in protected areas and national parks.
- **Finding**: the average decline in overall amphibian populations is 3.79% per year, although the rate of decline is more severe in some regions, such as West Coast and Rocky Mountains.
    - If this rate remains unchanged, these species would disappear from half of the habitats they occupy in about 20 years.

Harrison, S., Damschen, E.I. and J.B. Grace. 2010. Ecological contingency in the effects of climate warming on forest herb communities. www.pnas.org/lookup/suppl/doi:10.1073/pnas.1006823107/-/DCSupplemental.

- **Background**: Clear-cut logging was widespread [in the Klamath-Siskiyou] in the 1960s through the 1980s at low to moderate elevations, leaving a mosaic of secondary forests composed largely of the same species but in altered relative abundances and age classes (31).

Myer, G. 2013. The Rogue Basin Action Plan for Resilient Watersheds and Forests in a Changing Climate. Thaler, T., Griffith, G., Perry, A., Crossett, T., Rasker, R. (Eds). Model Forest Policy Program in association with the Southern Oregon Forest Restoration Collaborative, the Cumberland River Compact and Headwaters Economics; Sagle, ID. December, 2013.

- **Background**: The Rogue Basin of southwestern Oregon occupies part of the Klamath Province identified in the Northwest Forest Plan. The basin drains water from both the Klamath Mountains (Siskiyous) and the Cascade Mountains and forms a regional confluence of Western US floristic provinces as well. The variety of inland forests here follow complex environmental gradients reflecting hot dry summers and cool moist winters contributing to historically very frequent fire and fire-adapted vegetation.
- **Background**: Nearly 300,000 people live in the Rogue Basin. The area is highly valued for its scenic attractions and cultural significance. Many enjoy recreational uses, such as fishing, rafting, hiking, Off Highway Vehicle trails, wine tasting, hunting, camping, parks, scenic byways, horseback riding, boating, and nature viewing. The Rogue Basin provides clean drinking water, critical wildlife habitat, wood products, and non-timber forest products; it's also a large pear exporter, and is one of the most biologically diverse regions in North America. The Rogue River was named one of the original eight rivers in the Wild and Scenic Rivers Act of 1968 (National Wild and Scenic Rivers System). There are more than 4,000 miles of fish-bearing tributary streams found throughout the Rogue Basin. The Klamath-Siskiyou temperate coniferous forests are among the four most diverse of its kind in the world (World Wildlife Fund, 2008). The ecosystem services provided by the Rogue Basin are integral to the survival of the local culture and economy.
- **Background**: The Rogue Basin is comprised of 5 sub basins that drain to the Pacific Ocean (Figure 3): the Lower Rogue River, Middle Rogue River, Upper Rogue River, Illinois, and Applegate.
- **Background**: This report has a good overview of the physics of climate change. See report for details, page 9.
- **Background**: the city of Medford undertook a cost-benefit analysis on different methods to cooling the Rogue River due to their non-compliance of effluent water temperatures. They discovered that restoring riparian areas along the Rogue Basin would cost nearly half the amount of other methods of cooling water temperatures, and would have the highest benefits. They are using a water quality trading program with The Freshwater Trust (and ODEQ's approval) to conduct restoration work and mitigate the temperature impacts. The goal of the trading program is to plant almost 30 miles of riparian shade in the Rogue Basin over the next 20 years to obtain 400 million kilocalories of thermal credit in late fall (DEQ Approves Medford's Thermal Trading Program, 2011).
- **Ecological Considerations**: The American Pika lives in the Western U.S., including Oregon, in cold areas near mountain tops. Due to the warming temperatures snowfall is declining in higher elevations, causing the Pika to die off below elevations of 7,000 ft. (Figure 24). More than one third of their population has already disappeared.

- **Ecological Considerations**: Projections show significant declines in conditions for maritime evergreens, and two models show an increase in conditions for maritime needleleaf and temperate deciduous broadleafs (Figure 25). The dimensions of the changes that projections suggest might occur have the potential of devastating effects on many terrestrial communities.
    - In particular by late century, it is possible that: high elevation spruce/fir/hemlock associations will be eliminated, Douglas-fir associations will be reduced, ponderosa pine associations will expand, Oak-chapparral association will expand, and shrubland/grassland will expand. As species shift, the structure and function of the ecosystems in the Rogue Basin will be impacted.

Noss, Reed F. 2001. Beyond Kyoto: forest management in a time of rapid climate change. Conservation Biology 15(3): 578-590.

- **Background**: Although forests, as a class, have proved resilient to past changes in climate, today's fragmented and degraded forests are more vulnerable.
- **Background**: Climate change is a major threat to biodiversity over the coming century (Peters & Lovejoy 1992). Therefore, efforts to lessen global warming by reducing emissions of CO2 and other greenhouse gases or by increasing uptake of carbon by vegetation are of great interest to conservationists.
- **Background**: Although the present rate of warming is higher than previous rates over the last 10,000 years, forests apparently have weathered even faster changes in the past, albeit the most rapid changes were associated with mass extinctions (Graham 1999).
- **Background**: If climate change were the only factor menacing forests today, and if the landscape were still pristine, there arguably would be little cause for worry. The fossil record shows numerous examples of species migrating and persisting through past changes. By and large, climatic change may have been as great a force for speciation as for extinction (Sepkoski 1998; Hewitt 2000). Even with the rapidity of change predicted for the next few decades, in the absence of other threats most species could be expected to adjust to these changes as they have in the past.
- **Background**: Today, however, climate change is being played out on a very different court—one in which direct destruction, fragmentation, and degradation of ecosystems by humans, accompanied by vast invasions of alien species, are proceeding at a breakneck pace worldwide. It is in combination with these threats that global warming becomes so insidious (Peters & Darling 1985; Dudley 1998; Sala et al. 2000).
- **Background**: The Intergovernmental Panel on Climate Change (IPCC 1996) concluded that forests are highly sensitive to modern climate change. Although the details of expected change in forests on a regional scale are unclear, the scenarios of general circulation models (GCMs) predict major shifts in the area occupied by forest biomes (Neilson et al. 1994; Hadley Center for Climate Prediction and Research 1998). For example, globally, the area occupied by tropical and temperate forests is projected o expand by up to 20%, whereas boreal forests may decline by 50% (Krankina & Dixon 1993), if other causes of change are ignored.
- **Background**: Over an intermediate length of time, say thousands of years, the species in a given forest represent those that have evolved under a definable range of conditions, often called a "natural" or "historic" range of variability (Landres et al. 1999; Swetnam et al. 1999). Many ecologists consider this range the appropriate set of "reference conditions" for comparison with human-altered conditions and as a guide to management (Stephenson 1999).
- **Background**: Changes that occur at a faster rate, greater intensity, different pattern, or broader spatial scale than historically are likely to fall outside the limits of adaptability for some species.

- **Background**: Minimizing extinction during climate change requires that species be given opportunities to adapt. Adaptation of species to climate change can take place through phenotypic plasticity (acclimatization), adaptive evolution, or migration to suitable sites (Markham 1996; Bawa & Dayanandan 1998).
- **Background**: Migration appears to have been the primary way species responded to past climate changes. Few beetles, for example, showed morphological change over the Quaternary (Pleistocene and Holocene), whereas species shifted markedly in distribution over this period (Coope 1979).
- **Background**: Migration rates of trees recolonizing regions after glaciation have been estimated from paleoecological data as ranging from 50 m/year for American beech (Fagus grandifolia) (Davis 1983) to 2000 m/year for spruce (Picea sp.) (Dennis 1993). The slower rates are thought insufficient for response to the current pace of climate change, especially given dispersal barriers such as intensive agriculture and cities (Peters & Darling 1985).
    - Recently, however, paleontological evidence of rapid, long-distance migration of many tree species has arisen (Clark 1998; Clark et al. 1998), providing hope that at least some trees may be able to track a rapidly changing climate.
    - Haphazard, long-distance establishment events may explain the evidence of rapid migration (Clark et al. 1998). Incorporating such rare dispersal events into models is difficult, which is why empirical rates of plant migration are often substantially higher than modeled rates (Higgins & Richardson 1999).

Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T. and P.B. Moyle. 2006. Managing fire-prone forests in the western United States. Frontiers in Ecology and Environment 4(9): 481-487.

- **Background**: Key structural elements of western forests (eg old "veteran" trees), terrestrial and aquatic biodiversity, and habitats of many threatened and endangered species are already greatly diminished and at continuing risk of loss.
- **Background**: Currently, early-successional forests (naturally disturbed areas with a full array of legacies, ie not subject to post-fire logging) and forests experiencing natural regeneration (ie not seeded or planted), are among the most scarce habitat conditions in many regions.

Olson et al. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou Ecoregion. Nature Areas Journal 31: 65-74.

- **Ecological Considerations**: the vast majority of distinctive biodiversity for the ecoregion (all taxa being considered) occur within the coastal fog and transition zones (Figure 1; Sawyer 2007). The latter zone includes more mesic forests along the Siskiyou Crest (Oregon/California), Eddy Mountains (northwest California), Scott Mountains (northwest California), and Yolla Bolly's (southern limits of the ecoregion) that are relatively far from the coast.
- **Ecological Considerations**: Restricted-range (i.e., local endemic) species or relict taxa dependent on cool and moist habitats:
    - Brewer spruce (Picea breweriana)
    - Engelmann spruce (Picea engelmanni)
    - Foxtail pine (Pinus balfouriana) (Sawyer 2007)
    - Plethodon and Dicamptodon salamander species and subgoups (Bury 1973; Meadet al. 2005; Steele and Storfer 2006)
    - other plants (Sawyer 2007)
    - harvestman (Briggs 1969, 1971ab)
    - millipedes (Gardner and Shelley 1989; Olson 1992)

  - trapdoor spiders (Cokendolopher et al. 2005)
  - land snails (Frest and Johannes 1993)

Skinner, C.N., Taylor, A.H. and J.K. Agee. 2006. Chapter 9: Klamath Mountains Bioregion; In: Fire in California's Bioregions.

- **Background**: The very steep and complex terrain of the Klamath Mountains covers approximately 22,500 km2 (8,690 mi2), or 6% of California. The bioregion includes the Klamath and Trinity River systems, the headwaters of the Sacramento River, the most extensive exposure of ultramafic rocks in North America (Kruckeberg 1984), and the most diverse conifer forests in North America (Cheng 2004) (Map 9.1).
- **Background**: The Klamath Mountains have been deeply dissected by the Klamath, McCloud, Sacramento, and Trinity Rivers with no consistent directional trends. Only two sizable alluvial valleys, Scott Valley and Hayfork Valley, occur here (Oakeshott 1971, McKee 1972). Elevations in the Klamath Mountains range from 30 m (100 ft) to 2,755 m (9,038 ft). From north to south, several prominent ranges or ridge systems comprise the Klamath Mountains with Mt. Eddy being the highest peak (Oakeshott 1971, McKee 1972). The crests of these ridge systems are usually between 1,500 m (4,900 ft) and 2,200 m (7,200 ft) (Irwin 1966).
- **Background**: The complexity of the geology and terrain has a strong influence on the structure, composition, and productivity of vegetation in the Klamath Mountains (Whittaker 1960). The topography and vegetation influence fire regimes. Spatial variation in soil productivity combined with steep gradients of elevation and changes in slope aspect across landscapes control the connectivity, structure, and rates of fuel accumulation.
- **Background**: The climate of the Klamath Mountains is mediterranean, characterized by wet, cool winters and dry, warm summers. However, the local expression of this climate regime is remarkably variable due to a strong west to east moisture and temperature gradient caused by proximity to the Pacific Ocean and steep elevation gradients that influence temperature and the spatial pattern of precipitation via orographic effects. The contemporary climatic phase appears to have become established about 3,500–4,000 years ago (West 1985, 1988, 1989, 1990; Mohr et al. 2000).
- **Background**: Although most precipitation falls between October and April, there is considerable local and regional geographic variation in the amount of annual precipitation. Generally, less precipitation falls in valleys and canyons than in the surrounding uplands with strong gradients over short horizontal distances. Precipitation declines with distance from the coast in both the northern and southern Klamaths.
- **Background**: The Klamath Mountains are thought to be of central importance in the long-term evolution and development of western forest vegetation because of this diversity and the mixing of floras from the Cascade/Sierra Nevada axis and the Oregon/California coastal mountains that intersect in the Klamath Mountains (Whittaker 1961, Smith and Sawyer 1988). Vegetation and species diversity generally increases with distance from the coast and species diversity is highest in woodlands with a highly developed herb strata (Whittaker 1960).
- **Background**: The rugged, complex topography and resulting intermixing of vegetation in the Klamath Mountains defies a simple classification of ecological zones by elevation. Nevertheless, this chapter discusses three general zones:
  - (1) a diverse lower montane zone of mixed conifer and hardwood forests, woodlands, and shrublands;
  - (2) a mid-upper montane zone where white fir (Abies concolor) is abundant and hardwoods are less important;

  - (3) a subalpine zone where white fir, Douglas-fir (Pseudotsuga menziesii var. menziesii), sugar pine (Pinus lambertiana), and ponderosa pine (Pinus ponderosa) drop out and are replaced by upper montane and subalpine species such as Shasta red fir (Abies magnifica var. shastensis), mountain hemlock (Tsuga mertensiana), western white pine (Pinus monticola), Jeffrey pine (Pinus jeffreyi), whitebark pine (Pinus albicaulis), lodgepole pine (Pinus contorta spp. murrayana), foxtail pine (Pinus balfouriana), and curl-leaf mountain-mahogany (Cercocarpus ledifolius).
- **Background**: Contemporary vegetation assemblages coalesced approximately 3,000 to 4,000 years ago when the climate cooled and became moister compared to the previous several millennia (West 1985, 1988, 1989, 1990; Mohr et al. 2000). Because the dominant tree species have potential life spans of 500 to 1,000+ years (Brown 1996, 2002), the current forest assemblages have existed for only a few life spans of the dominant tree species.

Staus et al. 2002. Rate and pattern of forest disturbance in the Klamath-Siskiyou ecoregion, USA between 1972 and 1992. Landscape Ecology 17: 455-470.

- **Study**: We classified NALC (North American Landscape Characterization) imagery to forest-nonforest and examined forest change between 1972 and 1992 in the Klamath-Siskiyou ecoregion (USA) in relation to land ownership and fifth level watersheds.
- **Study**: We also analyzed changes in forest patterns by land ownership for three major river basins within the ecoregion (Eel, Klamath, and Rogue) using FRAGSTATS.
- **Study**: Therefore, we used satellite remote sensing data to examine the rates and patterns of coniferous forest landscape change over a 20-yr period in the Klamath- Siskiyou with special attention to land ownership. We first examined changes in the ecoregion as a whole to understand landscape changes at the regional level.
- **Background**: When landscapes are disturbed naturally or by humans, forest patches are often divided into smaller units that can become isolated in the surrounding nonforest matrix leading to fragmentation of the original vegetation communities (Franklin and Forman 1987).
  - This fragmentation can have far-reaching effects on the structural and functional characteristics of a landscape and can have serious consequences for maintaining native biodiversity (Harris 1984).
- **Background**: Spatial characteristics of forested landscapes such as patch size and abundance, amount of edge, and habitat connectedness directly influence organisms within the landscape (Harris 1984; Franklin and Forman 1987).
- **Finding**: Overall, forests covered 66.8% of the ecoregion in 1972 and 62.1% in 1992. Approximately 10.5% of the forest area was disturbed overall, translating into an annual disturbance rate of 0.53%. Although public lands accounted for a slightly higher total area of forest disturbance, private lands were cut at a slightly higher rate. Forest disturbance within fifth level watersheds averaged 13.2%, but reached as high as 93.2%.
- **Finding**: For the three river basins where spatial pattern of forest disturbance was analyzed, private lands were already more fragmented than public lands in 1972.
- **Finding**: Over the 20- year time period, forest fragmentation increased on all ownerships. Fragmentation rates on public lands were high for all basins especially the Rogue.
- **Finding**: Clear-cut logging on private lands was generally in larger adjacent tracts, whereas cuts on public lands were generally smaller and more dispersed.

- **Finding**: Our results illustrate the importance of considering landscape change history when planning for effective biodiversity conservation in forested ecoregions and when formulating ecologically sustainable forest management strategies.
- **Finding**: Although forest disturbance in the Klamath-Siskiyou was moderate compared to many other temperate forest regions, the fact that forest area continues to decline and fragmentation measurements continue to increase regardless of ownership is cause for concern. Some subregions showed particularly high disturbance rates (e.g., Rogue Basin).
- **Finding**: Spatial characteristics of the Klamath-Siskiyou forests have changed in important ways between 1972 and 1992. Overall, forest disturbance has outpaced regeneration and forest patches have decreased in size and connectivity.

Stralberg, D., Jongsomjit, D., Howell, C.A., Snyder, M.A., Alexander, J.D., Wiens, J.A. and T.L. Root. 2009. Re-shuffling of species with climate disruption: a no-analog future for California birds? PLoS ONE 4(9): e6825. doi:10.1371/journal.pone.0006825

- **Background**: current community dynamics such as predator-prey or competitive interactions may become affected as species assemblages are reshuffled in new ways [9]. New species interactions that develop within these no-analog assemblages may result in the decline or extirpation of species as they adjust or adapt to changing climates, especially when the climate is changing at a rapid rate.
- **Background**: Entirely unique combinations of species and the new interactions that occur among those species may lead to even greater rates of local extirpation if species cannot adapt quickly enough [19].
- **Background**: the high frequency of no-analog bird communities that may occur over the next century can be said to reflect the individualized nature of climate-change impacts on different species and the transient nature of current ecological communities as we know them [43,44].[12].

Strittholt, J.R. and D.A. DellaSala. 2001. Importance of roadless areas in biodiversity conservation in forested ecosystems: case study of the Klamath-Siskiyou Ecoregion of the United States. Conservation Biology 15(6): 1742-1754.

- **Background**: Roads allow access to pristine areas and fragment native ecosystems into smaller and smaller patches of various sizes and shapes (Dickman 1987; Atkinson & Cairns 1992).
- **Background**: According to the National Research Council (1997), there are approximately 4 million miles of roadway in the United States. That covers about 1% of the conterminous United States, but the negative ecological effects of the "road-effect zone" are often much greater-18-22% (Forman 2000).
- **Background**: Roads constructed to gain access to re- sources on public lands have been substantial, and in some cases extremely heavy, over the last 50 years. It is difficult to determine the number of all roads currently on public lands, but agency estimates exist. The U.S. Forest Service (USFS) maintains approximately 440,000 miles of roads, nearly 10 times the total length of the in- terstate highway system.
- **Background**: Roads and the maintenance of roads affect natural terrestrial and aquatic environments in many ways. Increased erosion, air, and water pollution, spread of invasive exotics, road mortality and avoidance, and habitat fragmentation all accompany roads (reviewed by Andrews 1990; Spellerberg 1998; Jones et al. 2000; Trombulak & Frissell 2000). Roads directly fragment natural ecosystems (Reed et al. 1996), but -more importantly- they also provide access to areas, which leads to subsequent human disturbances from activities such as

logging, mining, grazing, agriculture, and urban development. These disturbances result in substantial declines in native species and an overall degradation of ecosystem integrity.

- **Background**: As large unroaded lands disappear, a minimum size of 405 ha is now being examined for wilderness designation. (Was originally a min size of 2024 ha in 1964.)
- **Background**: The World Conservation Union (IUCN) considers the Klamath-Siskiyou an area of global botanical significance (Wagner 1997), and the World Wildlife Fund chose it as a global 200 ecoregion, meaning that it is of high biodiversity value and under considerable threat (Ricketts et al. 1999). The ecoregion, as we define it, covers over 43,000 km2, of which approximately 63% is in public ownership (83% of this by the USFS). Nearly 13% of the ecoregion is considered strictly protected, primarily through a number of relatively large, scattered wilderness areas (Fig. 1).
- **Background**: The Klamath-Siskiyou ecoregion is noted for its abundance of serpentine bedrock geology (13%, or 575,550 ha of the ecoregion). Serpentine is a metamorphic rock upon which ultramafic soils are built. Ultramafic soils are unique in many of their physical and chemical properties: they are low in exchangeable calcium and high in magnesium, and they tend to be deficient in many soil nutrients. Many of these soils contain high levels of heavy metals, such as nickel, chromium, and cobalt, that impede normal plant growth and development (Cole- man & Kruckeberg 1999). For these reasons, serpentine geology is one of several known factors that have contributed to species endemism in the Klamath-Siskiyou (DellaSala et al. 1999; Strittholt et al. 1999).
- **Background**: Based on interpretation of mid-1990s satellite images, approximately 22% of the Klamath-Siskiyou ecoregion contained late-seral forest (928,356 ha), and 80% of it was on public land (Strittholt et al. 1999). Late-seral forest, which once dominated much of the Pacific North-west, has been in significant decline since the end of World War II. Many species and natural processes de- pend upon older forests, and they are of special conservation concern in the Klamath-Siskiyou. Late seral was defined as any forest older than 100 years.
- **Background**: Late-seral condition is not equally important among the various forest types found in the Klamath-Siskiyou. For example, some globally imperiled forest types are found in the ecoregion, including white fir (Abies concolor), Port Orford cedar, Brewer spruce (Picea breweriana), and huckleberry oak (Quercus vaccinifolia), and these are of particular concern (DellaSala et al. 1999),
- **Background**: <u>Port Orford cedar</u> is an important southwestern Oregon-northwest California endemic tree species (Lang 1999) that grows primarily in riparian areas, where it provides channel stabilization, shade for waterways, and microhabitat for numerous aquatic species (Jimerson & Creasy 1997). In an area where migratory species-most notably salmon-make up the bulk of the region's fish fauna, streamside integrity is of paramount importance, and Port Orford cedar is one of the dominant riparian tree species throughout the western sections of the Klamath- Siskiyou ecoregion. These cedars are at risk because of their value in Asian markets (there is no major domestic market for Port Orford cedar) and, more important, from an imported root-rot fungus (Pbytopbtbora lateralis) (Lang 1999). This fungus is water-borne and is usually associated with the building and use of roads for logging, mining, and recreation (imerson & Creasy 1997). Spores are easily picked up from infected sites and transported to uninfected ones on the tires of vehicles. Infestation usually results in mortality (Zobel et al. 1985)
- **Background**: The extensive literature on the importance of intact natural habitats makes a compelling case for the potential role of roadless areas as refugia for native biodiversity and as

areas crucial to forest integrity and function. Equally impressive is the mounting body of evidence showing the ecological costs of roads.

- **Finding**: Roadless areas occupied more than twice the land area of wilderness (approximately 27% of the entire ecoregion) and contained approximately 36% of the known occurrences of heritage elements, 37% of the mapped serpentine habitats, 36% of the remaining late-seralforests, 60% of Port Orford cedar strongholds, and 42% of key watersheds for aquatic biodiversity.
- **Finding**: In addition, roadless areas were composed of significant amounts of low- and mid-elevation sites and a substantial number of the 214 mapped physical-biological habitat types with strong complementarity with designated wilderness.
- **Finding**: Fragmentation analyses showed that roadless areas contributed to regional connectivity in important ways. Also, small roadless areas were an important component of the roadless-areas conservation assessment.
- **Finding**: For the Klamath-Siskiyou ecoregion, roadless areas and designated wilderness provide an important foundation upon which to develop a comprehensive regional conservation strategy.
- **Finding**: The total road length of all surface types for the Klamath- Siskiyou mapped at 1:100,000 scale was 44,522 km.
- **Finding**: Designated wilderness in the ecoregion covered 533,700 ha in several large, scattered patches. We mapped nearly 500 roadless areas of >405 ha on public lands of the Klamath-Siskiyou ecoregion area, which totaled 1,186,422 ha, approximately 27% of the ecoregion and more than twice the area of designated wilderness (Fig. 2).
- **Finding**: We mapped 131 large roadless areas covering 871,815 ha and 367 smaller roadless areas covering 314,607 ha, or 26% of the total roadless area. The USFS lands accounted for most (92%) of the roadless area mapped, followed by Bureau of Land Management (7.6%) and other public lands (e.g., National Park Service, 0.4%).

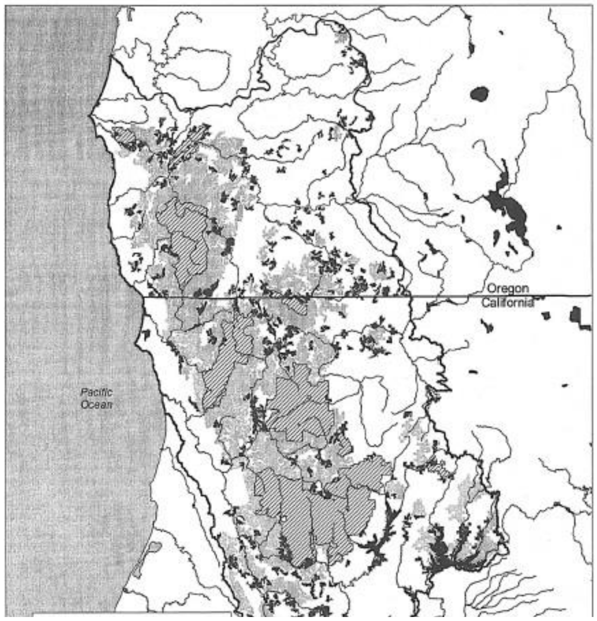


Table 1. Frequency of heritage-element occurrence records for existing wilderness and mapped roadless areas within the Klamath-Siskiyou ecoregion.

Element category	*No. of records*	*No. in wilderness*	*No. in roadless areas (≥405 ha)*	*No. in roadless areas (405–2,024 ha)*	*Wilderness (%)*	*Roadless areas (%)*	*Combined (%)*
Plants	3837	389	1306	341	10.1	34.0	44.1
Vertebrates	4652	212	1749	562	4.6	37.6	41.2
Invertebrates	132	2	80	26	1.5	60.6	62.1
Community	8	0	6	2	0.0	75.0	75.0
Aquatic	6	0	0	0	0.0	0.0	0.0
Special feature	158	36	36	0	22.8	22.8	45.6
Total	8793	639	3177	931	7.3	36.1	43.4

- **Finding**: Roadless areas contained nearly four times more heritage elements than designated wilderness areas; the largest gains occurred in the plant and vertebrate categories (Table 1). In general, roadless areas captured approximately 36% of all known heritage elements. When added to those within designated wilderness, the total number increased to 3816 records, or 43% of all known records (Table 1). Small roadless areas accounted for 931 element records, or 29% of the total roadless-area records, adding substantially more plant, vertebrate, and invertebrate occurrences.

- **Finding**: We found 209,051 ha (36%) of the existing serpentine geology in the Klamath-Siskiyou ecoregion in roadless areas. The contribution from the smaller roadless-area class was 47,090 ha, 22% of the roadless-area total. Designated wilderness areas captured 100,170 ha (17%) of serpentine geology in the ecoregion.
- **Finding**: Of the 928,356 ha of late-seral forest mapped for the Klamath-Siskiyou, 337,180 ha (36%) were in roadless areas. Small roadless areas accounted for 93,508 ha, or 28% of the roadless-area total. In comparison, designated wilderness areas contained only 16% (149,386 ha) of the remaining late-seral forest. We found no difference in the average density of late-seral forest between wilderness and roadless areas: both contained approximately 28% late-seral forest.
- **Finding**: Key watersheds covered 1,157,812 ha, or 26% of the Klamath-Siskiyou ecoregion. Over 42% of the key water- shed area (491,954 ha) was also roadless. The contribution from smaller roadless areas was 89,506 ha, or 18% of the roadless area total. Of the 333 key watersheds, 190 (57%) were 80% contained (54 were completely contained) within wilderness and roadless areas. Only 13 (4%) contained no roadless area.
- **Finding**: Wilderness and roadless areas showed a marked difference in elevation representation (Fig. 3). When com- pared to wilderness, roadless areas captured much more of the low- and medium-elevation classes (<1525 m) (Table 3). The small roadless areas made up about the same proportion (approximately 26%) of each elevation class, providing additional representation of low and medium elevations. Roadless areas did proportionally better than designated wilderness at representing low and medium elevations. Most of the existing high-elevation sites in the Klamath-Siskiyou were in designated wilderness.
- **Finding**: Roadless areas also contained many different habitat types than designated wilderness, with 96 new types (45%) represented at the -25% level (Fig. 4). When combined, designated wilderness and roadless areas complimented each other well, with 64% (138/214) of the classes represented at the >25% representation level. Although not visible in Fig. 4, smaller roadless areas made important contributions to 148 different habitat types, including 24 not found in any designated wilderness or large roadless areas.
- **Finding**: We also suspect that many more rare species are present in roadless areas than are presently known because of the remoteness of roadless areas, a lack of organized biological surveys, and a current sampling bias toward areas with road access. The actual importance of roadless areas with regard to this criterion may actually be higher than the current data analysis indicates.
- **Finding**: The amount of late-seral forest in roadless areas is considerable, but the percentage is about that found in wilderness areas (both are around 28% late seral). What is important is that these forests are part of relatively large, intact blocks of habitat representing important ecological values. Larger patches of forest that can support a wider range of species, including those requiring large home ranges, are more secure from human-induced effects and are large enough to allow natural processes such as fire to operate without human interference.
- **Finding**: The contribution roadless areas made to Port Orford cedar conservation was particularly significant. The road- less area and designated wilderness components of the best-

condition category were high; when combined, they accounted for nearly 88% of the best remaining areas of uninfected cedar.

- **Finding**: Our representation analyses suggest that an important role of roadless areas is adding low and medium elevations and many combined physical-biological habitat classes to the reserve network.
- **Finding**: Lower elevations contained most of the region's biological richness (DellaSala et al. 1999), and roadless areas were well represented at these elevations.
- **Finding**: Wilderness areas are concentrated on most of the forested and non- forested ecosystems at high elevations, including most of the red fir (Abies magnifica) and white fir (A. con- color) forests and much of the higher Jeffrey pine (Pinus jeffreyi), ponderosa pine (P. ponderosa), montane- hardwood conifer, and Klamath mixed-conifer forest types. Roadless areas added additional area to some of these habitat types, and-more important-picked up different physical zones for the same plant community types as well as totally new habitat types, including forests of Douglas-fir, montane hardwood, and Sierra mixed conifers growing under various physical zones defined and mapped for the region (Strittholt et al. 1999; Vance- Borland 1999). Smaller roadless areas were particularly important in contributing to 54 different habitat types and were exclusively responsible for capturing 24 habitat types not encountered at all in wilderness or the larger roadless areas.
- **Finding**: Small roadless areas in the Klamath-Siskiyou did not equally address all conservation issues examined, but they address many of them significantly, especially heritage elements, late-seral forests, elevation representation, habitat-type representation, and overall landscape connectivity
- **Finding**: Most biologically productive lands are already developed, and opportunities are limited to design effective protected-area networks without the necessity for substantial restoration. Roadless areas provide the remaining building blocks toward this end, so it is important to understand the contribution these areas make to an overall conservation strategy.

Spittlehouse and Stewart. 2003.

- **Background**: Predictions of biological changes over the next century range from large-scale biome shifts (Aber et al. 2001; Scott et al. 2002) to relatively less extensive disruptions in forest growth (Loehle 2000). Responses will be at the species level with the movement of species ranges northward and up in elevation, and the occurrence of new assemblages of species in space and time (Hebda 1997; Kirschbaum 2000; Hansen et al. 2001).
- **Governance**: Adaptation is not something to be applied only in the future; actions are needed now in anticipation of future conditions.
- **Finding**: We focus here on a framework for planning adaptive actions. The framework consists of four steps (see Table 1). The first is defining the issue. The second involves the assessment of the vulnerability to change (sensitivity, adaptive capacity) of the forest, forest communities, and society. This allows the development of adaptive actions to be taken now (step 3) and those required for the future (step 4) as change occurs.
- **Finding**: The precautionary principle advocates taking steps by implementing strategies that are useful now, but would also reduce the risk of unacceptable losses in the future. Many actions required to adapt to climate change benefit the present as well as the future (e.g., provenance trials). Forest policy needs to be assessed to ensure it encourages adaptation (Duniker 1990; Parker et al. 2000; Burton et al. 2002).
- **Finding**: Existing forests are quite resistant to climate variability (Noss 2001)—it is the regeneration phase that will initially be susceptible to the changed climate.

- **Finding**: Adaptive actions include: Identifying drought-tolerant genotypes (Farnum 1992). Assisting the migration of commercial tree species from their present to future ranges through artificial regeneration (Parker et al. 2000). The northward movement of certain species will, in some instances, be hindered by the lack of suitable soil conditions, such as nutrients, soil depth, and mycorrhizae. Planting provenances that grow adequately under a wide range of conditions and (or) planting stock from a range of provenances at a site (Ledig and Kitzmiller 1992). Controlling undesirable plant species, which become more competitive in a changed climate, through vegetation management treatments (Parker et al. 2000).
- **Finding**: In the case of most non-timber resources, management will likely be limited to minimizing impediments to autonomous adaptation through: Minimizing fragmentation of habitat and maintaining connectivity (Peters 1990; Noss 2001). Maintaining representative forest types across environmental gradients and protecting primary forests (Holling 2001; Noss 2001; Carey 2003). Established forests are often able to survive extensive periods of unfavourable climates and this inertia could extend the time period over which adaptation could take place. Maintaining diversity of functional groups as well as species within groups (Holling 2001; Noss 2001).

Strittholt, J.R., DellaSala, D.A. and H. Jiang. 2006. Status of Mature and Old-Growth Forests in the Pacific Northwest. Conservation Biology 20(2): 363-374.

- **Background**: For Douglas-fir forests, the definition of old growth ranges from 150 to 200 years (Haynes 1986). These forests are characterized by high densities of large (>100 cm in diameter) conifers, a broad array of tree sizes, a high percentage of trees with broken and dead tops, high densities of shade-tolerant trees, and high levels of snags and downed wood (Old-Growth Definition Task Group 1986; Spies & Franklin 1991; Wimberly et al. 2000).
- **Background**: Other forest types, including subalpine fir (Abies lasiocarpa [Hook.] Nutt.), white fir/grand fir (A. concolor [Gord. & Glend.] Lindl. ex Hildebr./A. grandis [Dougl. ex D. Don] Lindl.), and ponderosa pine (Pinus ponderosa P. & C. Lawson), have been assigned old growth age thresholds of 150 years, whereas others such as Pacific silver fir (A. amabilis [Dougl. ex Loud.]) are not considered old growth until they are 260 to 360 years old (Fierst 1993).
- **Background**: For Douglas-fir, mature forests are defined as being between 80 and 200 years of age, a period between the culmination of maximum growth and the development of old-growth characteristics (Franklin & Spies 1991b). These forests are also characterized by lower levels of snags and down wood than young, naturally regenerating forests and older age classes (Spies & Franklin 1991); the mature stage, however, represents an important intermediate age class from which old-growth conditions are likely to develop over time (Spies & Franklin 1991; Franklin et al. 2002).
- **Finding**: The historical extent of old-growth forest in the Pacific Northwest was roughly two-thirds (16,672,976 ha) of the total land area. Since the time of European settlement, approximately 72% of the original old-growth conifer forest has been lost, largely through logging and other developments.
- **Finding**: Of the remaining old growth, the Central and Southern Cascades and Klamath-Siskiyou account for nearly half. Mature conifer area (4,758,596 ha) nearly equaled the amount of old conifer. More than 78% of the old growth and 50% of mature forest were located on public lands. Approximately one-quarter (1,201,622 ha) of the old-growth conifer (or 7% of the historical old-growth area) was classified as GAP status 1 (strictly protected) or GAP status 2 (moderately protected).

- **Finding**: The total area of LSRs was slightly more than 3 million ha, approximately 36% (1,073,299 ha) of which contained old-growth conifer forest. Combined old and mature conifer within LSRs was approximately 59% of the total LSR area. The total amount of IRA for the Pacific Northwest was approximately 1,563,370 ha; of this, 526,912 ha (34%) was old growth. The combined area of old-growth conifer forest accounted for by protected areas (GAP 1 and 2), LSRs, and IRAs was 2,401,780 ha, which accounts for 66% of the old-growth conifer forests on public land, 51% of the old conifer in the region, and 14% of the amount that occurred historically.
- **Finding**: Outside these land designations, an additional 1,240,271 ha of old growth are on other public land and another 1,023,392 ha are on private lands throughout the Pacific Northwest. Our results indicate the need to periodically monitor status and condition of older forests and strengthen protections of old growth in the region.

Wright, Juanita. 2016 News Release. Southwest Oregon experiencing an increase in drought-related conifer mortality. Pacific Northwest Region Rogue River-Siskiyou National Forest.

- **Background**: The USDA Forest Service and the Oregon Department of Forestry have been doing an annual aerial tree mortality detection survey in Oregon since 1951. We can be confident that the data derived from the aerial survey provides us with good information on mortality trends over time; these data, maps, reports and related information are posted on the internet at http://www.fs.usda.gov/main/r6/forest-grasslandhealth/.
- **Finding**: The drought of 2013 followed by the snow drought of 2014 diminished tree defenses in the interior areas of Southwest Oregon, especially in very dense stands. Subsequently, tree mortality due to insects and plant pathogens has increased.
- **Finding**: in the Applegate Adaptive Management Area (AMA), which encompasses the entire Applegate River watershed, the 2015 overview aerial detection survey results illustrate a large increase in conifer mortality --- pines, firs and Douglas-fir --- as compared with previous years.
- **Finding**: These surveys and a number of studies have shown that particular types of tree mortality occur in pulses, often in response to drought or other weather conditions.
- **Finding**: Although last winter brought ample precipitation, it is likely that 2016 will be another year of elevated conifer mortality in Southwest Oregon. This is due, in part, to the enlarged beetle populations that exist within currently infested conifers and the life cycle length of the beetle species involved.

Herbaceous Plants

Chmura et al. 2011. Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. Forest Ecology and Management 261: 1121-1142.

- Ecological Considerations: In a P. menziesii mesocosm experiment, warming affected seasonal growth patterns and seedling height, but stem diameter, whole seedling biomass, and biomass allocation were unaffected by warming, [CO2], or their interaction (Olszyk et al., 1998a,b, 2003).
- Ecological Considerations: Elevated [CO2] directly affects plant physiological processes. Most trees are C3 plants in which CO2 and oxygen (O2) compete for the active site of the primary enzyme involved in photosynthesis, Rubisco.WhenCO2 is used as the substrate,CO2 assimilation occurs via photosynthesis (Ps), but when O2 is the substrate, CO2 is produced as an outcome of photorespiration. Elevated [CO2] increases the CO2 concentration in leaves and at the active sites of Rubisco, and can enhance light-saturated photosynthetic rates in woody plants by 2–280%, depending on species and environmental conditions (Curtis and Wang, 1998; Norby et al., 1999;Nowaket al., 2004; Ainsworth and Rogers, 2007).
- Ecological Considerations: Overall, our understanding of respiration at the cellular level is incomplete, and we cannot use information at the cellular level to predict the effects of elevated [CO2] on respiration of whole-trees or ecosystems (Drake et al., 1999; Valentini et al., 2000).
- Ecological Considerations: Nutrient availability, particularly nitrogen (N), may determine whether forests benefit from elevated [CO2] because there may be little response on nutrient-poor sites (Table 1; Curtis and Wang, 1998; Oren et al., 2001; McCarthy et al., 2010). Furthermore, increases in C assimilation may increase the demand for N to support additional plant growth, and increase the sequestration of C and N into long-lived pools (e.g., plant biomass and soil organic matter). This may lead to a subsequent decline in growth due to “progressive nitrogen limitation” (Luo et al., 2004).
- Ecological Considerations: Warmer temperatures tend to enhance plant biochemical and physiological processes as long as optimum temperatures are not exceeded and moisture is adequate.
- Ecological Considerations: Elevated concentration of atmospheric carbon dioxide – [CO2], generally warmer temperatures, and changing precipitation regimes will affect the exchange of energy, carbon, water and nutrients between forests and the environment, leading to changes in forest growth, survival and structure. Interactions with biotic and abiotic disturbance agents will also shape future forests.
- Management: To facilitate forest acclimation and adaptation, decision-makers need to understand the potential ecophysiological responses of trees and forests to climate change.

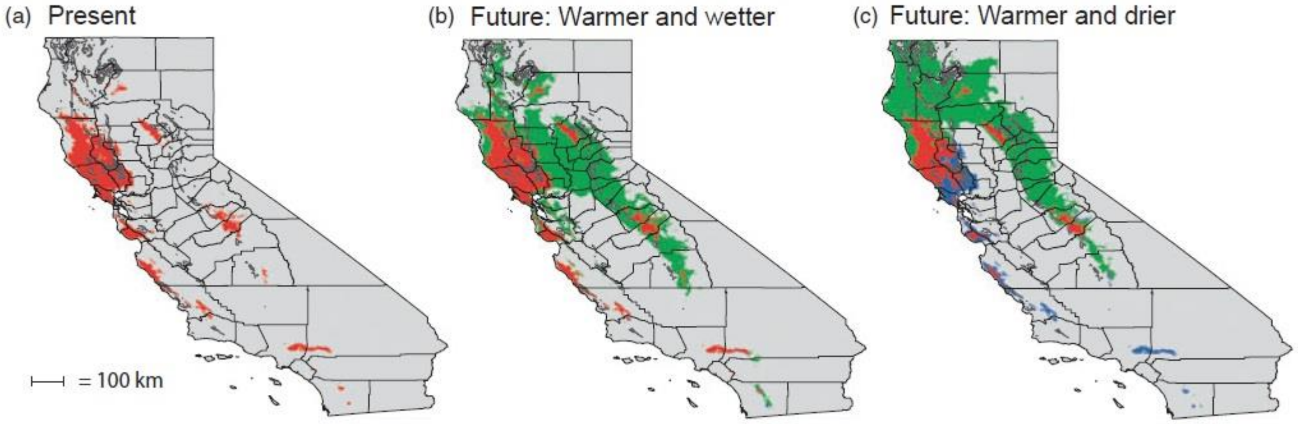
Damschen, E.I., Harrison, S., Ackerly, D.D., Fernandez-Going, B.M. and B.L. Anacker. 2012. Endemic plant communities on special soils: early victims or hardy survivors of climate change? Journal of Ecology 100: 1122-1130.

- **Background**: Predicting and mitigating climate change effects on ecological communities is a tremendous challenge. Little attention has been given to how endemic-rich communities on isolated patches of low-nutrient soil (e.g. serpentine) will respond to climate change.
- **Background**: Plant communities found on patches of unusual bedrock and soil types, such as serpentine, gypsum, limestone, dolomite and shale (i.e. 'special soil', 'azonal', or 'low nutrient' communities), contain many endemic species and make large contributions to regional floristic diversity.
    - For example, in California, 35% of the state's 1742 rare plant species occur on special substrates (Skinner & Pavlik 1994).
- **Background**: Plant communities on special soils have two distinctive attributes that may cause them to respond uniquely to climate change.
    - First, they are often found in discrete outcrops making them more spatially isolated from one another than 'normal' soils that tend to be more contiguous (hereafter, we refer to this set of considerations as 'spatial factors'). For example, serpentine outcrops across the world are seldomfound in outcrops of more than a few hundred square kilometres, with some notable exceptions including New Caledonia; southern Oregon, USA; Sulawesi; and eastern Cuba (Brooks 1987). This spatial isolation maymake itmuchmore difficult for species to successfully migrate under climate change.
    - Second, because these communities are on unproductive substrates, they may differ from communities on 'normal soils' in terms of limiting resources, functional traits, and the relative importance of disturbance, competition and other ecological processes (hereafter, we refer to these as 'non-spatial factors').
        - Plants in these special soil habitats often have traits associated with tolerance of drought and nutrient limitation [e.g. small stature, low-specific leaf area (SLA), high allocation to roots relative to shoots] because nutrient availability is limited, water can be scarce, and soils may have additional unusual chemistries (e.g. presence of heavy metals or particularly acidic or basic pH).
        - Special soil communities are more strongly water limited than others; therefore, they may be especially responsive to changes in available precipitation.
        - On the other hand, because plants on special soils already have adaptations for stress tolerance, they may be particularly well suited to withstand climatic changes.
- **Background**: Serpentinite and peridotite (collectively called ultramafic or simply serpentine) rocks are found throughout the world, primarily where oceanic crust and mantle have been exposed on continents (Alexander et al. 2006). Soils weathered from these rocks are extremely magnesium-rich and calcium-poor compared with most other soils and are also typically low in macronutrients (especially P and K) and sometimes also high in heavy metals (Ni, Cr, Co) (Alexander et al. 2006). In many cases, these soils have very high rock fragment content, leading to a scarcity of available water (Alexander et al. 2006). Sparse canopy cover may also contribute to high temperature and low moisture near the ground surface.
- **Background**: On limestone soils, Grime et al. (2000, 2008) experimentally manipulated temperature and precipitation and measured the effects on grassland communities in two settings: Buxton, UK, an unproductive limestone grassland, and Wytham, UK, an early successional productive limestone grassland. Over a 5-year period (Grime et al. 2000), the composition of the unproductive grassland changed considerably less in response to treatments than the productive grassland, and even after 13 years, changes in the unproductive grassland were strikingly small (Grime et al. 2008). This response was attributed in part to a suite of stresstolerant functional traits shared by the species on the unproductive site and in part to the

potential for individuals at the unproductive site to move among microhabitats determined by soil depth, allowing them to persist through climatic changes (Fridley et al. 2011).

- **Background**: On gypsum soils, Matesanz, Escudero & Valladares (2009) experimentally manipulated rainfall and measured the effects on a specialist shrub species, Centaurea hyssopifolia, across habitats that varied in, among other factors, their 'quality' as measured by plant cover and soil nutrient content. In poor quality habitat, reduced rainfall led to greater advancement of flowering and dispersal times, greater reduction in growth rate and greater increase in the fractions of senescent leaves, compared with individuals under similar rainfall treatment in higher-quality habitat.
- **Background**: Taken together, the above two studies suggest that climate change effects may be buffered by the community-level properties of plants on low-nutrient soils, but individual species may suffer stronger effects of climate change on low-nutrient soils than high-fertility soils.
- **Background**: In a study of chaparral and oak woodland in northern California, Harrison (1997) found that elevational and coast-to-inland gradients had no effect on local diversity on serpentine soils. However, local diversity on non-serpentine sedimentary soils decreased with distance inland, increased with elevation and slope interacted with both of these effects. These results indicate that local diversity on sedimentary soils is greater in favorable climates and is more variable along climatic gradients than on serpentine soils.
- **Background**: Using the fossil pollen record in six lakes, Briles et al. (2011) compared woody vegetation change during the Holocene on serpentine and non-serpentine soils (granitic) in the Klamath- Siskiyou Mountains. They found that shrub and tree abundances were less variable on serpentine in comparison to granitic substrates in response to the past 15 000 years of climatic variability. On serpentine, the relative abundances of the dominant species were altered, but there was little change in species composition. Briles et al. (2011) conclude that trees and shrubs on serpentine soils were able to persist under a range of past climate conditions for the same reasons that they can tolerate nutrient deficiencies and high heavy-metal concentrations. They caution against generalizing these results to all plant species responses to future climate change in that the paleorecord lacks the ability to detect many species-level responses, particularly for herbs.
- **Background**: Fernandez-Going, Anacker & Harrison (in press) compared temporal variability in diversity over 10 years for serpentine and non-serpentine grasslands in northern California, USA. They found that variability in species richness and composition in response to annual variation in precipitation was lower on serpentine than on non-serpentine soils. They also found that serpentine communities were less functionally diverse and had greater numbers of species with stress-tolerant traits (short stature, low-SLA, low foliar C⁄N ratio) than non-serpentine communities.
- **Background**: Damschen, Harrison & Grace (2010) examined long-term vegetation change in the Klamath-Siskiyou Mountains, Oregon, USA, using a historical data set originally collected by Robert Whittaker from 1949 to 1951 (Whittaker 1960). Whittaker sampled vegetation to determine how community composition changed along environmental gradients including elevation, topography and soil type.
    - Since that time, the region has shown an increase in mean annual temperatures of c. 2 ————————————C (Damschen, Harrison&Grace 2010).
    - In 2007, these communities were resampled to examine change over time on serpentine and non-serpentine soils. Cover of nearly all herb species either declined or remained the same on both serpentine and non-serpentine soils.

    - Species with functional traits associated with cool and moist habitats (i.e. high specific leaf areas (SLA), northern biogeographic affinities) declined more than those with opposite traits.
    - As a result, species composition of a given site today resembles that of a warmer (more southerly) topographical position in Whittaker's time.
    - The observed shifts in plant species richness and cover were of greater magnitude for serpentine vs. non-serpentine soils, but changes in functional traits and species composition were similar between soils.
    - Serpentine endemics also showed greater declines in cover than soil generalists.
    - These results suggest that herbaceous communities on serpentine have been as strongly affected by a warming climate as communities on non-serpentine soils.
- Finding: Other qualitative observations from the literature on the biogeography of serpentine plants likewise support the interpretation that the composition of non-serpentine communities may show greater variation over climate gradients than serpentine communities (Rune 1953; Whittaker 1960; Kruckeberg 1984; Brooks 1987; Borhidi 1991; see review in Harrison, Damschen & Going 2009).
- Finding: A surprising result of our models (See Fig. 2 and Appendix S1 in Supporting Information for model results) under the no-dispersal scenario was that species do not disproportionately suffer habitat loss as a result of being confined to serpentine. This implies that serpentine soils are just as abundant at higher elevations and higher latitudes where suitable climatic conditions are predicted to occur in the future, as in the geographical regions where the species exist now.
- Finding: Under the scenario that included dispersal, we found that to colonize the nearest serpentine patch in their newly suitable range from a patch within their current climate envelope, the 12 species had to make minimum initial dispersal distances averaging 596 m for the warmer–wetter and 1891 m for the warmer–drier climate projection models.
    - Subsequently, they must make minimum dispersal jumps averaging 663–8275 m to colonize each patch within their newly suitable ranges (i.e. these are the mean shortest edge-to-edge distances to each patch in the newly suitable range; Fig. 3).
    - Several lines of evidence suggest that plant dispersal on the order of kilometres across unsuitable intervening habitat is unlikely over relatively short timescales.


(a) Present

(b) Future: Warmer and wetter

(c) Future: Warmer and drier

Fig. 2. The (a) current range, (b) future range assuming a warmer and wetter climate and (c) future range assuming a warmer and drier climate for *Ceanothus jepsonii*, one of 12 species examined. In panel a, Red is the species range at present. In panels b and c, Red is the area of overlap between present and future ranges, Blue is the area that is lost due to climate change and Green is the area that is gained due to climate change. Serpentine outcrops and county boundaries are outlined in black. See Appendix S1 for maps of the remaining 11 species.

  - A recent review of dispersal studies found that plants disperse on average between 10–100 m and that average dispersal distances >1 km are uncommon (Kinlan & Gaines 2003).
  - Other studies have found that plants in spatially isolated habitats have evolved limited dispersal abilities (Cheptou et al. 2008; Riba et al. 2009).
- **Finding**: Our analyses also suggested that three species (Linanthus ambiguus, Polystichum lemmoni and Salix delnortensis) will have no climatically suitable serpentine outcrops in the future under one or both climate projection models, although we note the above caveat about the reliability of any such absolute predictions using current species distribution modelling methods.
- **Finding**: Three of the four studies indicate that serpentine communities may be less sensitive to climate change than communities on 'normal' soils.
- **Finding**: Of the four studies we found that evaluate the relative sensitivity of serpentine plant communities to those on non-serpentine soils, three studies (Harrison 1997; Briles et al. 2011; Fernandez-Going, Anacker & Harrison, in press) suggest that serpentine plant communities are less variable under climate change while one study (Damschen, Harrison & Grace 2010) indicates that they are at least as vulnerable as those on 'normal' soils.
- **Finding**: Our review of other (non-spatial) factors suggests that serpentine plant communities may be more resistant to climate change, but conflicting evidence demonstrates the importance of understanding the roles of species turnover, overstorey composition and species endemism.

De Frenne et al. 2013

- **Study**: Here we compiled plant occurrence data (1,032 species in total) from 1,409 resurveyed vegetation plots in temperate deciduous forests. The plots were distributed across 29 regions of temperate Europe and North America (Fig. 1 A and B) with an average interval of 34.5 y (range: 12–67 y) between the original and repeated vegetation surveys (Table S1). From these plots, we tested for plant community responses to recent macroclimate warming and assessed the potential role of changes in forest canopy cover in modulating such responses.
- **Climate Change Impacts**: The thermophilization of vegetation is consistent with the warming climate observed across the regions: the mean rise in Aprilto- September temperatures between the old and recent survey was 0.28 °C·decade−1 (Table S1).
- **Background**: Recent global warming is acting across marine, freshwater, and terrestrial ecosystems to favor species adapted to warmer conditions and/or reduce the abundance of cold-adapted organisms (i.e., "thermophilization" of communities).
- **Background**: the temperature experienced by organisms at ground level (microclimate) can substantially differ from the atmospheric temperature due to local land cover and terrain variation in terms of vegetation structure, shading, topography, or slope orientation (8–15).
- **Background**: The daytime or nighttime surface temperature in rough mountain terrain, for instance, can deviate by up to 9 °C from the air temperature (10).
- **Background**: Likewise, forest structure creates substantial temperature heterogeneity, with the interior daytime temperature in dense forests being commonly several degrees cooler than in more open habitats during the growing season (12–15).
- **Background**: forest understories, which play a key role in vital ecosystem services of forests such as tree regeneration, nutrient cycling, and pollination(17, 18).
- **Background**: Temperate forests comprise 16% (5.3 million km2) of the world's forests (19), and understory plants represent on average more than 80% of temperate forest plant diversity (17).

- **Background**: Changing forest management regimes due to altered socioeconomic conditions, but also eutrophication, climate warming, and fire suppression, have resulted in increased tree growth, standing stocks, and densities in many temperate forests of the northern hemisphere (20–25).
- **Background**: Dense tree canopies not only lower ground-layer temperatures but also increase relative air humidity and shade in the understory (12–15). Higher relative humidity in dense forests can also protect forest herbs and tree seedlings from summer drought, decreasing mortality and thus buffering the impacts of large-scale climate change (15, 29). Furthermore, many forest herbs are known to be slow-colonizing species (30). Given the high degree of habitat fragmentation in contemporary landscapes, microclimatic buffering in dense forests may be a critical mechanism to ensure the future conservation of temperate forest plant diversity.
- **Finding**: Here we show that microclimatic effects brought about by forest canopy closure can buffer biotic responses to macroclimate warming, thus explaining an apparent climatic lag.
- **Finding**: Using data from 1,409 vegetation plots in European and North American temperate forests, each surveyed at least twice over an interval of 12–67 y, we document significant thermophilization of ground-layer plant communities. These changes reflect concurrent declines in species adapted to cooler conditions and increases in species adapted to warmer conditions.
- **Finding**: However, thermophilization, particularly the increase of warm-adapted species, is attenuated in forests whose canopies have become denser, probably reflecting cooler growing-season ground temperatures via increased shading. As standing stocks of trees have increased in many temperate forests in recent decades, local microclimatic effects may commonly be moderating the impacts of macroclimate warming on forest understories.
- **Finding**: Significant community turnover took place over time in the temperate forests we sampled: on average, one-third of the species present in the old surveys has been replaced by other species today
- **Finding**: We found that local changes in forest canopy cover modulate the thermophilization of vegetation; thermophilization was lowest in forests that became denser, and highest in forests that became more open over time (Fig. 3A).
- **Management**: Conversely, increases in harvesting woody biomass—e.g., for bioenergy—may open forest canopies and accelerate thermophilization of temperate forest biodiversity.
- **Management**: The importance of increased canopy cover in influencing understory biodiversity (i.e., the ability of canopy cover to lessen temperature increases and humidity decreases) is particularly relevant in an era when forest management worldwide is confronted with increasing demands for woody biomass, not least as an alternative source of renewable energy (31, 32).
- **Management**: Large-scale reopening of the canopy for woody biomass harvesting may thus hasten thermophilization of understory plant communities of temperate forests.

Harrison, S., Damschen, E.I. and J.B. Grace. 2010. Ecological contingency in the effects of climate warming on forest herb communities. www.pnas.org/lookup/suppl/doi:10.1073/pnas.1006823107/-/DCSupplemental.

- **Findings**: In lower montane forests, regardless of land-use history, we found multiple herb community changes consistent with an effectively drier climate, including lower mean specific leaf area, lower relative cover by species of northern biogeographic affinity, and greater compositional resemblance to communities in southerly topographic positions.

    - These compositional changes were driven by small declines in the abundances of large numbers of species, with no species showing substantial increases in abundance (Fig. S1).
- **Findings**: At higher elevations we found qualitatively different and more modest changes, including increases in herbs of northern biogeographic affinity and in forest canopy cover.
    - This may be the result of the longer snow-free growing season (e.g., 5, 11, 12, 52). In turn, increased shading from a more vigorous overstory at these elevations may have suppressed herb cover and richness (11, 12) as well as contributing to the observed shift toward shade-tolerant herbs of northern biogeographic affinity.
- **Findings**: Species richness declined more in primary and secondary low-elevation forests (which did not differ significantly from each other) than in high-elevation forests (F=5.44,P=0.02), whereas declines in total cover did not differ between low and high elevations (F=0.45, P= 0.51).
- **Findings**: We found no change in the relative cover by herbs considered to be indicators of late-seral forest conditions in either primary lower montane forest (t = 0.65, P = 0.52) (Fig. S3) or upper montane to subalpine forest (t = 0.19, P = 0.85) (Fig. S3), suggesting these forests already were in late-successional condition in 1949–1951 (consistent with Whittaker's description of his site selection; ref. 25).
    - However, the secondary lower montane forests that were logged in the 1960s through the1980s showed the expected lower percent of cover by late-seral indicator herbs in 2007–2009 compared with 1949–1951 (t = 4.93, P < 0.001) (Fig. S3).
- **Findings**: In analyses using aerial photographs from 1940 and 2005 (41), mean canopy cover showed no change in primary lower montane forest (t = 0.95; df = 1, 3; P = 0.39) (Fig. S3), a slight and marginally significant decrease in secondary lower montane forest (t = 1.01; df=1, 23; P=0.06) (Fig. S3), and a significant increase in the primary upper montane to subalpine forest (t = 8.41; df = 1, 43; P < 0.001) (Fig. S3). These patterns are inconsistent with forest succession as a cause of the observed herb-community changes at low elevations, although they suggest a possible role for warming-induced canopy expansion at high elevations.
- **Findings**: Our study adds to growing ecological evidence for drier forest understory conditions in many parts of the world (e.g., 45, 46–49).

Harrison et al. 2015. Plant communities on infertile soils are less sensitive to climate change. Annals of Botany 116: 1017-1022.

- **Background**: Grime et al. (2000, 2008) showed that a native grassland on infertile limestone soils changed very little in response to a prolonged application of warming, drought and watering treatments that had caused dramatic compositional changes in other plant communities. These authors largely attributed the relative climate resistance of infertile limestone grasslands to a suite of plant functional traits associated with low relative growth rate and high tolerance for resource scarcity. [See also Damschen et al. (2012) for related evidence.]
- **Background**: Our research in recent years has focused on testing 'Grime's hypothesis' in native-dominated plant communities on infertile soils in the California Floristic Province. In this semi-arid region, climatic warming is expected to drive increased seasonal water deficits that will dominate the future impacts of climate change on natural vegetation (Cornwell et al., 2012; Hannah et al., 2012; Thorne et al., 2012), making water availability a natural focus.
- **Background**: Serpentine soils are high in Mg and low in Ca and primary nutrients; they are found throughout the world, and are particularly floristically rich in tropical and mediterranean climates (Brooks, 1987).

- **Background**: Prior to our recent work, several lines of evidence hinted at unusually low sensitivity to climatic variation in Californian serpentine plants. Vegetation on serpentine barrens looked scarcely different in photos taken several decades apart (Kruckeberg, 1984). Plant community turnover on a coastal-to-interior climatic gradient was much lower on serpentine than on non-serpentine soils (Harrison, 1999).
- **Background**: Since 2010, our work in serpentine plant communities has added considerably more evidence supporting both lower climate sensitivity on infertile soils and the causal role of plant functional traits.
    - In two multi-year experiments, the effects of watering on grassland biomass and/or composition were lower on serpentine soils (Eskelinen and Harrison, 2013; Fernandez-Going and Harrison, 2013).
    - In a 10-year observational study, grasslands on serpentine soils fluctuated less in response to annual variability in rainfall than those on non-serpentine soils, and functional traits were important predictors of this difference (Fernandez-Going et al., 2012).
    - In a geographical study across a 1200-km, 10-fold precipitation gradient, serpentine plant communities had consistently 'stress-tolerant' functional trait composition, while communities on more fertile soils varied strongly from 'stress tolerant' at the dry southern end to 'stress intolerant' at the wet northern end (Fernandez-Going et al., 2013).
    - Finally, in a 15-year observational analysis, grassland species diversity has declined and composition has changed to more 'stress tolerant' as the climate has become more arid, but less so on serpentine than on non-serpentine soils (S. Harrison, E. Gornish and S. Copeland, unpubl. data).
- **Background**: Overstorey shading is known to buffer forest understorey herbs against climate change by modulating temperature extremes (De Frenne et al., 2013)
- **Background**: A growing number of climate change studies are using SLA and other functional traits as both predictors and indicators of change (e.g. Harrison et al., 2010; Sandel et al., 2010; Soudzilovskaia et al., 2013). Traits show great promise as a currency of plant community change, because they are easily measured by highly repeatable means (e.g. Garnier et al., 2001; Cornelissen et al., 2003) and make it possible to compare responses among communities with few or no species in common (e.g. Wright et al., 2004; Westoby et al., 2006).
- **Finding**: We conclude that the balance of evidence supports what we have called Grime's hypothesis, linking soil infertility to a stress-tolerant functional trait syndrome that tends to confer unusually high resistance of plant species and communities to climate change.
    - We qualify this by saying that our evidence only applies to communities that are becoming effectively drier because of declining precipitation and/or increasing temperatures leading to greater water deficits.
    - Such aridification is both observed and projected in California, much of the western US, and other arid and semi-arid climates (Seager et al., 2007; Thorne et al., 2012).
    - We also caution that less sensitive does not mean insensitive, and that the future survival of endemic-rich communities on infertile soils could be undermined by nutrient deposition, stress-tolerant invasive species and habitat loss (Damschen et al., 2012).
- **Finding**: Overstorey cover, but not macroclimate or soil texture, was a significant covariate of community change over time. It strongly buffered understorey temperatures, was correlated with less change and averaged >50 % lower on serpentine soils, thereby counteracting the lower climate sensitivity of understorey herbs on these soils. Community mean specific leaf area

showed the predicted pattern of less change over time in serpentine than non-serpentine communities.

- **Finding**: Based on the current balance of evidence, plant communities on infertile serpentine soils are less sensitive to changes in the climatic water balance than communities on more fertile soils. However, this advantage may in some cases be lessened by their sparser overstorey cover.
- **Finding**: In support of our overstorey hypothesis, higher tree and shrub cover was associated with significantly lower mean
  (P<0
  001
) and maximum
  (P<0
  001
) understorey temperatures as measured in July 2014.
- **Finding**: Overstorey cover was negatively related to the biogeographical measure of community change, and interacted with soil to affect the topographic measure of community change (Table 2, Fig. 1). Overstorey cover was negatively related to the topographic measure of change on serpentine soils, but had no effect on non-serpentine soils.
- **Finding**: Using the regression relationship observed on serpentine soils, a serpentine community would change much less if it had the same overstorey cover as the average non-serpentine community (Fig. 1).
- **Finding**: As expected, community mean SLA was considerably lower on serpentine than on non-serpentine soils in both time periods (1949–1951 and 2007–2008), suggesting that serpentine species are more stress-tolerant on average. Also as expected, community mean SLA declined between these time periods on nonserpentine soils only (Fig. 2), indicating that on these soils, there was a differential loss of drought-intolerant (high SLA) species.
- **Finding**: Using as our measure of change the mean value of Specific Leaf Area (SLA), a key climate-related functional trait, we found a result that supported 'Grime's hypothesis' and helped to reconcile our historical study with other evidence: initially higher prevalence, followed by greater decline, of drought-intolerant species on fertile soils.
- **Finding**: we found that well-shaded understorey communities changed less over the six decades of climatic warming than did more open understories. This result agrees well with recent work suggesting that forest canopies buffer understorey herbs against climatic 'thermophilization' (De Frenne et al., 2013). Our results suggest that for herb communities on serpentine soils, the benefit of more stress-tolerant functional traits is counterbalanced by the disadvantage of less shading. Clearly, any generalizations about the relative vulnerability of plant communities on infertile soils to climate change (e.g. Grime et al., 2000, 2008; Damschen et al., 2012) need to take into account whether soil infertility is associated with lower overstorey cover.

Myer, G. 2013. The Rogue Basin Action Plan for Resilient Watersheds and Forests in a Changing Climate. Thaler, T., Griffith, G., Perry, A., Crossett, T., Rasker, R. (Eds). Model Forest Policy Program in association with the Southern Oregon Forest Restoration Collaborative, the Cumberland River Compact and Headwaters Economics; Sagle, ID. December, 2013.

- **Ecological Considerations**: Interestingly, serpentine soils of the Siskiyou Mountains have hosted unusual and diverse vegetation for millennia and this vegetation has not been responsive to changing climate (Briles et al. 2011). However, the relative stability of this vegetation could be due to dispersal limitations, suggesting a possible vulnerability in the face of anthropogenically driven climate change (e.g. Olson et al. 2012). In-fact, dramatic changes in endemic serpentine herb communities since 1960 suggest this may be the case (Damschen et al. 2010).

Birds

Dugger et al. 2016. The effects of habitat, climate, and Barred Owls on long-term demography of Northern Spotted Owls. The Condor 118: 57-116.

- **Finding**: Estimated mean annual rates of population change (lambda) suggested that Spotted Owl populations declined from 1.2% to 8.4% per year depending on the study area.
    - Klamath study area: -2.8% annual population change
    - Southern Cascades study area: -3.7% annual population change
    - NW California study area: -3.0% annual population change
    - Hoopa study area: -2.3% annual population change
- **Finding**: an estimated range-wide decline of 3.8% per year from 1985 to 2013.
- **Finding**: Barred Owl presence was associated with increased local extinction rates of Spotted Owl pairs for all 11 study areas
    - Our results indicate that competition with Barred Owls may be the primary cause of Northern Spotted Owl population declines across their range.
- **Finding**: recruitment rates were highest when both total precipitation (29 cm) and minimum winter temperature (9.58C) were lowest, with the lowest levels of recruitment occurring when conditions during the previous winter were cold and wet, and the highest levels of recruitment occurring when the previous winter was cold and dry.
    - There was no support for a lag effect of these covariates, so the relationships likely reflected direct effects on survival of non-territorial birds (potential recruits), particularly first-year birds, in the previous winter. The survival rate of nonterritorial or nonbreeding birds is usually difficult to measure, and, when estimated, is usually lower than the survival of territorial birds (Lenda et al. 2012).
- **Finding**: a greater amount of suitable owl habitat was generally associated with decreased extinction rates of northern spotted owl.
    - We observed strong positive associations between habitat characteristics, especially increased amounts of nesting and roosting habitat
    - Results were counterintuitive for the Green Diamond-R study area in northern California, where we observed higher estimates of habitat disturbance (HD) and edge habitat associated with higher colonization rates, and more core habitat associated with increased extinction rates. Northern Spotted Owls occupied younger-aged stands in the GDR study area compared with most other study areas, and it is possible that they responded differently to habitat disturbance and the amount of edge and core habitat in these study areas because of their local dependence on dusky-footed woodrats (Neotoma fuscipes) as prey (Sakai and Noon 1993, Hamm and Diller 2009).
- **Finding**: Mean fecundity of spotted owl females was highest for adults (0.309 +/- 0.027 SE), intermediate for 2-yr-olds (0.179 +/- 0.040 SE), and lowest for 1-yr-olds (0.065 +/- 0.022 SE).
- **Finding**: We found strong support for a negative effect of Barred Owl presence on apparent survival of Spotted Owls in 10 of 11 study areas, but found few strong effects of habitat on survival at the study area scale.
- **Finding**: meta-analysis results suggested that Spotted Owl survival was higher across all study areas when the Pacific Decadal Oscillation (PDO) was in a warming phase and the Southern Oscillation Index (SOI) was negative, with a strongly negative SOI indicative of El Ni ˜no events.
    - We observed higher survival rates when winters were warm (positive association with PDO) and dry (negative association with SOI), rather than higher survival when conditions were warm (positive association with PDO) and wet (positive association with

SOI) as observed in a meta-analysis of 6 Northern Spotted Owl study areas by Glenn et al. (2011a).

- **Finding**: In the study areas where habitat was an important source of variation for Spotted Owl demographics, vital rates were generally positively associated with a greater amount of suitable owl habitat.
- **Finding**: However, Barred Owl densities may now be high enough across the range of the Northern Spotted Owl that, despite the continued management and conservation of suitable owl habitat on federal lands, the long-term prognosis for the persistence of Northern Spotted Owls may be in question without additional management intervention.
- **Management**: Based on our study, the removal of Barred Owls from the Green Diamond Resources (GDR) study area had rapid, positive effects on Northern Spotted Owl survival and the rate of population change, supporting the hypothesis that, along with habitat conservation and management, Barred Owl removal may be able to slow or reverse Northern Spotted Owl population declines on at least a localized scale.

Stralberg, D., Jongsomjit, D., Howell, C.A., Snyder, M.A., Alexander, J.D., Wiens, J.A. and T.L. Root. 2009. Re-shuffling of species with climate disruption: a no-analog future for California birds? PLoS ONE 4(9): e6825. doi:10.1371/journal.pone.0006825

- **Finding**: Projections of future no-analog communities based on two climate models and two species-distribution-model algorithms indicate that by 2070 over half of California could be occupied by novel assemblages of bird species, implying the potential for dramatic community reshuffling and altered patterns of species interactions.
- **Finding**: The expected percentage of no-analog bird communities was dependent on the community scale examined, but consistent geographic patterns indicated several locations that are particularly likely to host novel bird communities in the future.
- **Finding**: Our analysis suggests that, by 2070, individualistic shifts in species' distributions may lead to dramatic changes in the composition of California's avian communities, such that as much as 57% of the state (based on the scales of communities that we examined) may be occupied by novel species assemblages.
- **Finding**: although net changes in the distributions of common species may be relatively small due to the combination of local decreases and increases, the cumulative effect on community composition is likely to be great due to variation in individual species' responses to climate disruption and resulting differences in geographic shifts.
- **Finding**: Based on the most refined delineation of communities, our analysis revealed several no-analog ''hotspots,'' primarily in arid inland portions of the state. These patterns may reflect the greater climatic variability of inland areas with continental climates and little or no moderating maritime influence, which are also likely to be more influenced by climate disruption [21].
- **Finding**: In addition, regions of high geologic diversity such as the Klamath Mountains in northern California, which represent the convergence of three mountain ranges [40], may also have high bird community heterogeneity and thus greater potential for the re-shuffling of species.

Streams, Riparian Areas, and Salmon

Asarian, J. Eli and Jeffrey D. Walker. 2016. Long-term trends in streamflow and precipitation in northwest California and southwest Oregon, 1953-2012. Journal of the American Waters Association, 52 (1): 241-261.

- **Background**: The conventional approach to increasing summer water supply is construction of new dams and reservoirs.
    - But dams have profound effects on river ecosystems, impeding species migration and affecting sediment dynamics
- **Background**: Dams have been identified as a primary cause of declining salmonid populations within the study area.
- **Ecological Considerations**: Declining streamflows—which occurred primarily at regulated (dam) sites in the fall and winter and at unregulated (non-dam) sites in the summer and fall—is a troubling indicator for the future of anadromous salmonid fisheries within the study area.
    - Decreasing summer streamflow reduces the quality and quantity of pools available where juvenile fish can survive during the dry summer months
    - Declining fall streamflow could affect migration and spawning of adult salmonids, which use flow increases as migratory cues and as a means to enter small streams
- **Management to Increase Streamflows**: A program to equip rural residences with tanks to store spring and winter runoff for summer use has reduced summer water withdrawals and resulted in measurable increases in summer low flows in the Mattole River at the south end of the study area.
- **Management to Increase Streamflows**: Increase the capacity of the landscape to store water by reconnecting floodplains and raising groundwater tables, including the use of native beavers and beaver dam analogs.
- **Management to Increase Streamflows**: Decrease human consumption of water.

Bottom et al. 2009. Reconnecting social and ecological resilience in salmon ecosystems. Ecology and Society 14(1): 5. [online] URL: http://www.ecologyandsociety.org/vol14/iss1/art5/

- **Background**: In an open letter to the Oregon State legislature in 1875, U.S. Commissioner of Fish and Fisheries Spencer Baird predicted that Columbia River salmon would suffer a similar fate to eastern salmon for the same reasons: habitat loss, excessive harvest, and dams and other impediments to fish migration.
    - The Commissioner enthusiastically endorsed hatchery technology as the means to maintain a stable salmon supply and to avoid the highly unpopular regulatory alternatives. Numerous state and federal fishery management agencies were established thereafter, and Baird's simple formula—artificial fish propagation to compensate for habitat loss and intensive harvest—was institutionalized, setting the priorities for U.S. fishery management for the next century (Bottom 1997).
- **Background**: The history of Pacific salmon conservation is a classic case of "command-and-control" management of renewable resources (Holling and Meffe 1996). Fishery management developed from an agricultural model of conservation (Bottom 1997). It devised methods to stabilize fish production at optimum levels by controlling or removing presumed limitations to survival and yield. Biologists selected salmon spawning partners and controlled rearing conditions in hatcheries; dictated the sizes, times, and locations for releasing hatchery fish; established predator control programs to eliminate threats from other fishes, birds, and mammals; and regulated harvest levels to achieve the maximum yield.

- **Background:** Throughout the western United States, approximately 29% of nearly 1400 historical salmonid populations (including the five species listed above and pink salmon, O. gorbuscha) are now extinct (Gustafson et al. 2007), and 27 salmonid stock groups are formally listed as threatened or endangered (http://www.nwr.noaa.gov/ESA-Salmon-Listings/).
- **Background:** Salmon ecosystems are defined by the long chain of freshwater, estuarine, and marine habitats that individuals in a population must navigate to complete their anadromous life cycles. Salmon may spawn and rear in a diversity of freshwater habitats from small headwater streams and lakes to larger rivers and estuaries, and feed for months or years in coastal and open marine waters of the North Pacific Ocean (Fig. 1).
- **Background**: Paleoecological studies have documented large fluctuations in abundance and shifts in the dominance of pelagic marine fish species in the North Pacific well before intensive fisheries had any impact on fish stocks (Soutar and Isaacs 1969, 1974). A 2200-year reconstruction of Alaska sockeye salmon abundances demonstrated dramatic jumps from high to low productivity that lasted for centuries even without any anthropogenic influence (Finney et al. 2002).
- **Background**: Salmon populations are directly responsible for conveying three of the four categories of ecosystem services defined by the Millennium Ecosystem Assessment (2005): provisioning, cultural, and supporting (Fig. 2).
    - In the last two decades, ecological studies have detailed many ecosystem supporting services also provided by salmon populations. Salmon are the principal food item of many terrestrial wildlife species (Willson and Halupka 1995, Merz and Moyle 2006) and a source of marine-derived nutrients to coastal lakes and streams (Bilby et al. 1996, Cederholm et al. 1999, Finney et al. 2000). They act as watershed engineers that structure streambed habitats and alter sediment composition during spawning (Schindler et al. 2003).
    - Ecosystem provisioning, cultural, and regulating services ultimately may depend on the supporting services of salmon populations that drive nutrient and energy flows in coastal watersheds.
    - Salmon carcasses, eggs, and sperm left behind after spawning deliver a continuous flow of nutrients and energy from the ocean to small coastal streams, rivers, and lakes.
    - Predation by terrestrial scavengers and nutrient uptake by riparian vegetation transfers marine-derived nutrients to terrestrial plants and animals.
    - Marine-derived nutrients from salmon even provide direct economic benefits through nutrient inputs to agricultural crops in fields near salmon rivers (Merz and Moyle 2006).
    - The growth of riparian trees that shade freshwater systems, regulate stream temperatures, and provide in-stream habitat structure may at least partially depend on healthy salmon populations (Helfield and Naiman 2001, Naiman et al. 2002).
- **Background**: Salmon also are sensitive indicators of regulating services in coastal watersheds. Because the environmental tolerances of salmon species are relatively narrow and habitat requirements at each life stage are very specific, populations are sensitive to water quality and habitat structure throughout a watershed. Thus, many of the same habitats that support robust salmon populations—functional wetlands and floodplains and intact riparian systems, for example—also support regulating ecosystem services (e.g., water purification, flood control, and temperature regulation) that benefit people (Fig. 2).
- **Background**: By one estimate, only 6%–7% of the historical subsidy of marine-derived nitrogen and phosphorous now reaches rivers across the Pacific Northwest (due to salmon population declines) (Gresh et al. 2000).

- Ecological Considerations: Because salmon convey important provisioning, cultural, and supporting services to their local watersheds, widespread population decline has undermined both human well-being and ecosystem resilience.
- Ecological Considerations: Healthy salmon ecosystems will provide important ecosystem services, including those clean water, ample stream flows, functional wetlands and floodplains, intact riparian systems, and abundant fish populations.
- Ecological Considerations: Widespread salmon decline may affect regional biodiversity of terrestrial-dependent wildlife species (Willson and Halupka 1995).
    - Others hypothesize that disruption of the marine feedback loop to coastal rivers could cause a downward spiral in freshwater ecosystems and a shift to a persistent low-productivity regime that is resistant to salmon recovery (Gresh et al. 2000, Schindler et al. 2003).
- Management: Strengthening resilience of salmon ecosystems will require expanding habitat opportunities for salmon populations to express their maximum life-history variation.
- Management: because ecosystems have limits in their capacities to reorganize and repair themselves following disturbance, human actions must work within the resilient capacities of salmon to avoid placing important ecosystem services at risk. A resilience-based management approach, therefore, seeks to strengthen the self-repairing capacity of ecosystems to support the services that people value.
- Management: Warming of the world's oceans, reduced snow packs, and other effects of global climate change are creating new uncertainties about the adaptive capacities of salmon populations in the region (Mote et al. 2003). Such trends suggest a need to strengthen ecosystem resilience as a strategy to cope with unpredictable social–ecological changes (Carpenter and Folke 2006).
- Management: Resilience perspective argues for a more explicit accounting of all of the salmon ecosystem services that natural-resource management programs influence and hope to maintain (Carpenter et al. 2001).

Climate Leadership Initiative, National Center for Conservation Science and Policy, Pacific Northwest Research Station. 2008. Preparing for Climate Change in the Rogue River Basin of Southwest Oregon.

- Ecological Considerations for aquatic and terrestrial species in Rogue Basin:
    - Threats to recruitment and survival of native fish
        - Increased storms and wildfires will increase sediment loads, nutrient loads, persistent organic pollutants, and other contaminants entering Rogue River and its tributaries
        - Hotter weather will increase water temperatures
        - Possible disconnection between timing of fish life stages and availability of primary foods due to shifts in timing of stream flows and emergence of aquatic invertebrates
        - Warmer water temperatures and extended low summer base flows extending well past the summer months are likely to decrease dissolved oxygen, produce more disease, and create conditions lethal to native fish
- Management: Recommendations to prepare aquatic and terrestrial systems for climate change:
    - Aquatic systems
        - Restore and maintain stream complexity and connectivity
            - To improve spawning habitat
            - To allow movement to new areas if others become too warm

        - Restore and maintain critical landscapes
            - High elevation riparian areas
            - Floodplains
            - Tributary junctions
            - North-facing streams
            - Stream reaches with gravels and topographic complexity
        - Manage fisheries to protect genetic diversity and life history diversity

Myer, G. 2013. The Rogue Basin Action Plan for Resilient Watersheds and Forests in a Changing Climate. Thaler, T., Griffith, G., Perry, A., Crossett, T., Rasker, R. (Eds). Model Forest Policy Program in association with the Southern Oregon Forest Restoration Collaborative, the Cumberland River Compact and Headwaters Economics; Sagle, ID. December, 2013.

- **Background**: Streams in the Rogue Basin provide habitat for many cold-water species including Coho salmon, spring Chinook salmon, fall Chinook salmon, summer and winter steelhead, many species of trout, amphibians, and other fish such as the Pacific lamprey, green sturgeon, white sturgeon, Klamath smallscale sucker, speckled dace, prickly sculpin, and others (ODEQ 2012).
- **Ecological Considerations**: As temperatures increase, salmon populations will be at greater risk of thermal stress from warm water temperatures (Heyn 2008; Mantua 2010). High water temperatures can limit distribution, migration, health, and performance of salmonids (Mantua 2010). Projected temperatures in the Pacific Northwest suggest a decrease in habitat for cold water aquatic species.
    - In the Rogue Basin salmon runs are relatively strong, but it must be protected and resilient to climate change for these runs to be able continue.
- **Ecological Considerations**: Invasive species, also a large concern in the Rogue Basin with Himalayan Blackberry overrunning several riparian areas, are also likely to increase as native vegetation is stressed by changes in precipitation and temperatures.
- **Ecological Considerations**: Additionally, over 137 species depend on salmon directly for survival. Salmon are a keystone species and an indicator species: if salmon disappear, there will be a domino effect, threatening the ecological and economic vitality of the region. Salmon are even important to the health of forests. Their decomposing bodies provide nutrients important for tree growth. When salmon are abundant, trees grow up to three times as fast as when salmon are scarce (Helfield, 2001 and Reimchen, 2003). Salmon are also important for providing streams and lakes with carbon, nitrogen, phosphorus, and micronutrients (Helfield, 2001 and Reimchen, 2003).

Sarr, D.A., Hibbs, D.E., Shatford, J.P.A. and R. Momsen. 2011. Influences of life history, environmental gradients, and disturbance on riparian tree regeneration in Western Oregon. Forest Ecology and Management 261: 1241-1253.

- **Background**: Riparian forests are among the most dynamic and complex ecosystems in nature and add disproportionately to landscape diversity where they occur (Naiman et al., 1993; Acker et al., 2003; Sabo et al., 2005).
- **Background** Background: Recent work by Pabst and Spies (1998, 1999) and Sarr and Hibbs (2007a,b) have demonstrated that riparian vegetation composition, diversity, and structure vary substantially across sites in geographically complex regions such as western Oregon. For long-lived tree species, as are many of the conifers occurring in riparian forests of the Pacific Northwest, the distribution of adult trees may not be a strong predictor of conditions for

current regeneration. Rather, regeneration is likely favored by an opportunistic interaction between seed availability and near-ground regeneration environment.

- **Background**: Seed size and tolerances of shade, drought, heat, and flooding are attributes that often differentiate establishment of species along environmental or successional gradients (Huston and Smith, 1987). Where several species share life history traits, they likely will show similar functional responses to their environment (e.g., regenerate in similar environments).
- **Background**: In the Pacific Northwest (USA), streamside forests occupy a central role in landscape conservation, containing a disproportionate share of landscape biological diversity and directly influencing the integrity of stream ecosystems, including anadromous fish and amphibian species (Gregory et al., 1991; Bury, 2008). Due to the rugged topography of the region, most riparian forests are embedded in steep, forested landscapes and directly influenced by upslope land uses. They provide an important buffering role between upland land uses and aquatic life and provide corridors for dispersal of riparian-dependent wildlife.
- **Finding**: See table 1 for riparian tree species encountered in the four study watersheds, western Oregon, with four letter species codes, and functional group membership. Life history attributes are ranked from 1 (lowest tolerance or seed size) to 10 (highest) for each species.

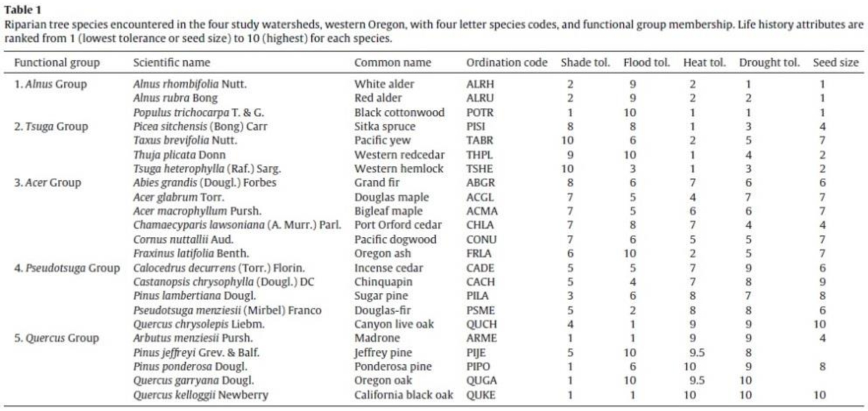
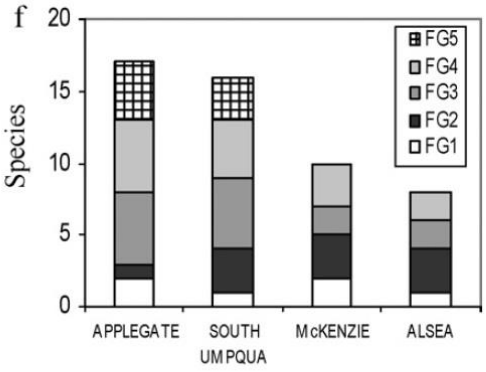


Table 1
Riparian tree species encountered in the four study watersheds, western Oregon, with four letter species codes, and functional group membership. Life history attributes are ranked from 1 (lowest tolerance or seed size) to 10 (highest) for each species.

Functional group	Scientific name	Common name	Ordination code	Shade tol.	Flood tol.	Heat tol.	Drought tol.	Seed size
1. *Alnus* Group	*Alnus rhombifolia* Nutt.	White alder	ALRH	2	9	2	1	1
	Alnus rubra Bong	Red alder	ALRU	2	9	2	2	1
	Populus trichocarpa T. & G.	Black cottonwood	POTR	1	10	1	1	1
2. *Tsuga* Group	*Picea sitchensis* (Bong) Carr	Sitka spruce	PISI	8	8	1	3	4
	Taxus brevifolia Nutt.	Pacific yew	TABR	10	6	2	5	7
	Thuja plicata Donn	Western redcedar	THPL	9	10	1	4	2
	Tsuga heterophylla (Raf.) Sarg.	Western hemlock	TSHE	10	3	1	3	2
3. *Acer* Group	*Abies grandis* (Dougl.) Forbes	Grand fir	ABGR	8	6	7	6	6
	Acer glabrum Torr.	Douglas maple	ACGL	7	5	4	7	7
	Acer macrophyllum Pursh.	Bigleaf maple	ACMA	7	5	6	6	7
	Chamaecyparis lawsoniana (A. Murr.) Parl.	Port Orford cedar	CHLA	7	8	7	4	4
	Cornus nuttallii Aud.	Pacific dogwood	CONU	7	6	5	5	7
	Fraxinus latifolia Benth.	Oregon ash	FRLA	6	10	2	5	7
4. *Pseudotsuga* Group	*Calocedrus decurrens* (Torr.) Florin.	Incense cedar	CADE	5	5	7	9	6
	Castanopsis chrysophylla (Dougl.) DC	Chinquapin	CACH	5	4	7	8	9
	Pinus lambertiana Dougl.	Sugar pine	PILA	3	6	8	7	8
	Pseudotsuga menziesii (Mirbel) Franco	Douglas-fir	PSME	5	2	8	8	6
	Quercus chrysolepis Liebm.	Canyon live oak	QUCH	4	1	9	9	10
5. *Quercus* Group	*Arbutus menziesii* Pursh.	Madrone	ARME	1	1	9	9	4
	Pinus jeffreyi Grev. & Balf.	Jeffrey pine	PIJE	5	10	9.5	8	
	Pinus ponderosa Dougl.	Ponderosa pine	PIPO	1	6	10	9	8
	Quercus garryana Dougl.	Oregon oak	QUGA	1	10	9.5	10	
	Quercus kelloggii Newberry	California black oak	QUKE	1	1	10	10	10

- **Finding**: Twenty-three tree species were classified by life history traits into five functional groups that differed in shade and drought tolerance; distribution and abundance of tree regeneration were analyzed by group. For most groups, seedling abundance varied substantially across the large scale climate gradient. In particular, drought tolerant species decreased sharply in abundance from the drier to wetter watersheds. Overall seedling frequency and diversity also decreased from the driest to wettest watersheds, while nurse log use increased. Regeneration of most, but not all, species was greater in gaps.
- **Finding**: Each functional group is hereafter designated by its functional group abbreviation, and, for ease in interpretation, the generic name of the most common species in the group:
  - Functional Group 1 (FG1), the Alnus Group, is a distinctive drought and shade intolerant group of broadleaved deciduous riparian species. The species in Functional Groups 2–5 show tradeoffs in shade and drought tolerance; the most drought tolerant species have low shade tolerance and vice versa (Fig. 2).
  - Functional Group 2 (FG2), the Tsuga Group, is a drought intolerant, but very shade tolerant group of coniferous species.
  - Functional Group 3 (FG3), the Acer Group, is a moderately drought tolerant, shade tolerant group of broadleaved deciduous and coniferous species.
  - Functional Group 4 (FG4), the Pseudotsuga Group, is composed of drought tolerant, moderately shade tolerant coniferous and broadleaved evergreen tree species.
  - Lastly, Functional Group 5 (FG5), the Quercus Group, is a group of very drought tolerant, shade intolerant conifers (pines) and both broadleaved deciduous and evergreen trees.

- **Finding**: We recorded major shifts in composition, frequency, and abundance of tree regeneration from southwest to northwest Oregon, i.e., from the Applegate, South Umpqua, McKenzie, and Alsea watersheds, respectively (Fig. 3). The frequency of regenerating trees in sampling plots decreased south to north. Frequency was 82.3%, 70.1%, 57.6%, and 14.9%, respectively, in the four watersheds, while the number of species recorded in each was 17, 16, 11, and 8 (Fig. 3f).
- **Finding**: Seedlings of the Alnus Group were most frequent and abundant near streams in all four watersheds (Fig. 3a, Table 3).
- **Finding**: In contrast to alders (Alnus spp.) which were relatively common along all streams in the region, we saw relatively few P. trichocarpa seedlings at our study sites along mountain streams. Those we saw were primarily at open, very disturbed areas, where local conditions (well-lit gravelly and cobbly terraces) appeared similar to those found along the larger alluvial rivers where the species is common (Dykaar and Wigington, 2000).
- **Finding**: Abundances for Tsuga Group species were highest in the South Umpqua and McKenzie watersheds, where the group, especially T. heterophylla, composed the majority of all tree regeneration (Fig.3b).
- **Finding**: After Acer macrophyllum, Abies grandis (Dougl.) Forbes was the most frequently regenerating species of the Acer Group (Table 3). Trees in this group showed a pronounced decline in seedling frequency and abundance from south to north. These species were most frequent close to streams in the Applegate and McKenzie watersheds and rarest on terraces in the Alsea watershed (Fig. 3c).
- **Finding**: Pseudotsuga Group species regenerated most frequently in the two southern watersheds (Fig. 3d, Table 3). Pseudotsuga menziesii and Castanopsis chrysophylla (Dougl.) DC. regenerated in all four watersheds, but were much more abundant in the south (Table 3). Quercus chrysolepis Liebm. was the most abundantly regenerating tree in the Applegate watershed, but was absent elsewhere (Table 3). Pinus lambertiana Dougl. and Calocedrus decurrens (Torr.) Florin regenerated sporadically in all three southern watersheds (Table 3).
- **Finding**: Regeneration of the Quercus Group was limited to the Applegate and South Umpqua watersheds and typically occurred at higher topographic positions (Fig. 3e, Table 3). No species was abundant. Quercus kelloggii Newberry was the most common, followed by Quercus garryana Dougl. and Arbutus menziesii Pursh. Pinus ponderosa Dougl. and Pinus jeffreyi Grev. & Balf. were uncommon and occurred primarily at high microelevations.
- **Finding**: Nurse logs were important regeneration surfaces for conifers, principally those in the Tsuga Group, and secondarily in Pseudotsuga Group, but were typically used less than 10% of the time by the remaining species (Fig. 5a–e). The proportion of total seedlings on logs differed strongly among conifer species, from >75% for P. sitchensis and T. heterophylla, 20–35% for T. plicata, T. brevifolia, and P. menziesii, to 0% for Pinus spp. Among hardwood species, the proportions on logs were much lower, with a high of 11% for C. chrysophylla and less than 2% for all other species. Nurse log use was greatest in the Cascades watersheds, where down logs were prevalent and Tsuga dominated the regeneration layer.



Species richness by functional group

- **Finding**: This study provided compelling evidence that riparian tree regeneration is an outcome of highly interactive factors operating at a multiple spatial scales. A central finding of this paper was that the frequency and composition of regenerating riparian trees can vary greatly across a geographically complex region such as western Oregon. To our surprise, the riparian forests in the relatively harsh, summer dry climates of the Applegate and South Umpqua watersheds of southwest Oregon had a much higher frequency of tree regeneration than wetter forests in the Alsea and McKenzie watersheds of northwest Oregon, although total seedling abundances were comparable (Fig. 2, Tables 3 and 4).
- **Finding**: Why should the frequency and abundance of regeneration decline in the highly productive riparian forests of the wetter climates? Although alternate explanations, such as local effects of pathogens or seed limitations are undoubtedly important for some species, we believe that interplant competition poses the primary limitation on riparian tree regeneration in the wetter, more productive Alsea and McKenzie watersheds.
- **Finding**: In the McKenzie watershed, where T. heterophylla cast deep shade on the floodplains of many streams, even species of reportedly high shade tolerance (e.g., A. grandis, Cornus nuttallii Aud.) regenerated only in gaps (Table 4). However, these same sites often had abundant T. heterophylla regeneration under the forest canopy (Table 3), suggesting that through shading, litter accumulation, and soil acidification, T. heterophylla modifies sites to its own advantage
- **Finding**: Riparian forest gaps yielded higher density of regeneration than nongaps for most species, suggesting such fine scale disturbances provide potentially important regeneration opportunities in these riparian forests, as in forests elsewhere (Hibbs, 1982; Veblen, 1989; Whitmore, 1989). However, species showed considerable variation in their dependence upon gaps for regeneration.
- **Finding**: This study confirmed the importance of organic substrates such as nurse logs as regeneration sites for conifers in wet riparian forests, but also demonstrated that that they are much less important in drier riparian forests of the Applegate watershed (Fig. 4).
- **Finding**: In all watersheds, the regeneration of trees in the Alnus Group was strongly linked to wet streamside environments with ample light and mineral soils and showed a strong affinity with forest gaps, confirming that these species are ruderal (Grime, 1977) or pioneer (Whitmore, 1989) species that are adapted to establish in fluvially disturbed environments.
- **Finding**: Trees in the Tsuga group showed the opposite pattern with respect to shade and seedbed preferences as the Alnus Group, commonly regenerating under conifer canopies and on organic seedbeds. Tsuga Group trees employ the continuous regeneration mode (Veblen, 1992) characteristic of climax species (Whitmore, 1989), being less dependent upon disturbance than the other species measured.
- **Finding**: Trees in Acer, Pseudotsuga, and Quercus Groups, together containing 16 species, fell between Whitmore's (1989) pioneer and climax typologies. Tree species in the Acer Group showed the strongest evidence of context-dependent regeneration behavior. Although species in the Acer Group are typically described as shade tolerant, climax species in mixed conifer and mixed evergreen forests (Waring and Major, 1964; Minore, 1979; Burns and Honkala, 1990a,b), they showed a marked decrease in abundance in forests with the heavily shade tolerant trees of the Tsuga Group, or with clonal shrubs such as R. spectabilis, adopting pioneer behavior in such settings. Regeneration of both A. macrophyllum and A. grandis in the Acer Group also appeared to occur most frequently on floodplains in the South Umpqua and Applegate watersheds, suggesting that the moist, deep soils in those summer dry climates allow suitable establishment conditions for these moderately drought tolerant species.

- **Finding**: The drought tolerant and less shade tolerant species in the Pseudotsuga and Quercus groups showed sharp drops in regeneration frequency and abundance from driest to wettest watersheds, and a strong association with gaps wherever they occurred. These tree species appear to be the stress tolerators of these riparian forests (Grime, 1977). Because several of the species in these groups (e.g., Q. chrysolepis) showed southern affinities, their lower abundances in the northern watersheds may reflect seed source as well as ecological limitations.
- **Finding**: In contrast, dominant, reproductively mature P. menziesii were present in most of the stands we sampled in northwest Oregon, suggesting ecological factors, such as competition, are driving the low levels of regeneration we observed. The microsites where these species regenerated, often with thin, rocky, soils, and on steep, hot south-facing slopes with considerable summer drought stress, are abundant in the Applegate watershed, but become less widespread in the wetter watersheds.
- **Finding**: The general impression is that regeneration behavior is relatively complex and strongly opportunistic; species will regenerate wherever local conditions fall within their environmental tolerances and they can effectively compete for space.

Welsh, Jr., H.H. and A.J. Lind. 2002. Multiscale habitat relationships of stream amphibians in the Klamath-Siskiyou Region of California and Oregon. Journal of Wildlife Management 66(3): 581-602.

- **Background**: Bury and Pearl (1999) reported that stream amphibian populations in the Oregon Coast Range had not recovered 35-50 years after clearcut harvesting
- **Background**: Welsh (1993) analyzed data from 156 sites, and from a greater proportion of the range of the Pacific giant salamander in California, and reported both a higher incidence and higher relative abundance of salamanders both nearer the Pacific Coast and northward. He interpreted this pattern as resulting from the direction of the prevailing cooler, moister, maritime-modified climate (Froehlich et al. 1982), which creates and sustains the region's temperate rainforests and provides optimum conditions for D. tenebrosus in the northwest portions of the state.
- **Background**: Patch dynamics of the surrounding landscape directly affect the stream network within by influencing hydrologic patterns, microclimates, sediment loads, and energy inputs, and thus affect the incidence and abundance of the associated riparian and stream biota (Schlosser 1991, Zwick 1992, Malanson 1993, Gregory 1997, Jules et al. 1999, Naiman et al. 2000).
- **Finding**: We captured 7 species, 97% of which were larval and paedomorphic Pacific giant salamanders (Dicamptodon tenebrosus) and larval and adult tailed frogs (Ascaphus truei).
- **Finding**: Streams in late seral forests supported both the highest diversity of amphibians and the highest densities of A. truei. Overall, A. truei distribution was patchy in occurrence, while D. tenebrosus distribution was widespread throughout the region at all scales.
- **Finding**: The incidence of A. truei was assessable at the landscape, macroenvironment, and microenvironment scales; however, variation in density was most predictable at the microenvironment scale. Changes in density of D. tenebrosus were detected only at the microenvironment scale.
- **Finding**: Tree size class and plant species composition variables distinguishing younger from older, more structurally complex forests, and forest microclimates and in-stream attributes best determined the presence and density for both life stages of A. truei.
- **Finding**: However, only in-stream conditions were good predictors of D. tenebrosus density. A. truei occupied a narrower range of habitat conditions than D. tenebrosus, exhibiting an ecological dependence on lotic and riparian environments found more reliably in late seral forests.

- **Finding**: We captured 1,400 individuals of 7 species in 39 streams. Amphibian diversity (SDI) was greater in streams traversing stands with greater forest age; 21% of the variance was explained by this single variable (Fig. 2).

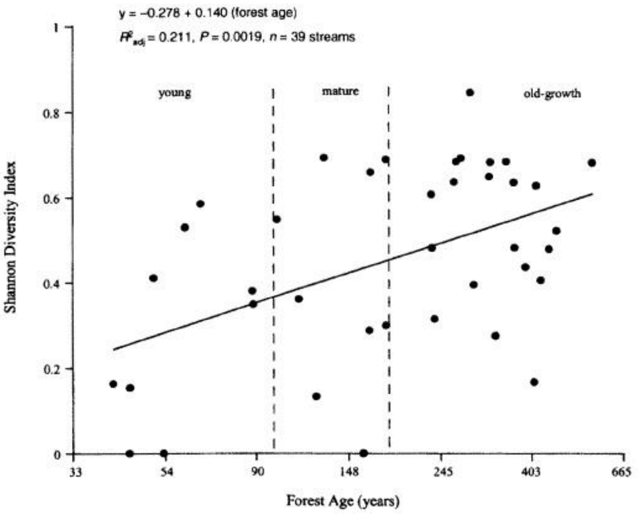


Fig. 2. Amphibian diversity (Shannon Diversity Index) of the stream amphibian assemblage relative to forest age in the Douglas-fir–hardwood forests of the Klamath–Siskiyou Region. Data and regression equation reflect natural log transformation of forest age; *X*-axis was back-transformed to show actual forest age.

- **Finding**: Five of the 7 species occurred in relatively low numbers (0.1-1.5% of total obser- vations). We found 2 California slender salamanders (Batrachoseps attenuatus), 6 black salamanders (Aneides flavipunctatus), 11 southern torrent salamanders (Rhyacotriton variegatus), 23 adult foot-hill yellow-legged frogs (Rana boylii), and 3 rough-skinned newts (Taricha granulosa). The 2 remaining species constituted 96.9% of all cap- tures. Tailed frogs (Ascaphus truei; larvae and adults, n = 487) were present in 21 of 39 streams. We found A. truei larvae in 21 streams and 50 of 117 reaches, and adult frogs in 16 streams and 38 of 117 reaches. Pacific giant salamanders (Dicamptodon tenebrosus; larvae and paedomorphs, n = 870) were present in all but a single stream, and in 109 of 117 reaches.
- **Finding**: While our approach to understanding the multiscale habitat relationships of A. truei and D. tenebrous was primarily descriptive, our analyses demonstrated that distinct distribution patterns were present and detectable and that a substantial amount of variation in incidence and density (34-69%) could be explained by habitat variables, though our predictions of absence were more accurate than our predictions of presence (Table 3)
- **Finding**: The key difference between landscape scale models for the 2 life stages of A. truei was the addition of rainfall (cm/yr) for the mostly terrestrial adult frogs. Higher annual rainfall, a good indicator of moister sites, also is a good predictor of forest that can better support adult A. truei, which require high environmental moisture to frequent terrestrial microenvironments (Claussen 1973a,b). Given that A. truei larvae are strictly aquatic, the negative association with air temperature probably reflects the close correspondence between air and stream temperature (Mitchell 1999).
- **Finding**: There is a much more compelling explanation for increases in A. truei with elevation at the landscape scale in the KS Region (and elsewhere; see Hawkins et al. 1994). This explanation lies in the pronounced physiological limitations of this unique frog species. Experiments with adult A. truei indicated that their tolerance to desiccation was lower than 17 other North American frog species tested (Claussen 1973a,b). Brown (1975, 1989) found this species to have the narrowest tolerance range (5-18.5 'C), and the lowest upper limit temperature for development (18.5 'C) of any frog in North America. Our study was conducted at the southern end of the range of A. truei (Metter 1968, Stebbins 1985). In this region, the incidence of A. truei is patchy (Bury 1968). This patchy distribution probably results from the limited capacity of this cold-adapted, moisture- dependent frog to tolerate the dry, warm conditions found throughout this portion of its range.

- **Finding**: The negative relationships between salamander numbers and density of understory hardwoods and grass cover suggest that a relatively closed overstory and lack of disturbance (where young hardwoods and grass are precluded) may be attributes of the upland environment adjacent to streams sup- porting higher densities of D. tenebrosus
- **Finding**: The positive associations between adult tailed frogs and pools, and tailed frog larvae with cobble and waterfalls, is an expression of morphological and physiological adaptations unique to each life stage. A. truei tadpoles, with rock-gripping, sucker-disk mouths, and associated feeding and breathing structures, are highly adapted to life in the fast-moving water (Gradwell 1971, Altig and Brodie 1972). Turbulence created by high water velocities over coarse substrates provides protection from predators such as D. tenebrosus (Metter 1963). Tadpoles attach readily to rock surfaces in strong currents, where potential predators have to fight currents and contend with the visual impairment of "white water" which serves to hide the larvae (Welsh 1993:80).
- **Finding**: Correlative evidence from earlier work on adult A. truei showed that they were found mostly under cobbles and boulders in slower water than tadpoles (Metter 1964, Nussbaum et al. 1983, Bury et al. 1991). We demonstrated that adult A. truei select pool habitats and cobble-sized rock cover more frequently than do other life stages, possibly as summer refuge from desiccating temperatures in terrestrial environments.
- **Finding**: The association of giant salamander larvae with narrow, shaded stream reaches dominated by pools and coarse substrates (see also Parker 1991) may be related to their foraging strategy. D. tenebrosus larvae are predominantly sit-and-wait predators (Parker 1994), and these conditions provide both cover and an abundance of ambush foraging sites.
- **Finding**: Our multivariate models suggest that for predicting A. truei presence, stream temperature is more important than aspects of forest structure; however, conditions of forest structure and microclimate are closely linked (Chen et al. 1993, 1999).

Wildfire

Cahall, Rebecca E. and John P. Hayes. 2009. Influences of postfire salvage logging on forest birds in the Eastern Cascades, Oregon, USA. Forest Ecology and Management 257: 1119-1128.

- **Study**: We compared densities and relative abundances of forest birds after fire in unsalvaged stands and stands subjected to one of two intensities of salvage logging (moderate, 30 snags retained per ha and heavy, 5–6 snags retained per ha) in mixed-conifer forests in central Oregon.
- **Ecological Considerations**: Cavity-nesting birds (Hutto, 1995; Saab and Dudley, 1998; Kotliar et al., 2002), aerial insectivores (Hutto, 1995; Caton, 1996; Kotliar et al., 2002), and ground- and shrub-foraging birds (Bock and Lynch, 1970; Caton, 1996) often increase in abundance following fire, and burned forests may be necessary for the persistence of some species of birds (Raphael and White, 1984; Raphael et al., 1987; Hutto, 1995; Murphy and Lehnhausen, 1998; Hobson and Schieck, 1999; Hoyt and Hannon, 2002).
- **Ecological Considerations**: The abundance and characteristics of snags (Everett et al., 2000; Smith, 2000), abundance of insect prey (Muona and Rutanen, 1994; Rasmussen et al., 1996; McHugh et al., 2003), and characteristics of the forest floor and herbaceous and shrub communities (Kauffman, 1990; Agee, 1993; Smith, 2000) following stand-replacing fire are important habitat elements contributing to responses of wildlife to postfire conditions.
- **Ecological Considerations**: The black-backed woodpecker is closely associated with burned forests, and abundances typically dramatically increase after fire (Blackford, 1955; Hutto, 1995; Murphy and Lehnhausen, 1998; Dixon and Saab, 2000), and as a consequence are of particular conservation concern (USDI, 2003; Oregon Natural Heritage Information Center, 2004; Montana Natural Heritage Program and Montana Fish Wildlife and Parks, 2006). Our findings of lower numbers in salvaged stands are consistent with those of other studies that have demonstrated negative effects of salvage logging on the black-backed woodpecker (Caton, 1996; Hutto and Gallo, 2006; Koivula and Schmiegelow, 2007; Saab et al., 2007), even in partially salvaged stands (Saab and Dudley, 1998; Haggard and Gaines, 2001).
- **Ecological Considerations**: Similarly, numbers of the hairy woodpecker appear to be negatively influenced by salvage logging at both intensities considered in our study, consistent with findings in other regions where near complete removal of snags occurred (Caton, 1996; Saab and Dudley, 1998; Haggard and Gaines, 2001; Hutto and Gallo, 2006; Koivula and Schmiegelow, 2007; Saab et al., 2007). Yet, findings for response of the hairy woodpecker to partial salvage logging relative to unsalvaged and complete salvage have been mixed (Saab and Dudley, 1998; Haggard and Gaines, 2001; Saab et al., 2007), suggesting that further investigation of different salvage intensities are necessary to better understand the response of the hairy woodpecker.
- **Finding**: We did not detect significant differences among treatments in densities or relative abundances for eight (of sixteen) species and one genus of birds.
- **Finding**: We detected significant differences for seven species, though the patterns differed among species.
    - Relative abundances or densities of the black-backed woodpecker (Picoides arcticus), hairy woodpecker (P. villosus), brown creeper (Certhia americana), western wood-pewee (Contopus sordidulus) and yellow-rumped warbler (Dendroica coronata) were lower in the heavy and moderate salvage treatment compared to the unsalvaged treatment

  - Densities of the dark-eyed junco (Junco hyemalis) and fox sparrow (Passerella iliaca) were greater in the moderately and heavily salvaged stands than in the unsalvaged treatment.
  - We detected significant differences between years for four species of birds.
- **Finding**: Our findings suggest that both cavity-nesting and cup-nesting species respond to salvage logging, and that some species respond uniquely to habitat features influenced by salvage logging.
- **Finding**: For species that responded negatively to salvage logging, the moderate salvage intensity did not appear to mitigate the negative influence of salvage logging.
- **Finding**: Areas of unlogged burned forest appear to provide important habitat for some species of birds following forest fires. Our findings parallel those of other recent studies of these species, suggesting robust patterns that transcend particular locations.
- **Finding**: Densities of the fox sparrow were strongly positively correlated with volume of shrubs which increased with decreasing density of snags. The fox sparrow selects brushy habitat (Austin, 1968; Weckstein et al., 2002), and densities of the fox sparrow increase as shrub density increases following fire (Bock and Lynch, 1970; Raphael et al., 1987). Changes in shrub volume in the salvaged stands may have been an underlying mechanism for observed differences in densities of the fox sparrow.

Campbell, John L., Mark E. Harmon, and Stephen R. Mitchell. 2011. Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? Frontiers in Ecology and the Environment 10.2: 83-90.

- **Background**: The amount of biomass combusted in a high-severity crown fire is unquestionably greater than the amount combusted in a low-severity surface fire. The difference, however, is smaller than that suggested by some authors (eg Hurteau et al. 2008).
  - Even under the most extreme fuel-moisture conditions, the water content of live wood frequently prohibits combustion beyond surface char; this is evident in the retention of even the smallest canopy branches after high-severity burns (Campbell et al. 2007).
  - Moreover, the consumption of fine surface fuels (ie leaf litter, fallen branches, and understory vegetation), though variable, can be high even in low-severity burns.
- **Background**: Campbell et al. (2007) found that patches of mature mixed-conifer forest in southwestern Oregon that were subject to low-severity fire (ie 0–10% overstory mortality) released 70% as much C per unit area as did locations experiencing high-severity fire (ie > 80% overstory mortality).
  - When scaled over an entire wildfire perimeter, the importance of high-severity fire in driving pyrogenic emissions is further diminished because crown fires are generally patchy while surface fires are nearly ubiquitous (Meigs et al. 2009).
- **Background**: A study conducted by North et al. (2007) in the Sierra Nevada found that net losses in large-diameter trees between 1865 and 2007 were more than compensated for by the infilling of small-diameter trees, such that total live-wood volume remained unchanged over this period of fire suppression.
- **Finding**: Over multiple fire cycles, forests that burn less often store more C than forests that burn more often
- **Finding**: According to Campbell et al. (2007), less than 20% of the estimated 3.8 teragrams of C released to the atmosphere by the 2002 Biscuit Fire in the Siskiyou National Forest of southern Oregon and northern California (Figure 1) arose from overstory combustion.

  - Simply put, because most pyrogenic emissions arise from the combustion of surface fuels, and most of the area within a typical wildfire experiences surface-fuel combustion, efforts to minimize overstory fire mortality and subsequent necromass decay are limited in their ability to reduce fire-wide pyrogenic emissions.
- **Finding**: It is reasonable to expect that in the first decade or two after a forest-replacing fire, the decomposition of firekilled trees may exceed the net primary production (NPP) of re-establishing vegetation, thus driving net ecosystem production (NEP) below zero.
- **Finding**: Empirical evidence shows that most pyrogenic C emissions arise from the combustion of surface fuels, and because surface fuel is combusted in almost all fire types, high-severity wildfires burn only 30% more biomass than do the low-severity fires that fuel treatment is intended to promote (Figure 1).
- **Finding**: Long-term simulations of forest growth, decomposition, and combustion illustrate how, despite a negative feedback between fire frequency and fuel-driven severity, a regime of low-frequency, high-severity fire stores more C over time than a regime of high-frequency, low-severity fire (Figure 5).

DellaSala, Dominick A. 2016 White Paper. Do mountain pine beetle outbreaks increase the risk of high-severity fires in Western forests: a summary of recent field studies. Geos Institute.

- **Finding**: There is now substantial field-based evidence showing that beetle outbreaks do not contribute to severe fires nor do outbreak areas burn more severely when a fire does occur.
- **Finding**: As mountain pine beetle outbreaks increased across the western United States, fires did not track outbreaks and where fires did occur they were by and large were not in the areas affected by mountain pine beetle (fig2).
- **Finding**: In mixed-evergreen forests below 5,000 feet in the San Bernardino Mountains of California, pre-fire tree mortality from drought and western pine beetles did not influence subsequent fire severity in stands where most pre-fire dead trees had retained needles6.
- **Finding**: Empirical studies of forest fuel levels immediately following outbreaks and retrospective studies of fires that burned in lodgepole pine and spruce-fir forests throughout the U.S. Rockies that were recently affected by outbreaks suggest that outbreaks may actually decrease risk of high-severity fires. This is the case even during and immediately following outbreaks. There is general agreement that the risk of active high-severity crown fires actually decreases in years to decades following outbreaks due to reduced forest canopy density (i.e., more dead trees means forest canopies are less dense).
- **Finding**: In upper Douglas-fir forests of Wyoming, pre-fire outbreak severity did not increase fire severity when fires occurred4. In another study, also in Douglas-fir forests of Greater Yellowstone, beetle outbreaks killed 38-83% of the basal area within forest stands resulting in a reduction in canopy fuel loads and bulk crown density during the red stage that continued into the silver stage5. These studies demonstrate that following beetle outbreaks there is actually a reduction in the likelihood of subsequent crown fires for decades given reduced forest crown densities and fuels.
- **Finding**: Research conducted on beetle outbreaks has consistently shown that fire-weather and climate are more important factors than effects of outbreaks in determining fire behavior in western forests1-5.
- **Background**: In sum, the observed effect of beetle outbreaks on severe fires appears to be negligible. This is true for “red-stage stands” (needles fade to red within a year of tree death) to “gray-stage stands” (needles have fallen off and are no longer present within 2-3 years of tree death) during peak years of wildfire activity based on multiple studies1-7.

Fontaine, J.B., Donato, D.C., Robinson, W.D., Law, B.E. and J.B. Kauffman. 2009. Bird communities following high-severity fire: response to single and repeat fires in a mixed-evergreen forest, Oregon, USA. Forest Ecology and Management 257: 1496-1504.

- **Background**: Over time, the frequency and intensity of repeated fires may act to retain or exclude particular species and regulate forest structure and seral stage (Agee, 1993; Pyne et al., 1996).
- **Background**: Recent increases in the frequency and extent of large wildfires in western North America (Westerling et al., 2006) raises the probability of recurrent (short-interval) high-severity fires via greater probability of fire overlap.
- **Background**: Many species of <u>birds</u> are adapted to, or dependent upon, disturbances such as fire or insect outbreaks in all or portions of their distribution (MacArthur, 1958; Brennan et al., 1998; Saab and Powell, 2005).
- **Background**: Fire heavily influences vertical and horizontal heterogeneity of vegetation; characteristics well known to structure avian communities in terms of abundance and species richness (MacArthur and MacArthur, 1961; Holmes et al., 1979).
- **Background**: Research has largely been focused on short-term (<5 years) responses of birds to single high-severity fire events in boreal (Morissette et al., 2002) and mixed conifer forests (Smucker et al., 2005) and single prescribed fires in pine-dominated forests (Bock and Block, 2005; Engstrom et al., 2005; Hurteau et al., 2008). Studies of repeated fire and fire interval on birds are limited to repeated prescribed surface fire in longleaf pine forests (Provencher et al., 2002; Whiting et al., 2007) and grasslands (Reinking, 2005).
    - Thus avian response to short-interval high-severity fires in forested ecosystems remains poorly studied. This is key information for forest managers tasked with conserving disturbance-dependent bird species as well as landscape-scale avian biodiversity.
- **Background**: The mixed severity fire regime—found in the Klamath-Siskiyou region—is among the most complex and least understood of ecological disturbance regimes; the combination of surface and stand-replacement fire over varying spatial and temporal scales results in a complex mosaic of plant communities and successional stages on the landscape (Agee, 1993). In stand-replacement patches, rapid vegetation recovery and resulting fuel continuity create the potential for recurrent high-severity fires over short (decadal, <50 years) time scales (Thompson et al., 2007).
- **Background**: A related study (Donato et al., 2009) found that nearly all plant species found in mature/old-growth stands were present at similar relative abundance in both long-interval and short-interval burns, indicating high community persistence through multiple high-severity fires. The short interval burn had the highest species richness and total plant cover with additions of disturbance-associated forbs and low shrubs, likely due to a propagule bank of early seral species that developed between fires.
- **Background**: In a separate study of avian response to salvage logging of the Biscuit Fire, Fontaine (2007) found non-significant responses of most species to salvage logging and, most importantly, very little change in overall community composition (see also Section 2). The few published studies examining the effects of postfire salvage logging from the western United States, where logging prescriptions are similar, have shown some negative responses of cavity-nesting species (e.g. Saab et al., 2007) but no extirpations of the species detected in this study or broad changes in community composition (Hutto and Gallo, 2006; Cahall and Hayes, 2009).

- **Background**: Schieck and Song (2006) reviewed bird community succession in boreal forests, noting that logged and burned communities within the same forest type converged once snags fell and communities became dominated by shrub-associated birds after ~25 years.
- Finding: Avian species richness did not differ significantly among habitats. Bird density was highest 17 and 18 years after fire, lowest 2 years after fire, and intermediate in repeat burns and unburned forest. Bird community composition varied significantly with habitat type (A = 0.24, P < 0.0001) with two distinct gradients in species composition relating to tree structure (live to dead) and shrub stature. Using indicator species analysis, repeat burns were characterized by shrub-nesting and ground-foraging bird species while unburned mature forests were characterized by conifer-nesting and foliage-gleaning species.
- Finding: Contrary to expectations, repeated high-severity fire did not reduce species richness, and bird densities were greater in repeat burns than in once-burned habitats. Broad-leaved hardwoods and shrubs appear to play a major role in structuring avian communities in the Klamath-Siskiyou region.
- Finding: Vegetation: The short-term effect of high-severity fire was to transition mature forest from high basal area of live conifers to a high basal area in sound snags (Fig. 2a). The older burn was characterized by low amounts of tree basal area, most of which was composed of regenerating conifers and hardwoods (Fig. 2a). The repeat burn also had low tree basal area but was composed largely of snags (Fig. 2a). Post fire shrub growth (canopy volume accumulation) was significantly greater in repeat burn stands at 7200m3 ha—1 by 3 years post fire, than in recent once burned stands (3027m3 ha—1) (Fig. 2b). Additional effects of the Biscuit Fire included a reduction in litter cover and an increase in bare ground (Table B1); repeat burn stands had higher forb cover than any other treatment type (Table B1). Dominant hardwoods and shrubs such as tanoak, madrone, snowbrush, and chinquapin (see Table B1 for scientific names) were present in all treatments while repeat burn stands had reduced amounts of Sadler oak and old burn stands had the highest cover of madrone (Table B1).
- Finding: Estimates of avian species richness per point count had overlapping confidence intervals for all treatments and years, showing no statistical difference (Fig. 3a).
- Finding: In contrast to species richness, avian density was significantly different among treatments based on lack of confidence interval overlap (Fig. 3b); recent burn stands had the lowest densities of birds in both years while mature forest and old burn stands had higher bird density. Avian density in repeat burn stands was intermediate between recent burn and old burn, and showed a significant increase in density from 2004 to 2005 (2 and 3 years after fire), paralleling the increase in shrub volume over the same period (Fig. 2b).
- Finding: Mature forest and repeat burn treatments had the largest numbers of species with indicator values >40, reflecting their more unique species composition. Single burn treatments (recent and old) had smaller numbers of indicator species (Table 2). Several rare species with significant associations but low indicator values were identified (e.g. green-tailed towhee, golden-crowned kinglet, winter wren; see Appendix C for scientific names and relative frequency of each species within treatments) while species with high indicator values reflected both abundance and restricted occurrence in one treatment (e.g. lazuli bunting, hermit warbler, hairy woodpecker, Table 2).
- Finding: In both years, the basal area of snags was a poor predictor of avian density with correlation coefficients of —0.26 and —0.25 in 2004 and 2005, respectively, and slope estimates not different from zero (2005 values: slope = —0.01, SE = 0.01, t =

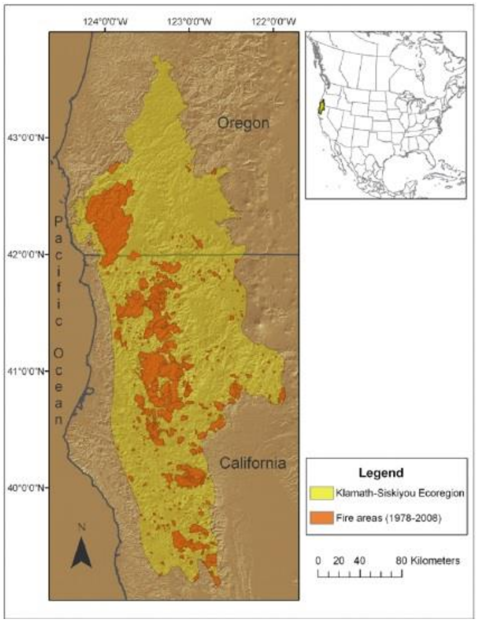
————————————1.3, P = 0.22). In contrast, shrub height was positively correlated with avian density with correlation coefficients of 0.67 and 0.75 in 2004 and 2005, respectively, and positive slope estimates significantly different from zero (2005 values: slope = 2.76, SE = 0.50, t = 5.5, P < 0.0001).

- **Finding**: Bird community composition shortly after high-severity fire in our study was similar to those reported from other forest types (Bock and Lynch, 1970; Morissette et al., 2002; Smucker et al., 2005; Kotliar et al., 2007). Species associated with dead wood (hairy woodpecker), bare ground (dark-eyed junco) and aerial foraging (Townsend's solitaire) were prevalent whereas fire obligate species typical of stand-replacement fire regime forests such as black-backed (Picoides arcticus) and American three-toed woodpeckers (P. dorsalis) did not occur in our study area (Hutto, 1995; Koivula and Schmiegelow, 2007). The observation of decreased avian densities is consistent with the decrease in vegetation complexity following high-severity fire.
- **Finding**: Longer-term (17 and 18 years) response of birds was consistent with Raphael et al. (1987) who characterized bird communities following high-severity fire in the Sierra Nevada of California. Important structural elements in older post-fire stands are dense broad-leaved shrubs and scattered snags in advanced stages of decay. Shrub-associated species such as wrentit and weak excavators such as acorn woodpecker were prevalent in old burn stands we studied.
    - Old burn stands also possessed the highest estimate of species richness and bird densities similar to unburned forest despite possessing much simpler vegetation complexity. This likely results from the intermediate nature of these stands possessing some bird species characteristic of both recent burns (dark-eyed junco, hairy woodpecker) and mature forest (Swainson's thrush, hermit warbler).
- **Finding**: Similar to the review of boreal bird and fire studies by Schieck and Song (2006), our ordination results placed old fire patches between mature forest and recent burns. This suggests that, as expected, avian community succession is following a trajectory of recovery from recent burn to old burn to mature forest. In particular, our results suggest that bird densities are strongly related to the rate of vegetation recovery following fire.
- **Finding**: The effect of a repeat burn on bird communities was not to simply 'reset' the successional clock; rather, it resulted in a species assemblage (defined in terms of composition and abundance) unique from both recent and old burns. This result likely stemmed from legacy effects of the initial fire disturbance, which created an early seral plant community characterized by snags and regenerating shrubs and hardwoods. Propagule banks for both seeding and sprouting early seral vegetation were likely larger prior to the second fire, leading in part to the rapid recovery of shrubs and hardwoods following the repeat burn (Donato et al., 2009).
- **Finding**: Ordination results were consistent with the expectation that, over time, twice burned and once-burned avian communities may converge. Convergence of bird community composition could occur after once-burned stands possess a more developed shrub component, small snags fall resulting in more open stands, and large snags advance in decay stage, losing their bark and fine branches.
- **Finding**: In our study, shrub stature was an important predictor of both avian abundance and composition while snag abundance was associated with compositional differences but not abundance.
- **Finding**: See table 2 for indicator species value of different bird species for each habitat type: mature forest, recent burn, old burn, and repeat burn (i.e., see which bird species associate with each of these habitats).

Halofsky et al. 2011. Mixed-severity fire regimes: lessons and hypotheses from the Klamath-Siskiyou Ecoregion. Ecosphere 2(4): 1-19.

- **Background**: Although mixed-severity fires are among the most widespread disturbances influencing western North American forests, they remain the least understood.
- **Background**: The Klamath-Siskiyou Mountains of southwestern Oregon and northwestern California provide an excellent laboratory for studies of mixed-severity fire effects, as structurally diverse vegetation types in the region foster, and partly arise from, fires of variable severity. In addition, many mixed-severity fires have occurred in the region in the last several decades, including the nationally significant 200,000-ha Biscuit Fire.
- **Background**: Typically defined as mortality of dominant vegetation (e.g., overstory trees), severity ranges from low, or non-lethal surface fires, to high, or stand-replacing crown fires (Agee 1993, Keeley 2009).
- **Background**: Mixed-severity (M-S) fire regimes have been described for portions of several major forest types, including coastal Douglas-fir (Pseudotsuga menziesii) (Morrison and Swanson 1990), interior mixed-conifer (Arno et al. 2000, Fule´ et al. 2003, Schoennagel et al. 2004, Hessburg et al. 2007), and ponderosa pine (Pinus ponderosa) (Shinneman and Baker 2003). M-S fire regimes are generally recognized as the most complex and least understood fire regimes in North America because of the varied importance of climate and fuels as drivers and the complex burn patterns that result (e.g., Schoennagel et al. 2004, Agee 2005, Lentile et al. 2005).
- **Background**: The concept of M-S fire is scale-dependent and is typically defined at meso-scales (e.g., forest stand or loworder watershed), because at the finest scales (e.g., individual tree), fire effects such as mortality are binary, while at a coarser scale (e.g., large or multiple watersheds), nearly all fires exhibit some degree of mixed fire effects (Turner and Romme 1994, Baker et al. 2007).
- **Background**: The Klamath-Siskiyou Mountains of southwestern Oregon and northwestern California (Fig. 1) provide an excellent laboratory for studies of M-S fire effects. Fires in the area are variable in frequency and severity, both spatially and temporally (Agee 1993, Taylor and Skinner 1998). Situated at the convergence of major North American floristic zones (Whittaker 1960), the region is characterized by an exceptionally diverse flora, with strong components of broadleaf hardwood, coniferous, and herbaceous vegetation. Mosaics of these structurally diverse vegetation types foster and may, in part, arise from repeated exposure to variable fire frequency and severity (Agee 1991, 1993).
- **Background**: Fire behavior and resulting severity is a product of interactions between weather, fuels, and topography (Agee 1993). Interactions between, and varying strength of, these three drivers of fire severity in the Klamath-Siskiyou region result in system behavior that is difficult to predict;
- **Background**: For the Klamath-Siskiyou region, the Biscuit Fire appears to have been unusually severe, as estimates of crown damage greatly exceed estimates from historical fires within the region (e.g., Weatherspoon and Skinner 1995, Odion et al. 2004, Alexander et al. 2006). The high severity of the Biscuit Fire was likely due in part to the dominance of weather as a driver; an earlier fire in the same area, the Silver Fire, burned under cooler conditions and resulted in generally lower fire severity (Thompson et al. 2007, Thompson and Spies 2010; Fig. 2). This importance of weather as a dominant driver of M-S fire is consistent with studies in other M-S fire regions (Bradstock et al. 2010; Schoennagel et al. in press).

- **Background**: Smucker et al. (2005) and Kotliar et al. (2007) both found intriguing wildlife dynamics such as hump-shaped patterns of response to varying fire severity following M-S fires in forests of western Montana and New Mexico, respectively. This higher abundance in moderate/mixed severity conditions suggests a suite of species responds most positively to increased edge and heterogeneity in fire effects. Examples reported such as dark-eyed junco (Junco hyemalis) and western tanager (Piranga rubra) also showed high abundances in the Biscuit Fire (Fontaine et al. 2009). Similarity in species responses to fire across regions, some of which have very different vegetation composition and understory structure (Kennedy and Fontaine 2009), further suggests that burn mosaic structure may be a dominant driver of wildlife response across M-S fire regions.
- **Background**: Examining the effects of longer fire intervals, Odion et al. (2004) concluded that severity of the 1987 fires in the Klamath-Siskiyou region was lower in closed forests where fire had been absent since 1920 compared to areas burned more recently. Odion et al. (2004) suggest that as combustible understory fuels (i.e., shrubs and evergreen hardwoods) decrease with succession due to shading and as height to live crown increases in the absence of fire in this region, the likelihood of a fire transitioning to the canopy decreases. Thus, following a stand-replacing fire, there may be a temporal threshold in the likelihood of additional stand-replacing fires, with positive feedbacks (i.e., high-severity fire followed by high-severity fire) over short timescales (,30 years) owing to the rapid growth and dominance of evergreen hardwoods and shrubs, and negative feedbacks (i.e., high-severity fire followed by low-severity fire) over longer timescales (.75 years) owing to the development of higher crown base heights and less continuous understory fuels. The nature and timing of such a threshold would have important implications for long-term landscape structure (see Odion et al. 2010) and is an important direction for further research on M-S regimes.



- **Finding**: Our studies in the Klamath-Siskiyou Ecoregion suggest that forests with mixed-severity fire regimes are characterized primarily by their intimately mixed patches of vegetation of varied age, resulting from complex variations in both fire frequency and severity and species responses to this variation.
- **Finding**: Based on our findings, we hypothesize that the proximity of living and dead forest after mixed-severity fire, and the close mingling of early- and late-seral communities, results in unique vegetation and wildlife responses compared to predominantly low- or high-severity fires.
    - These factors also appear to contribute to high resilience of plant and wildlife species to mixed-severity fire in the Klamath-Siskiyou Ecoregion. More informed management of ecosystems with mixed-severity regimes requires understanding of their wide variability in space and time, and the particular ecological responses that this variability elicits.
- **Finding**: high moisture conditions and associated vegetation/fuel conditions in riparian areas influenced fire behavior and effects; canopy and soil damage (but not tree mortality) were lower in riparian areas compared to uplands in the Biscuit Fire, particularly along larger streams (Halofsky and Hibbs 2008; T. Spies, unpublished manuscript).

- **Finding**: Evergreen hardwoods, an important structural and compositional component in forests in the region, experienced relatively high levels of burn damage in the subcanopies below conifers. However, there was no evidence that hardwood presence increased fire severity
- **Finding**: Somewhat surprisingly, low-productivity, sparsely treed sites on ultramafic soils experienced the highest rates of conifer crown damage (Thompson and Spies 2009). However, these sites were found to have high shrub cover, and there was a positive relationship between shrub cover and crown damage in the Biscuit Fire (Thompson and Spies 2009).
- **Finding**: Few places within the Biscuit Fire perimeter were entirely unburned; 98% of the area was affected by surface fire (Campbell et al. 2007, Thompson and Spies 2009).
- **Finding**: Across the entire fire, approximately half the conifer crowns remained intact, and there were few areas greater than several hectares that did not contain a mixture of both live and dead trees (Thompson and Spies 2009). This pattern was also found in other fires in the Klamath-Siskiyou region over the last 20 years (Shatford et al. 2007).
- **Finding**: Topography in the Klamath-Siskiyou region generally results in drier and more flammable fuels on southwesterly aspects and in upper topographic positions, which generally leads to higher fire severity (Weatherspoon and Skinner 1995, Taylor and Skinner 1998, Alexander et al. 2006).
- **Finding**: Surprisingly, however, severity patterns in the Biscuit Fire were not strongly associated with topography (slope, aspect, elevation), with weather and vegetation instead being the main drivers (Thompson and Spies 2009)—a finding similar to conclusions from the 1988 Yellowstone Fires.
    - It is possible that dry winds out of the northeast and a maritime climate influence on west facing slopes confounded any positive relationship between southwest aspects and fire severity in the Biscuit Fire (Thompson and Spies 2009).
    - Relationships between burn patterns and topography could thus vary by region and should be explored in future fires in the Klamath-Siskiyou and other regions with M-S fire regimes.
- **Finding**: Supporting evidence included profound changes in soil properties in some stands subject to high-severity fire, where combustion temperatures over 6608C and convective erosion in the fire's plume apparently contributed to losses of about 2.5 cm of fine mineral soil and one-third of soil nitrogen (N) and half of soil carbon (C) (Bormann et al. 2008). Stands with partial or no fire mortality had lower C and N losses from mineral soil.
- **Finding**: The resulting contrast in soil productivity between low- and high-severity patches suggests the potential for long-term legacies of burn severity patterns. Such legacies of M-S fire could be one factor underlying the well-known variation in vegetation productivity, structure, and composition of the Klamath-Siskiyou region (e.g., conifer forest and broadleaf vegetation such as sclerophyllous shrubs).
    - At our current state of knowledge, however, the long-term consequences of these soil changes remain unclear, and it is possible that N-fixing shrubs (e.g., Ceanothus)— which are often abundant in this region following severe fire (Shatford et al. 2007, Fontaine et al. 2009)—could help offset losses in some areas.
- **Finding**: Other geochemical dynamics varied surprisingly little across the mixed-severity mosaic of the Biscuit Fire, such as overall C emissions. Compared to the patchy nature of canopy combustion, the combustion of surface fuels (e.g., litter, duff, and fine woody debris) was relatively uniform and near complete across the entirety of the Biscuit (Campbell et al. 2007). This, combined with the fact that dead surface fuels have higher combustion efficiencies than do standing live components, meant that nearly 60% of the estimated 3.8 Tg C released to the

atmosphere during the Biscuit arose from surface fuels (Campbell et al. 2007). This analysis of fuel consumption across a large MS fire reveals that the majority of pyrogenic emissions are not strongly related to canopy mortality.

- **Finding**: Vegetation responses to M-S fire regimes are as complex as the burn patterns themselves. Spatial variation in fire severity has a vegetation legacy effect and perhaps a soil fertility effect.
    - These fire effects coupled with variation in regeneration strategies by different plant groups—conifers by seed dispersal, broad-leaved trees primarily by sprouting, shrubs by both sprouting and seed banking—results in a diverse post-fire vegetation mosaic.
- **Finding**: As a result of these edge effects, small-to-medium burn patches and edges of large patches contained conifer seedlings and sprouting hardwoods, while interiors of large patches (.400 m from edge) were characterized by hardwood regeneration with delayed or no conifer establishment four years post-fire (Donato et al. 2009a). Burn patch size thus had a threshold effect on regeneration composition, resulting in potentially different successional pathways in the interior versus perimeter of larger patches.
- **Finding**: Conifer- and hardwood-dominated riparian plant communities, each found in specific topographic settings, were self-replacing. In both riparian and upland sites, abundant regeneration and the self-replacement of pre-fire vegetation communities after the Biscuit Fire suggest high species and community resilience after M-S fire.
- **Finding**: Working in several post-fire landscapes (n = 11 fires) throughout the Klamath-Siskiyou region, Shatford et al. (2007) found that conifer regeneration continued over a two-decade period across highly variable ecological settings. Shrub and sprouting hardwood communities were also abundant and diverse, forming a dominant to co-dominant canopy with conifers during early successional stages across a range of sites. Aspect, precipitation and elevation were found to be important predictors of all vegetation recovery processes (Lopez Ortiz 2007, Shatford et al. 2007). Only on very dry sites was conifer regeneration scarce or lacking, suggesting that early-colonizing shrubs and hardwoods are more likely to maintain long-term dominance in these locations.
- **Finding**: The interaction between patch-size and seed source dynamics was remarkably similar between small M-S fires and the exceptionally large Biscuit Fire; most high-severity burn area was ,400 m from edge, and conifer regeneration was generally abundant within this distance (Shatford et al. 2007, Donato et al. 2009a).
- **Finding**: M-S fire regimes appear to play a role in maintaining a significant hardwood presence in the Klamath-Siskiyou region. All of the hardwoods basal-sprout vigorously after fire; all except tanoak (Lithocarpus densiflorus) are at least moderately shade intolerant; and all have a mature height much shorter than the associated conifers. In coniferous forest, hardwoods form a shrub and mid-layer canopy (Franklin and Dyrness 1973, Agee 1993) that provides structural diversity and habitat for a large suite of wildlife species (Hagar 2007). Short intervals (less than 30 years) between fires maintain an open canopy in places, providing the ecological space for these species to persist (Agee 1993, Odion et al. 2010).
- **Finding**: We found that early post-fire hardwood cover is moderate to high (Shatford et al. 2007, Donato et al. 2009a, Fontaine et al. 2009), providing important habitat for open-cup nesting birds (Betts et al. 2010; M. Donaghy Cannon, unpublished manuscript) and contributing to soil function and mycorrhizal networks (Borchers and Perry 1990).
- **Finding**: In mesic forest types such as the Klamath-Siskiyou and western Cascade Mountains, conifer regeneration densities are often high in areas burned with low- to moderate severity and several hundred meters into high-severity patches (Shatford et al. 2007, Chappell and Agee

1996, Donato et al. 2009a), while in drier forest types such as ponderosa pine, regeneration can be mostly absent from high-severity patches except near edges (Bonnet et al. 2005, Lentile et al. 2005, but see Haire and McGarigal 2010).

- **Finding**: Thus, the longterm importance of burn patch structure may vary along a spectrum of forest types, from dry interior pine forests in which burn mosaics may persist strongly (with purported state changes in patch interiors), to moist forest types in which burn mosaics may have an important but more ephemeral effect on gross vegetation composition.
    - The Klamath-Siskiyou region would appear to lie near the middle of the moisture-regeneration continuum among forests affected by M-S fire.
- **Finding**: Data from the Klamath-Siskiyou region suggest that the vegetation mosaic and broadleaf abundance associated with the M-S regime are important drivers of wildlife response to fire (Fontaine et al. 2009, Meehan and George 2003, Betts et al. 2010; Clark et al. in press). Avian community composition and abundance within high-severity portions of the Biscuit Fire were remarkably resilient relative to unburned, late-successional reference forests outside the fire (Fontaine et al. 2009). While avian communities in unburned and burned patches were distinct in composition, species richness was not reduced by high-severity fire and density was reduced by ;50%, likely a consequence of the fine-grained burn mosaic and regenerating broad-leaved vegetation (Betts et al. 2010, Fontaine et al. 2009). Following disturbance, many broadleaved species resprout and may rapidly grow (.2 m in height 4 yrs post-fire, J. Fontaine, unpublished data), providing foraging and nesting substrates for a range of species. This effect may persist for two decades or longer following fire (Fontaine et al. 2009).
    - Species such as lazuli bunting (Passerina amoena), Nashville warbler (Vermivora ruficapilla), and black-headed grosbeak (Pheucticus melanocephalus) heavily utilize this regenerating vegetation (Betts et al. 2010, Fontaine et al. 2009).
- **Finding**: Certain species thought of as late-successional forest specialists may also use recently burned areas, a response likely associated with the presence of a complex burn mosaic. For example, interspersion of low- and high-severity patches allowed for the persistence of birds that nest and forage in canopy foliage (e.g., hermit warbler (Dendroica occidentalis) M. Donaghy Cannon, unpublished data). Amount of edge habitat was positively associated with olive-sided flycatcher (Contopus cooperi) prevalence post-fire (Meehan and George 2003).
- **Finding**: Over long time scales it is evident that fire maintains the broad-leaved vegetation and landscape heterogeneity on which many bird species depend (Betts et al. 2010, Franklin et al. 2000, Schlossberg and King 2008). However, in the short-term further research is required to test questions addressing the relative importance of the post-fire mosaic (coarse-scale) and vegetation regeneration patterns (fine-scale) for determining post-fire wildlife abundance across a range of fire severities (see Kotliar et al. 2007, 2008).
- **Finding**: Recent evidence from the Klamath-Siskiyou region suggests that the interval between fires, and thus successional stage when burned, is a key determinant of how strongly sequential fires interact. Where the Biscuit Fire burned over the 15-year-old M-S Silver Fire, fire severity was strongly influenced by the severity mosaic of the earlier fire, after accounting for other biotic and abiotic factors. Low-severity patches were more likely to reburn with low severity, and highseverity patches reburned with high severity (Thompson et al. 2007, Thompson and Spies 2010; Fig. 2). Thus, sequential disturbances separated by 15 years exhibited a positive feedback, reinforcing the spatial pattern on the landscape.
- **Finding**: The shrub and hardwood dominated vegetation that establishes after fire in this region is highly combustible and can maintain dominance for up to approximately 30 years without fire (Odion et al. 2010).

- **Finding**: Surprisingly, two sequential fires led not to a depleted forest community, but rather to an increase in plant species richness, with little evidence of species extirpation (Donato et al. 2009b). Increases in species richness were largely due to increases in fire-ephemeral species (e.g., Epilobium spp.).
- **Finding**: Wildlife showed similar responses to recurrent M-S fires. Compared to once-burned areas, bird species richness and density in twice-burned areas were higher and dominated by shruband hardwood-nesting species (Fontaine et al. 2009). Shrub- and hardwood-nesting and disturbance- adapted bird species (e.g., lazuli bunting (Passerina amoena)) were strong indicators of twice-burned habitats. Small mammal species richness and community structure in twiceburned areas were similar to once-burned areas but with significantly higher densities (Fontaine 2007).
- **Finding**: Observations in the Klamath-Siskiyou region suggest that variation in dominant drivers of fire behavior (fuels, topography, and weather) leads to varied burn patterns both within and among M-S fires. The range in fire effects—fire severity, patch size, and legacy generation—appears to be a major driver of ecosystem dynamics in these systems, as we have described here.
- **Finding**: The edge-to-interior ratio of burn patches is typically much higher in M-S fires than in low- and high-severity fires (Agee 2005); i.e., edge abundance is non-linearly related to severity regime. The M-S fire is therefore characterized by the mixing at relatively fine scales (tens to a few hundreds of meters) of patches of vegetation burned to varied levels of severity. Similarly, the irregularity of the fire return interval leads to highly variable patch age.
- **Finding**: our studies in the Klamath-Siskiyou region suggest that, taken together, the suite of M-S fire characteristics may give rise to unique ecological dynamics in M-S regimes (Table 1). We observed that varied fire effects result in (and result from) fine-scale variation in patch age and composition, which provides habitat for a variety of species in relatively close proximity.
- **Finding**: A consistent finding among the diverse ecosystem responses summarized here is the high resilience of plant and wildlife species composition in Klamath-Siskiyou forests to M-S fire. Although the 2002 Biscuit Fire made national headlines and was considered to be outside characteristic ranges in terms of size and severity, several studies of this and nearby fires showed rapid and sustained response of both flora and fauna, even in areas that had burned twice with high-severity within a 15-year period.

Myer, G. 2013. The Rogue Basin Action Plan for Resilient Watersheds and Forests in a Changing Climate. Thaler, T., Griffith, G., Perry, A., Crossett, T., Rasker, R. (Eds). Model Forest Policy Program in association with the Southern Oregon Forest Restoration Collaborative, the Cumberland River Compact and Headwaters Economics; Sagle, ID. December, 2013.

- **Background**: Fire suppression, widespread even-aged stand management, land use, and other stressors have dramatically reduced and degraded critical wildlife habitat and generated dense overcrowded stands, leading to tree stress and low vigor, and placing the oldest most structurally important trees at risk of uncharacteristic wildfire. Younger stands are threatened by density driven wildfire risk, and moisture competition; without active management their development into mature stands dominated by large trees is slowed. Forest diversity, a hallmark of the region, has been reduced at both the landscape and stand scale.

Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T. and P.B. Moyle. 2006. Managing fire-prone forests in the western United States. Frontiers in Ecology and Environment 4(9): 481-487.

- **Background**: The management of fire-prone forests is one of the most controversial natural resource issues in the US today, particularly in the west of the country. Although vegetation and wildlife in these forests are adapted to fire, the historical range of fire frequency and severity was huge. When fire regimes are altered by human activity, major effects on biodiversity and ecosystem function are unavoidable.
- **Background**: Increased human habitation of wildlands has intensified problems of managing fire, especially at the wildland- urban interface (Dombeck et al. 2004).
- **Background**: Fire provides fundamental services, including recycling nutrients, regulating the density and composition of young trees, creating and shaping wildlife and fish habitat, structuring the spatial pattern of landscapes, and influencing water and sediment delivery across watersheds. Many plant and animal species are adapted to postfire conditions, and populations of some (eg many bird species; Figure 1) decline after fire exclusion or post-fire logging (Hutto 1995). Different species benefit from different fire severities and intervals between fires.
- **Background**: Fires recur in western forests from once a decade or less in some dry ponderosa pine (Pinus ponderosa) forests to a cycle of 250-400 years or more in coastal forests (Hemstrom and Franklin 1982; Covington et al. 1997; Agee 1998).
- **Background**: High severity fires kill most or all trees in substantial portions of the burn, although fire pattern is often a mosaic that includes areas of unburned or less severely burned forest (Figure 2).
- **Background**: Many large, high severity fires are associated with infrequent, severe droughts (Westerling et al 2003), often related to broad-scale climatic anomalies (Gedalof et al 2005). Fire exclusion has had minimal effect on most forests characterized by high severity fire - a fact that is especially relevant to fire policy.
- **Background**: Human activities in western forests following European settlement - including fire exclusion, grazing, logging, and tree planting - dramatically modified the fuel structure in these forests.
    - Grazing reduced the fine fuels that carry surface fires and facilitated dense tree reproduction by reducing or eliminating herbaceous competition (Rummell 1951; Savage and Swetnam 1990; Belsky and Blumenthal 1997).
    - Logging also promoted higher stand densities in many dry ponderosa pine forests by stimulating dense natural regeneration (Agee 1993; Kaufmann et al. 2000).
    - These forests therefore changed from relatively open stands with low fuel loadings to dense stands that can carry crown fires (Skinner 1995).
- **Background**: Topographically complex mountain landscapes may be especially prone to mixed severity fire, because drier, south-facing slopes with lower fuel loads may burn at low severity while adjacent, moister, northfacing slopes that support higher tree densities experience high severity fire (Taylor and Skinner 2003; Spies et al. 2006) or escape fire due to wetter conditions.
- **Background**: Overall species diversity, measured as number of species - at least of higher plants and vertebrates - is often highest following a natural stand replacement disturbance and before redevelopment of closed-canopy forest (Lindenmayer and Franklin 2002).
- **Finding**: Fire exclusion led to major deviations from historical variability in many dry, low-elevation forests, but not in other forests, such as those characterized by high severity fires recurring at intervals longer than the period of active fire exclusion.
- **Finding**: The complexity created by variability in fire regimes defies a one-size-fits-all management prescription

- **Finding**: Restoration is warranted where fire exclusion has led to substantial alterations in ecosystem qualities
- **Finding**: Restoration and management of fire-prone forests should be precautionary, allow or mimic natural fire regimes as much as possible, and generally avoid intensive practices such as post-fire logging and planting.
- **Finding**: Post-fire logging usually has no ecological benefits and many negative impacts; the same is often true for post-fire seeding.
- **Finding**: The inherent variability of mixed-severity fire regimes precludes easy analysis of fire-exclusion effects, because high tree density or an abundance of shade-tolerant trees is not necessarily the result of fire exclusion. The complexity created by variability in fire regimes defies a simple, one-size-fits-all prescription for restoration.
- **Finding**: See Table 1: Fire regimes of major western forests and some examples of plant association groups in each type

Odion, D.C., Frost, E.J., Strittholt, J.R., Jiang, H., DellaSala, D. and M.A. Moritz. 2004. Patterns of fire severity and forest conditions in the western Klamath Mountains, California. Conservation Biology 18: 927-936.

- **Background**: The Klamath-Siskiyou region of northwestern California and southwestern Oregon supports globally outstanding temperate biodiversity. Fire has been important in the evolutionary history that shaped this diversity, but recent human influences have altered the fire environment.
- **Background**: A complex, mixed-severity fire regime has shaped the composition and structure of Klamath-Siskiyou vegetation. Because of steep climatic, edaphic gradients, and rugged topography, fire frequencies and severities have been highly variable (Agee 1993; Taylor & Skinner 1998, 2003).
    - Such spatial and temporal variation in disturbance is believed fundamental to promoting species diversity because non-equilibrium processes enhance habitat heterogeneity (Connell 1978; Huston 1979).
    - Biodiversity is likely to be threatened where changes in fire regime become incompatible with evolutionary history (Bond & van Wilgen 1996; Swetnam et al. 1999).
- **Background**: Fire regimes have been recently modified where fire has been successfully excluded, especially if biomass that is receptive to combustion accumulates in the absence of fire (Covington 2000; Dale et al. 2000). This scenario has been commonly cited as the primary factor contributing to recent large fires in forests of the western United States (Covington 2000; Arno & Allison-Bunnell 2002; Agee 2002).
    - As a result, current land-management policies in the United States are calling for widespread tree harvests and other mechanical treatments aimed at reducing fuel.
    - However, the effects of these treatments on biodiversity remain unclear.
- **Background**: In addition, the problem of fuel build-up leading to increased fire severity has mainly been documented in formerly open forests of ponderosa pine (Pinus ponderosa Dougl. ex Laws.) that have his- torically been maintained by remarkably frequent surface fire (Covington 2000). Fire plays a very different role in many other forests (Turner et al. 2003), raising concerns that the surface-fire model of fuel dynamics is uncritically accepted in forests where it may not apply (Baker & Ehle 2001; Gutsell et al. 2001; Ehle & Baker 2003; Johnson 2003).

- **Background**: Historical fire regimes for the study area and nearby are generally described as mixed, with fire-severity proportions ranging, in order of abundance, from low to moderate to high (crown fire) (Agee 1993).
    - Fires also have had highly variable return intervals, depending on vegetation type, topography, and elevation.
    - For Douglas-fir hardwood forests, recent fire return intervals have ranged from 3 to 71 years (Wills & Stuart 1994; Taylor & Skinner 1998) within the study area.
    - White-fir forests just west of the study area burned at intervals ranging from 12 to 161 years prior to fire suppression (Stuart & Salazar 2000).
    - Fire suppression reportedly became effective in reducing the area burned on the KNF in the 1940s (Taylor & Skinner 1998).
- **Background**: During the past few thousand years, charcoal-accumulation rates in lakes in the region have been both higher and lower than rates in recent centuries, and there has been much variation (Mohr et al. 2000; Whitlock et al. 2003).
    - In sum, extensive mixed-severity fires of variable frequency were likely instrumental in creating patchy landscape patterns and variable age-class distributions in this region for millennia.
    - The importance of patchy landscape structure in maintaining species diversity has been demonstrated in studies of age mosaics created by stand-replacing fire (Baker 1992).
- **Background**: In addition, shading decreases the leaf area of understory conifers (Waring & Schlesinger 1985); they may have relatively little high-energy foliar fuel per unit volume in their canopy. This is by far the most available aerial fuel in trees such as Douglas-fir (Fahnestock & Agee 1983). Understory temperatures are also reduced by shading, which can lower fire severity (Countryman 1955). Thus, the biological and physical effects of shading may lead to a reduction in surface-heat output during fire and, likely, in the production of firebrands
- **Background**: Because of such dynamics, in many regions of the world the long absence of fire causes vegetation that is relatively receptive to combustion to develop into vegetation that is not (Bond & van Wilgen 1996). In Tasmania, relatively long fire-return intervals (100+ years) result in the replacement of combustible vegetation with tall, open forests with a subcanopy of sclerophyll hard- woods, which are considerably less prone to combustion (Jackson 1968). These dynamics lead to alternative stable states that can be maintained by fire (Bond & van Wilgen 1996). The dynamics are similar to stand development in the structurally similar, moist temperate Douglas-fir- hardwood forests of our study area, as described by Stuart et al. (1993) and Wills and Stuart (1994).
- **Background**: Weather conditions often override the sensitivity of a fire regime to internally regulated biomass processes op- erating over time. This has been demonstrated in empir- ical studies (e.g., Moritz 2003), through analysis of stan- dard equations for predicting fire spread (Bessie & John- son 1995), and in simulation modeling (Turner & Romme 1994). Extreme fire weather was previously invoked as the primary explanation for fire-severity patterns in the 1987 fires in the Klamath-Siskiyou region (Agee 1997), although strong local effects of plantations and logging were also observed (Weatherspoon & Skinner 1995).
- **Finding**: Despite human influences and a fire-suppression policy, most large wildland fires have been dominated by low-severity fire, with variable proportions of moderate and high severity. This is consistent with historical estimates inferred from stand age structure as shown in Fig. 3 (from Taylor & Skinner 1998).

  - One factor that contributed to the heterogeneity in fire patterns in 1987, and presumably in other large fire events, is that the fires burned under a variety of weather conditions for many weeks (Reider 1988).
- **Finding**: We found:
  - (1) a trend of increasing fire size in recent decades;
  - (2) that overall fire-severity proportions were 59% low, 29% moderate, and 12% high, which is comparable to both contemporary and historic fires in the region;
  - (3) that multi-aged, closed forests, the predominant vegetation, burned with much lower severity than did open forest and shrubby non-forest vegetation;
  - (4) that considerably less high-severity fire occurred where fire had previously be absent since 1920 in closed forests compared to where the forests had burned since 1920 (7% vs. 16%);
  - (5) that non-forest vegetation burned with greater severity where there was a history of fire since 1920 and in roaded areas;
  - (6) that tree plantations experienced twice as much severe fire as multi-aged-forests
- **Finding**: We found evidence for important changes in combustibility over time because the probability of stand-replacing fire was lower in long-unburned forests. A number of factors may contribute to this pattern.
  - Whether a forest will experience surface or crown fire depends on the height of the tree canopy, the amount of available fuel it contains per unit volume, and rates of fire spread and surface heat output (Van Wagner 1977; Johnson 2003).
- **Finding**: The much greater fire severity we found in early successional, non-forest vegetation will tend to favor the persistence of this vegetation. In the long absence of stand-replacing fire, however, it is replaced by forests (Wills & Stuart 1994).
- **Finding**: Even-aged plantations are a patch type that can persist regardless of fire frequency. Plantations of any age are more receptive to combustion than co-occurring forests in our study area. Because plantations are often established following high-severity fire, a self-reinforcing relationship is possible (Perry 1995). An ecological analog may exist where exotic species invade and become abundant through positive feedback with fire (Mack & D'Antionio 1998). Plantations in our study area have grown to cover about one-third of the roaded area burned in 1987, increasing the likelihood of future positive feed- back effects. In concert with climate change (McKenzie et al. 2004), these landscape dynamics provide reason to expect the trend of increasing fire size (Fig. 1) to continue, especially in roaded areas.

Odion, D.C., Moritz, M.A. and D.A. DellaSala. 2010. Alternative community states maintained by fire in the Klamath Mountains, USA. Journal of Ecology 98: 96-105.

- **Background**: Plants have interacted with fire for millions of years and can influence their own fire regimes, potentially affecting their own fitness (Mutch 1970; Bond & van Wilgen 1996; Schwilk 2003). Bond & Keeley (2005) point out how plant traits that promote fire contribute to a large mismatch between climate and potential vegetation. At a global scale, Bond, Woodward & Midgley (2005) found that half the area that could be occupied by forest is instead occupied by pyrogenic vegetation like savanna or shrublands maintained by fire.
- **Background**: High-severity fire in the study area is most common on drier and more southerly aspects and wind-exposed ridges (Weatherspoon & Skinner 1995; Taylor & Skinner 1998; Alexander et al. 2006). In these environments, succession to forest is slower, especially where soil productivity is lower as a result of the cumulative effects of fire history. Thus, climate, topography, soils, vegetation and fire tend to be mutually reinforcing determinants of landscape

patterns. However, climate and topography, particularly as they affect wind, can override other factors and control fire–vegetation patterns (e.g.Geldenhuys 1994).

- **Background**: In the study region, episodic weather-driven fire events kill patches of forest when severe drought and weather conditions may allow even the most fire-resistant stands to burn. Once sclerophyll vegetation replaces forests, its self-reinforcing relationship with fire can alter successional pathways to favour its retention (Fig. 4). Sclerophyll vegetation may effectively create a 'fire trap', preventing tree species from developing to adult sizes (Gignoux et al. 2009; Hoffmann et al. 2009).
- **Background**: The cumulative effects of severe fire in reducing soil carbon and site productivity over time (Fig. 4) can slow growth rates of forest tree species (Waring & Schlesinger 1985), increasing the time they are vulnerable to the fire trap. This is an example of how sclerophyll vegetation can modify the underlying environment to favour its retention (Wilson & Agnew 1992).
- **Background**: Although climate change could potentially increase rates of burning, this may not apply to the study region (Krawchuk et al. 2009). Moreover, decreases in vegetation pyrogenicity can override effects of changing climate on fire (Higuera et al. 2009).
- **Finding**: Our findings are consistent with the occurrence of alternative community states established and maintained by different self-reinforcing feedbacks with fire. Sclerophyll vegetation was more pyrogenic, especially where time-since-fire (TSF) was relatively short, a favourable relationship for this fire-dependent vegetation. Forests were much less pyrogenic, especially where TSF was long, favouring their maintenance. Fire exclusion therefore has led to afforestation and rapid retreat of fire-dependent vegetation.
- **Finding**: We have documented how different self-reinforcing combustion properties of forest and sclerophyll vegetation can naturally produce alternative states coexisting side-by-side in the same environment. Such fire-mediated alternative states may be underappreciated, in part, because they are difficult to demonstrate definitively. In addition, the dynamics they exhibit contrast with common perceptions that fire hazard increases deterministically with TSF in forests and shrublands. Addressing the impacts of fire exclusion will probably require a management shift to better allow fire to perform its ecological role in shaping landscape diversity and maintaining firedependent biota.
- **Finding**: Sclerophyll vegetation was much more pyrogenic than forests (Fig. 2a) and the null hypothesis of no association between fire severity and natural vegetation was rejected (v22 = 10.1, P = 0.006). Plantations experienced more highseverity fire than natural forests (Fig. 2a)
- **Finding**: Much of the high-severity fire within the 1987 perimeter occurred in areas that had previously burned in 1966 and particularly in 1977 (Fig. 1). Roughly 60% of the area that burned at high severity in the 1977 fire and also burned in the 1987 fires burned again at high severity in 1987, and many of the patch boundaries were identical. Much of this area was forested at the time of the 1977 fires (Odion et al. 2004) and has been sclerophyll vegetation since.
- **Finding**: We found the vegetation in the Klamath Mountains to have different combustion properties and this was a function of TSF (time since fire) at the landscape scale. Consistent with the hypothesis that co-occurring vegetation states in this landscape can be maintained by different self-reinforcing relationships with fire, sclerophyll vegetation was pyrogenic, and its highest severity as well as relative abundance occurred where TSF was shortest. Conversely, the lowest fire severity and greatest abundance of forests occurred where TSF was longest (Fig. 2b,c).
- **Finding**: With sufficiently long fire intervals conifers can escape the fire trap and reach a threshold beyond which positive feedbacks between reduced fire and vegetation pyrogenicity

increasingly favour forests (Fig. 2b). These feedbacks lead to less fire-related mortality. We also found that fire intervals >75 years led to a much lower probability and maximum size of large high-severity burned patches than where TSF was shorter (Figs 2b, 3 and Table 2).

- **Finding**: Biomass that is most available to flaming combustion, canopy foliage and fine wood on the forest floor, may reach equilibrium (Jenny, Gessel & Bingham 1949; Kittredge 1955; Waring & Schlesinger 1985), but support lower fire severity because the height of the canopy above the forest floor increases (Azuma, Donnegan & Gedney 2004). Tanoak and other hardwoods have also been associated with low fire severity in long-unburned stands in the study region (Azuma, Donnegan & Gedney 2004; Odion et al. 2004). Hardwoods in the oak family often have high lignin content and have generally been found to be much less pyrogenic than conifers (Mutch 1970;Williamson&Black 1981; Rebertus,Williamson &Moser 1989; Pausas et al. 2004).
- **Finding**: We found that alternative states of pyrogenic and non-pyrogenic vegetation are maintained in the same environment by different self-reinforcing relationships with fire. In fire-prone environments, such self-organizing dynamics between vegetation and fire may lead to sharp vegetation boundaries that do not correspond to underlying environmental gradients (Wilson & Agnew 1992).
- **Ecological Considerations**: In addition, because conifers depend on dispersal to re-colonize burned patches, they can be inhibited if patch sizes exceed a dispersal distance threshold, beyondwhich conifer regeneration may diminish rapidly (Romme et al. 1998).
- **Ecological Considerations**: Paradoxically, although the sclerophyll vegetation may inhibit forests through fire-related mechanisms, conifers can also be facilitated by shrubs. Conifer seedlings survive better under shrub canopies, where drought stress is reduced (Zavitkovski &Newton 1968; Dunne & Parker 1999) and their long-term growth potential may be increased by nitrogen-fixing Ceanothus spp. (Busse, Cochran & Barrett 1996).
- **Ecological Considerations**: As forests develop, tanoak is not excluded like pyrogenic shrubs. Instead, it transforms from shrubby, xerophytic forms with dense, small, thick and waxy leaves to more arborescent, mesophytic forms with large, shade-tolerant leaves. Phenotypic plasticity, as exemplified by these changes, is a key trait among species that are important immediately after disturbance and can remain so late in succession despite a change in the environment (Platt & Connell 2003)
- **Ecological Considerations**: Because tanoak can both persist and also recruit new canopy stems in mature forests in the absence of fire (Hunter 1997), whereas conifers like Douglas-fir rely on cohort regeneration after fire (Wills & Stuart 1994), tanoak may eventually become more dominant in the study region with fire exclusion. However, fire exclusion may increase the susceptibility of tanoak, as well as California black oak, to a highly virulent nonnative pathogen causing Sudden Oak Death disease (Moritz & Odion 2005). Thus, other hardwoods that also do not require fire for reproduction may eventually increase if fire exclusion persists, which would further reduce forest pyrogenicity.

Serra-Diaz et al. 2017. Disequilibrium of fire-prone forests sets the stage for a rapid decline in conifer dominance during the 21st century. doi: http://dx.doi.org/10.1101/163899

- **Finding**: Using a landscape simulation model, we estimate that 1/3 of the Klamath could transition from conifer forest to shrub/hardwood chaparral, triggered by an enhanced fire activity coupled with lower post-fire conifer establishment.

    - Such shifts were more prevalent under higher climate change forcing (RCP 8.5) but were also simulated under the climate of 1950-2000, reflecting the joint influences of early warming trends and historical forest legacies.
- **Finding**: Our results demonstrate that there is a large potential for loss of conifer forest dominance—and associated carbon stocks and biodiversity-- in the Klamath before the end of the century, and that some losses would likely occur even without the influence of climate change.
- **Finding**: Thus, in the Klamath and other forested landscapes subject to similar feedback dynamics, major ecosystem shifts should be expected when climate change disrupts key stabilizing feedbacks that maintain the dominance of long-lived, slowly regenerating trees.

Skinner, C.N., Taylor, A.H. and J.K. Agee. 2006. Chapter 9: Klamath Mountains Bioregion; In: Fire in California's Bioregions.

- **Background**: Overall, critical fire weather is associated with any weather condition that creates sustained periods of high-velocity winds with low humidity. In the Klamath Mountains, critical fire weather conditions are created by three different weather patterns described by Hull et al. (1966): (1) Pacific High–Post-Frontal (Post-Frontal), (2) Pacific High–Pre-Frontal (Pre-Frontal), and (3) Subtropical High Aloft (Subtropical High).
    - Post-Frontal conditions occur when high pressure following the passage of a cold front causes strong winds from the north and northeast. Temperatures rise and humidity declines with these winds.
    - Pre-Frontal conditions occur when strong, southwesterly or westerly winds are generated by the dry, southern tail of a rapidly moving cold front. Strong winds are the key here because temperatures usually drop and relative humidity rises as the front passes.
    - Subtropical High conditions occur when the region is under the influence of descending air from high pressure that causes temperatures to rise and humidity to drop. In the Klamath Mountains, these conditions lead to fires controlled mostly by local topography. Subtropical High conditions also promote the development of strong temperature inversions that inhibit smoke from venting out of the canyons and valley bottoms. The combination of smoke and lack of vertical mixing created by strong inversions, especially following initiation of widespread lightning-caused fires, reduces fire intensity.
- **Background**: Lightning is common in the Klamath Mountains with 12.8 strikes (range 6.4–26.4)/yr/100 km2 (33.7 strikes [range 16.8–69.4]/yr/100 mi2). Lightning-caused fires have accounted for most area burned in recent decades (e.g., 1977, 1987, 1999, and 2002). Lightning may ignite hundreds of fires in a 24- hour period.
- **Background**: Lightning occurrence increases with distance from the coast and with increasing elevation (van Wagtendonk and Cayan 2007).
- **Background**: Storms that produce lightning-caused fires are associated with higher instability and higher dew point depression (drier air) than storms that produce the most lightning strikes (Rorig and Ferguson 1999, 2002). Additionally, in both 1987 and 1999, a single storm episode was responsible for nearly all of the area burned by lightning-caused fires.
- **Background**: Fire regimes characteristic of the pre-settlement period (i.e., 1600 A.D.–1850 A.D.) have been in place for approximately the last 1,000 years (Mohr et al. 2000).
- **Background**: Native people of the Klamath Mountains used fire in many ways:

  - (1) to promote production of plants for food (e.g., acorns, berries, roots) and fiber (e.g., basket materials);
  - (2) for ceremonial purposes;
  - (3) to improve hunting conditions (Lewis 1990, 1993; Pullen 1995).
  - Though native ignitions appear to have been widespread, we do not know the extent of their influence on fire regimes and vegetation at broad scales.
- **Background**: Several fire history studies describe fire regimes in parts of the Klamath Mountains over the last few centuries (Agee 1991; Wills and Stuart 1994; Taylor and Skinner 1997, 1998, 2003; Stuart and Salazar 2000; Skinner 2003a, 2003b; Fry and Stephens 2006).
  - These studies indicate there are two periods with distinctly different fire regimes:
    - (1) the Native American period, which usually includes both the pre-historic and European settlement period, and
    - (2) the fire suppression period.
  - Though there is variation among sites as to when fire suppression became effective, the temporal patterns of fire occurrence in the pre–fire suppression period indicate that most stands experienced at least several fires each century.
  - This suggests a general fire regime of frequent, low- to moderate- intensity fires.
- **Background**: Before fire suppression, fires of higher spatial complexity created openings of variable size within a matrix of forest that was generally more open than today (Taylor and Skinner 1998). This heterogeneous pattern has been replaced by a more homogenous pattern of smaller openings in a matrix of denser forests (Skinner 1995a). Thus, spatial complexity has been reduced. The ecological consequences of these changes are likely to be regional in scope, but they are not yet well understood.
- **Background**: A typical pattern of fire severity is illustrated in Figure 9.7 (Taylor and Skinner 1998). Generally, the upper third of slopes and the ridgetops, especially on south- and west-facing aspects, experience the highest proportion of high-severity burn.
- **Background**: Douglas-fir, once mature, is very resistant to low- to moderate-intensity surface fires due to a variety of characteristics. Douglas-fir has very thick bark, a deep rooting habit, high crowns (Agee 1993), short needles, heals fire wounds rapidly, and does not slough bark. In fact, Douglas-fir is the most fire-resistant tree species in the Klamath Mountains. Its common conifer associates, ponderosa, Jeffrey, and sugar pine, are also fire resistant and have thick bark, root deeply, and have high, open crowns.

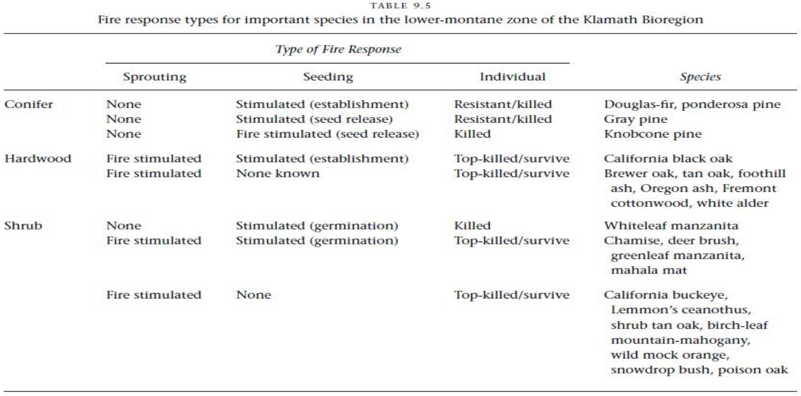
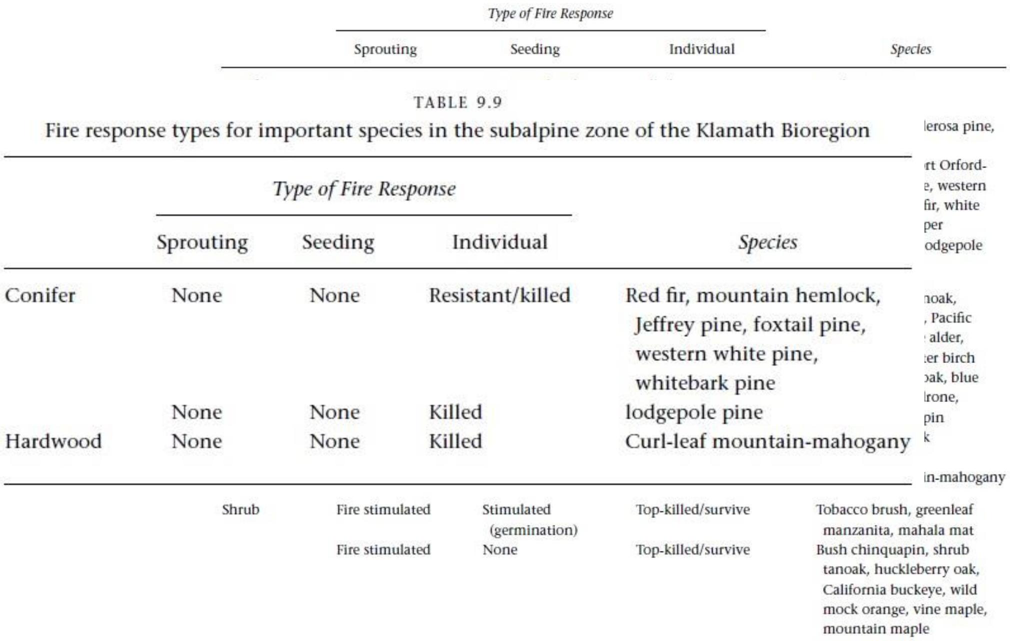


TABLE 9.5

Fire response types for important species in the lower-montane zone of the Klamath Bioregion

	Type of Fire Response			
	Sprouting	Seeding	Individual	Species
Conifer	None	Stimulated (establishment)	Resistant/killed	Douglas-fir, ponderosa pine
	None	Stimulated (seed release)	Resistant/killed	Gray pine
	None	Fire stimulated (seed release)	Killed	Knobcone pine
Hardwood	Fire stimulated	Stimulated (establishment)	Top-killed/survive	California black oak
	Fire stimulated	None known	Top-killed/survive	Brewer oak, tan oak, foothill ash, Oregon ash, Fremont cottonwood, white alder
Shrub	None	Stimulated (germination)	Killed	Whiteleaf manzanita
	Fire stimulated	Stimulated (germination)	Top-killed/survive	Chamise, deer brush, greenleaf manzanita, mahala mat
	Fire stimulated	None	Top-killed/survive	California buckeye, Lemmon's ceanothus, shrub tan oak, birch-leaf mountain-mahogany, wild mock orange, snowdrop bush, poison oak

- **Background**: White fir has thin bark when young, but its bark is not shed and thickens with age, making it more fire tolerant when mature. Shasta red fir is similar but appears to be more sensitive than white fir at all ages. Port Orford cedar stands often include trees more than 300 years old with open, charred wounds (cat faces) indicating they commonly survived low to moderate-intensity surface fires (Table 9.7).
- **Background**: Most tree species in the subalpine zone, including mountain hemlock, Shasta red fir, white bark pine, western white pine, foxtail pine, lodgepole pine, and curl-leaf mountain mahogany have thinner bark than species found at lower elevations and are easily damaged or killed by moderate-intensity fire or the consumption of heavy surface fuels at the base of the tree.



	Type of Fire Response			
	Sprouting	Seeding	Individual	Species

lerosa pine,
rt Orford-
e, western
fir, white
per
odgepole
noak,
, Pacific
alder,
er birch
oak, blue
lrone,
pin
k
in-mahogany

TABLE 9.9

Fire response types for important species in the subalpine zone of the Klamath Bioregion

	Type of Fire Response			
	Sprouting	Seeding	Individual	Species
Conifer	None	None	Resistant/killed	Red fir, mountain hemlock, Jeffrey pine, foxtail pine, western white pine, whitebark pine
	None	None	Killed	lodgepole pine
Hardwood	None	None	Killed	Curl-leaf mountain-mahogany

Shrub	Fire stimulated	Stimulated (germination)	Top-killed/survive	Tobacco brush, greenleaf manzanita, mahala mat
	Fire stimulated	None	Top-killed/survive	Bush chinquapin, shrub tanoak, huckleberry oak, California buckeye, wild mock orange, vine maple, mountain maple

- **Background**: More-recent management activities, such as logging and replacement of multi-aged old-growth forests with even-aged forest plantations and continued fire suppression have reduced forest heterogeneity, increased the proportion of even-aged forests, and altered habitat conditions for forest-dwelling species compared to conditions in the pre–fire-suppression landscape (USDAs-USDI 1994).
- **Background**: Primarily due to the annual summer drought and ample winter precipitation, fires were historically frequent and generally of low to moderate and mixed severity in most vegetation assemblages, especially those that cover large portions of the Klamath Mountains. Fire exclusion and other management activities have led to considerable changes in Klamath Mountain ecosystems over the last century. Of all management activities that have contributed to altering ecosystems in the Klamath Mountains, fire suppression has been the most pervasive since it alone has been ubiquitously applied.

Taylor and Skinner 2003.

- **Study**: The goal of this study is to better understand the spatial and temporal patterns of, and controls on, fire regimes and forest structure in mixed conifer forests of the Klamath Mountains.
- **Study**: Our study was conducted in a 2325-ha area of two small watersheds in the Shasta-Trinity National For- ests, 8 km west of Hayfork, California in the south- central Klamath Mountains (Fig. 1). Elevations range from 640 to 1360 m. The climate is characterized by warm, dry summers and cool, wet winters.

- **Background**: Fire exclusion in mixed conifer forests has increased the risk of fire due to decades of fuel accumulation.
- **Background**: Nearly a century of fire exclusion in forests that once experienced frequent low- and moderate-severity fires has reduced compositional and structural diversity in forest stands and forested landscapes. For example, in California's mixed conifer forests the reduction in the frequency and extent of fire has caused an increase in forest density, a compositional shift to more fire-sensitive species, and a shift from coarse to fine grain forest mosaics (Vankat and Major 1978, Parsons and DeBenedetti 1979, Skinner 1995, Taylor 2000). Reduced fire frequency has also caused unprecedented accumulations of surface and aerial fuels and dramatically increased the risk of high-severity fires (Weath- erspoon et al. 1992).
- **Background**: Variation in fire frequency and fire severity vary with topographically related variables such as aspect, spe- cies composition, elevation, and soil type in some mixed conifer landscapes (Caprio and Swetnam 1995, Fites-Kauffman 1997, Taylor and Skinner 1998, Taylor 2000, Beaty and Taylor 2001, Bekker and Taylor 2001) but not in others (Heyerdahl et al. 2001).
- **Background**: Forests in the study area are diverse and any of six conifer species: ponderosa pine (Pinus ponderosa) (no- menclature follows Hickman 1993), Douglas-fir (Pseudotsuga menziesii var. menziesii), incense cedar (Calocedrus decurrens), sugar pine (Pinus lambertiana), Jeffrey pine (Pinus jeffreyi), and white fir (Abies con- color) may co-occur and share dominance in a stand depending on site conditions and stand history (Bar- bour 1988, Parker 1994). A subcanopy of the evergreen hardwoods Pacific madrone (Arbutus menziesii), gold- en chinquapin (Chrysolepis chrysophylla), and canyon live oak (Quercus chrysolepis) and the deciduous hard- woods California black oak (Quercus kelloggii), big- leaf maple (Acer macrophyllum), Oregon white oak (Quercus garryana), and dogwood (Cornus nuttallii) occur beneath the mixed conifer canopy. Stand com- position is strongly influenced by elevation, site mois- ture availability, and substrate.
- **Background**: A fire suppression policy was introduced in 1905 when the Trinity Forest Reserve was established as part of the National Forest Reserve System (Shrader 1965). Small-scale logging along ridge- tops began in the 1960s and extensive clear-cut logging occurred between 1980 and 1990.
- **Background**: Five forest compositional groups were identified from the cluster analysis of species importance values and the groups are segregated by elevation and potential soil moisture ($P < 0.05$, Kruskal-Wallis H test) (Table 1). The ponderosa pine-sugar pine group ($n = 18$) occupies mainly south- and west-facing slopes and xeric upper slopes and ridgetops. The two pines share codominance and canyon live oak and Douglas-fir are important associates. The Douglas-fir group ($n = 30$) occupies mesic north-facing slopes at mid-elevations and is strongly dominated by Douglas-fir with sugar pine and hardwoods as important associates. The Douglas-fir-ponderosa pine-incense cedar group ($n = 17$) occupies mainly east-facing slopes at low and midelevation and is a variable mixture of the three species. The Douglas-fir-sugar pine group ($n = 41$) is compositionally variable and occupies midslope positions on north- and east-facing slopes. Ponderosa pine is the most important associate and a diverse assemblage of hardwoods is character tic of this group. The Douglasfir-white fir group ($n = 13$) occupies higher elevation sites on north- and east-facing slopes with sugar pine and ponderosa pine as the most important associates.
- **Background**: The prevalence of Douglas-fir and the diversity of hardwood species distinguish mixed conifer forests in the Klam- ath Mountains from those elsewhere in the Cascade Range, Sierra Nevada, San Bernardino Mountains, and Sierra San Pedro Martir (Whittaker 1960, Barbour 1988).

- **Background**: features (i.e., streams, riparian zones, sharp changes in aspect, changes in parent material) that act as im- pediments to fire spread.
- **Background**: Even small streams and narrow riparian strips with water, higher humidity, and vegetation with high live fuel moisture are effective barriers to fire spread in forests that experience frequent, low-intensity surface fires (Skinner 1997). Moreover, differences in fuel bed char- acteristics that occur at abrupt changes in aspect, in riparian areas, or at parent material boundaries are suf- ficient to inhibit the spread of fire under typical con- ditions (e.g., Taylor 2000, Stephens 2001). Parent ma- terials, especially where ultramafic rock is interspersed with other rock types as in our study area, may affect fire spread patterns due to different levels of fuel pro- duction. Historically, even bare foot paths were re- ported to stop many fires in the vicinity of our study area (Wilson 1904).
- **Background**: Variation in fire severity is an important source of structural diversity in forested landscapes because burns may kill all trees in some stands and few in others.
- **Background**: Stands that have experienced high-severity fires are even aged or several aged with stems in relatively few age classes while those that experience mainly low- and moderate-severity fires have stems in a wide range of age classes because fires kill few trees in the stand (Agee 1993). Forest stands in our study area were mul- tiaged and virtually all stands had stems >250 yr old, and many included older stems of relatively fire-sen- sitive white fir. This suggests that burns were mainly low or moderate in severity and patchy enough to allow white fir to grow to a fire-resistant size (e.g., Agee 1993).
- **Background**: The age structure of mixed conifer forests, however, are not uniformly multiaged. In the Klamath Mountains and southern Cascades, large (>100 ha) mainly even-aged patches of trees are present indicating that high-sever- ity burns played an integral role in shaping forest struc- ture at stand and landscape scales at least in some areas (e.g., Taylor and Skinner 1998, Beaty and Taylor 2001, Bekker and Taylor 2001).
- **Background**: Forest changes caused by fire suppression have been documented in the mixed conifer forests in the Sierra Nevada (Vankat and Major 1978, Parsons and De- Benedetti 1979), the San Bernardino Mountains (Min- nich et al. 1995, Savage 1997), and southern Cascade Range (Dolph et al. 1995, Taylor 2000). Overall, forests have increased in density and shifted in composition from more fire-resistant to more fire-sensitive species, reducing the structural diversity of forests at both stand and landscape scales (Vankat and Major 1978).
- **Finding**: Forests were multiaged and burned frequently at low and moderate severity, but forest age structure did not vary with aspect, elevation, or topographic position.
- **Finding**: Recently there has been an increase in forest density and a forest compositional shift to shade-tolerant species.
- **Finding**: Median fire return intervals (FRI) ranged from 11.5 to 16.5 yr and varied with aspect but not with forest composition or elevation. The median area burned was 106 ha, and the pre-Euro-American fire rotation of 19 yr increased to 238 yr after 1905.
- **Finding**: Median site Fire Return Intervals (FRIs) were statistically longer on north-facing slopes than on other aspects ($P < 0.05$, Kruskal-Wallis H test) (Table 2).
- **Finding**: the median area burned in the pre-Euro-American (128 ha, range 25-1541 ha) and settlement (106 ha, range 25-1188 ha) periods were similar. Median area burned was smaller (25 ha) in the fire suppression period.
- **Finding**: Fire rotation for the pre-Euro-American periods was 20 yr. Fire rotations were shorter during the 19th century (15 yr) and settlement period (18 yr) due to the proportionately greater area burned during these periods.

- **Finding**: The ordination of - 100-yr-old and >100-yr-old stems shows that Douglas-fir and white fir have regen- erated more successfully than other conifer species dur- ing the fire suppression period
- **Finding**: Ponderosa pine, sugar pine, and canyon live oak were most abundant on dry south-facing slopes and ridgetops while white fir was most abundant on high elevation mesic sites. In contrast, Douglas-fir, California black oak, Pacific madrone, and golden chinquapin were most abundant on more mesic north-facing slopes at low elevation.
- **Finding**: fuel production rates on warmer, low-elevation, pine-dominated sites are higher than on cooler, higher elevation, fir-dominated sites (Agee et al. 1978, Stohlgren 1988; J. W. van Wagten- donk, personal communication). Consequently, fuel re- covery after fire is faster so a low elevation site can burn again sooner. Second, fuels dry out sooner each year on low elevation sites so the period fires can burn each year is longer than at higher elevation.
- **Finding**: In the Hayfork study area, spatial variation in fire frequency was associated with aspect and not elevation or forest species composition. Fires were less frequent on north-facing slopes than on other slope aspects. Al- though this difference was statistically significant, the small difference in median FRI between north-facing and other aspects may not be significant from a man- agement perspective.
- **Finding**: What may be more important is the greater variation in median FRIs on the north- and west-facing aspects compared to the south- and east- facing aspects. The variation in FRIs on the west-facing aspects may be due to the dry, shallow soils of low productivity associated with them (cf. USFS 1983). Indeed, these slopes were more likely to have a greater component of canyon live oak. Where canyon live oak makes up a major portion of the canopy, it is often associated with sites of low productivity (USFS 1983) characterized by sparse, discontinuous surface fuels that do not carry fire well except under more extreme conditions (Skinner and Chang 1996). Instead of more humid, mesic conditions inhibiting fires, the xeric, steep, west-facing slopes may not have been able to consistently produce fuels to carry fires as often as the south- or east-facing slopes.
- **Finding**: the coincidence of fire occurrence group boundaries with topographic features known to affect fire behavior suggests that topography is the primary control on the spatial pattern of fire in the highly complex terrain in our study area
- **Finding**: Even-aged stands in the Klamath Mountains and southern Cascade Range, are proportionately more abundant on upper slope posi- tions suggesting that topography may also be an im- portant control on fire severity and stand age structure at landscape scales (Skinner 1995, Taylor and Skinner 1998, Beaty and Taylor 2001). Mid- and upper-slope positions often experience higher fire intensities than lower slopes due to preheating of fuels, higher effective windspeeds, and lower canopy cover (Rothermel 1983, Weatherspoon and Skinner 1995, Taylor and Skinner 1998).
- **Finding**: Our understanding of the influence of topography on patterns of fire severity is currently insufficient to untangle the potential long- term effects of topography from the short-term effects of extreme fire weather on fire severity and forest age structure patterns.
- **Finding**: The predominant increase in density in Klamath Mountains with fire suppression was for Douglas-fir or a mixture of Douglas-fir and white fir. Douglas-fir is shade tolerant on drier sites in the Klamath Mountains (Herman and Lavender 1990), and Douglas-fir and white fir are more fire-sensitive than the pines when they are small. But Douglas-fir is as fire tolerant as the pines when it ma- tures due to its thick bark, which prevents injury by low- and moderate-intensity fires (Agee 1993).

Tepley et al. 2017. Vulnerability to forest loss through altered postfire recovery dynamics in a warming climate in the Klamath Mountains. Global Change Biology 2017: 1-16.

- **Abstract**: In the context of ongoing climatic warming, certain landscapes could be near a tipping point where relatively small changes to their fire regimes or their postfire forest recovery dynamics could bring about extensive forest loss, with associated effects on biodiversity and carbon-cycle feedbacks to climate change. Such concerns are particularly valid in the Klamath Region of northern California and southwestern Oregon, where severe fire initially converts montane conifer forests to systems dominated by broadleaf trees and shrubs. Conifers eventually overtop the competing vegetation, but until they do, these systems could be perpetuated by a cycle of reburning. To assess the vulnerability of conifer forests to increased fire activity and altered forest recovery dynamics in a warmer, drier climate, we characterized vegetation dynamics following severe fire in nine fire years over the last three decades across the climatic aridity gradient of montane conifer forests. Postfire conifer recruitment was limited to a narrow window, with 89% of recruitment in the first 4 years, and height growth tended to decrease as the lag between the fire year and the recruitment year increased. Growth reductions at longer lags were more pronounced at drier sites, where conifers comprised a smaller portion of live woody biomass. An interaction between seed-source availability and climatic aridity drove substantial variation in the density of regenerating conifers. With increasing climatic water deficit, higher propagule pressure (i.e., smaller patch sizes for high-severity fire) was needed to support a given conifer seedling density, which implies that projected future increases in aridity could limit postfire regeneration across a growing portion of the landscape. Under a more severe prospective warming scenario, by the end of the century more than half of the area currently capable of supporting montane conifer forest could become subject to minimal conifer regeneration in even moderate-sized (10s of ha) high-severity patches.

Climate Refuge

Anacker, Brian L. and Susan P. Harrison. 2012. Climate and the evolution of serpentine endism in California. Evol. Ecol. 26: 1011-1023.

- **Finding**: Our results are consistent with the notion that benign climates (i.e., high rainfall and less extreme temperatures) promote the persistence of small populations with novel adaptations (i.e., endemics)

Anacker, B.L., Gogol-Prokurat, M., Leidholm, K. and S. Schoenig. 2013. Climate change vulnerability assessment of rare plants in California. Madrono 60(3): 193-210.

- **Finding**: Species in topographically dissected landscapes may be less vulnerable to climate change because they can find suitable climates locally as climate changes.

DellaSala et al. 2010. Climate-adapted conservation planning. Powerpoint presentation.

- **Background**: Klamath-Siskiyou acted as refugia in the past
    - Proximity to California Current, which lessens cold and heat extremes and produces abundant fog and precipitation
    - Located at a crossroads for species mixing
    - Extremely complex terrain provides microclimates
    - Past refugia locations are centered mostly on or near the coast, and coincide with areas of higher precipitation

Dobrowski. 2011

- **Study**: Here I examine the climatic basis for microrefugia and assert that the interaction between regional advective influences and local terrain influences will define the distribution and nature of microrefugia. I review the climatic processes that can support their subsistence and from this climatic basis: (1) infer traits of the spatial distribution of microrefugia and how this may change through time; (2) review assertions about their landscape position and what it can tell us about regional climates; and (3) demonstrate an approach to forecasting where microrefugia may occur in the future.
- **Background**: Microrefugia (Definition)— Microrefugia are sites that support locally favorable climates amidst unfavorable regional climates, which allow populations of species to persist outside of their main distributions.
- **Background**: The response of biota to climate change of the past is pertinent to understanding present day biotic response to anthropogenic warming (Noss, 2001; Pearson, 2006; Provan & Bennet, 2008).
- **Background**: Climatic refugia are typically thought of as large regions in which organisms took refuge during glacial advances and retreats during the Pleistocene (2.5 million years ago to 11 500 years ago), which then acted as sources for colonization during more favorable climatic periods (Hewitt, 2000; Davis & Shaw, 2001).
- **Background**: there is compelling evidence that climatic refugia occurred at local scales during the LGM and were also utilized during interglacial warm periods, including the current interglacial (Willis & Van Andel, 2004; Birks & Willis, 2008). These 'microrefugia' or 'cryptic refugia' were sites that supported isolated low-density populations of species

beyond their reconstructed range boundaries. It is hypothesized that these refugial habitats occurred in favorable microclimates during periods of unfavorable regional climate and allowed for postglacial colonization via local dispersal (McLachlan et al., 2005; Pearson, 2006; Birks & Willis, 2008; Provan & Bennet, 2008).

- **Background**: During interglacial stages, microrefugia were presumably found in areas with cooler microclimates that allowed for the persistence of cold-adapted species. During the longer glacial stages, microrefugia presumably supported warm microclimates that allowed for the persistence of thermophilous species (Table 1) (Birks & Willis, 2008; Rull, 2009).
- **Background**: Coughlan & Running (1997) demonstrated that after canopy cover, net solar radiation is the most important factor affecting snowpack duration.
- **Background**: For example, the author (Dobrowski et al., 2009) decomposed in situ temperature measurements into components associated with regional free-air temperature and local physiographic effects and found that roughly 20–30% of the temperature variance of a mountainous region over an 11 year period could be attributed to spatial variance in physiographic features. This influence is likely to be even greater at sites with pronounced topoclimatic effects.
- **Background**: Valleys promote the persistence of cold air pools which result in lower minimum temperatures on average than upland locations.
- **Background**: Topographic depressions could also have protected thermophilous taxa from the desiccating influence of wind. This description is more consistent with the physiographic characteristics of valley bottoms and is an important distinction in that it suggests a different limiting climatic factor, namely water availability as opposed to minimum temperature.
- **Finding**: In the current interglacial period, microrefugia are likely to have lower temperatures and support more mesic environments than their surroundings. These represent climatic environments that will become increasingly scarce in the next century due to anthropogenic warming (IPCC, 2007; Williams et al., 2007).
- **Finding**: Additionally, warming over the past century has been asymmetric with minimum temperature increasing nearly twice as rapidly as maximum temperature (IPCC, 2007). Because minimum temperature is rising at a greater rate than maximum temperature under anthropogenic warming, current, and future microrefugia are likely to support minimum temperature regimes of extant climates.
- **Finding**: Here I draw attention to three terrain influences that affect the level of coupling between the boundary layer and the free atmosphere, and drive local variation in air temperature and water balance: (1) cold air drainage, (2) elevation, and (3) slope and aspect effects.
- **Finding**: Terrain positions that consistently promote cold-air pooling and the maintenance of temperature inversions are primary candidates for microrefugia. This is because they represent landscape positions whose climatic environments are consistently decoupled from regional circulation patterns (Lundquist et al., 2008; Daly et al., 2009). Convergent environments (e.g. valley bottoms, local depressions, coves, sinks,

basins, etc.) also accumulate water and soil (which helps retain water). Thus, they conceivably could act as microrefugia for mesophilous taxa in arid regions (Table 1).

- **Finding**: Cold air pooling is a widespread phenomenon in areas of complex terrain. In the absence of strong winds, temperatures drop rapidly after sunset resulting in strong nocturnal cooling near the ground surface. Cold dense air drains into convergent environments, resulting in stable cold air pools that can be hundreds of meters thick (Lindkvist et al., 2000; Whiteman et al., 2004). This results in an increase in temperature with increasing elevation (inversion). Inversions are promoted by stable atmospheric conditions. In many cases, sites in topographic depressions (e.g. heavily incised valleys) are sheltered from regional advective influences. The lack of vertical mixing within these cold air pools decouples air within the inversion from the free atmosphere above (Whiteman, 1982; Whiteman et al., 2004; Daly et al., 2009).
- **Finding**: Cold air pooling occurs frequently in basins, valleys, and sinks of mountainous regions. It has been documented to occur as often as 30–60% of the daily observations made in mountainous regions around the globe (Bolstad et al., 1998; Iijima & Shinoda, 2000; Dobrowski et al., 2007; Blandford et al., 2008). Cold air pools are not solely nocturnal phenomena, but also influence diurnal temperature patterns. Researchers have demonstrated that inversions can last from 3 to 6 h past sunrise (Whiteman, 1982; Muller & Whitemen, 1988; Colette et al., 2003).
- **Finding**: Slope and aspect influence near-surface temperature and water availability due to varying exposure to solar radiation and wind (Mccutchan & Fox, 1986; Barry, 1992; Bolstad et al., 1998). Solar radiation has been used as a predictor variable in modeling temperature in complex terrain (Geiger, 1965; Lookingbill & Urban, 2003; Chung & Yun, 2004; Dobrowski et al., 2009; Fridley, 2009).
    - However, many of these authors note that the effect of direct beam solar radiation is most pronounced on daily maximum temperatures and has little influence on minimum temperature.
    - Further, this effect is strongly modified by cloud cover which diminishes radiation differences between exposures, as well as by high soil moisture or canopy cover which can shift the conversion of shortwave radiation to latent as opposed to sensible heat flux.
- **Finding**: In the Great Smoky Mountains of the Eastern US, Fridley (2009) showed that topoclimatic effects resulted in 2–4 1C of in situ temperature variance, depending on the temperature variable (minimum or maximum), and time of year.
- **Finding**: In the Sierra Nevada, USA the author demonstrated that physiographic effects on climate can result in average temperature differences up to 5 1C during the winter months, minimum temperature differentials of 5–8 1C, and over a 20% difference in reference evapotranspiration between proximal sites at the same elevation (Dobrowski et al., 2009).
- **Finding**: In a particularly relevant example, Daly et al., (2009) demonstrates that topoclimatic modeling of coldair pooling coupled with projected climate warming, can result in widely divergent temperature changes of up to 6 1C for proximal locations (o2

km) in mountainous terrain. These topoclimatic effects exceeded values of the imposed regional temperature change.

- **Finding**: sites with weak coupling to the free atmosphere (e.g. valley bottom sites), have the largest variance in trend magnitude, exhibiting both warming and cooling trends [fig. 4c and d; (Pepin & Lundquist, 2008)]. Consequently, these sites have a greater potential to support temperature trends that deviate from regional averages and are more likely to be able to support relict climates through time.
- **Finding**: The physiographic settings and climatic processes that can potentially support microrefugia are widespread in areas of complex terrain. Consequently, the utilization of microrefugia is likely to be an adaptive strategy that is widespread.
- **Finding**: As time passes and regional climate becomes less suitable for a given species, the number of microrefugia that can support a locally favorable climate for that species will decrease with those remaining becoming increasingly isolated.
- **Finding**: The first assumption to look at is that terrain position can result in sites with consistent climate deviations from regional averages. This contention has received much attention in this review and is well supported by research in climate science, meteorology, and landscape ecology.
- **Finding**: we can posit that climate change impacts will be most prevalent and readily observed at sites that are strongly coupled to the free atmosphere (e.g. Alpine sites, nival summits, etc.).
- **Finding**: In contrast to glacial stages, convergent environments may act as thermal refugia for cold-tolerant or mesophilous species during interglacial warm periods (Table 1). A potential mechanism for this is that the lower minimum temperatures in these locations may actually exclude more competitively dominant thermophilous taxa, thus reducing competitive pressure on cold-adapted species (e.g. Alpines; Birks & Willis, 2008).
    - **Finding**: An extreme example of this is known as a ‘vegetation inversion’ (Geiger, 1965; Whiteman et al., 2004) and occurs where high elevation species find habitat in low elevation depressions or sinks.
- **Finding**: Further, temperature effects due to slope must be balanced against water loss at these sites.
- **Finding**: north-facing slopes can support microrefugia for mesophilous taxa in that they have lower evaporative demand than south-facing slopes.
- **Finding**: However, slope and aspect are topographic proxies of moisture, light, and temperature. Species may respond to each of these in an idiosyncratic fashion which may undermine the utility of slope and aspect in identifying microrefugia (Warren, 2010).
- **Finding**: This review has noted that the proximal climatic mechanisms that shape microrefugia are likely to occur at local scales. As such, our ability to identify microrefugia will be strongly dependent on the use of appropriately scaled and physiographically informed climate data.

- **Finding**: Approaches that couple physiographically informed climate data with SDM are likely to provide the foundation for efforts aimed at identifying and mapping microrefugia under historic and future climates.
- **Finding**: Microrefugia are likely to be found in terrain positions that promote the consistent decoupling of the boundary layer from the free-atmosphere. These terrain positions are likely to have climate states and trends that are decoupled from regional averages, a requisite for microrefugia to persist through time. Convergent environments (local depressions, valley bottoms, sinks, and basins) are primary candidates for microrefugia based on these criteria.

Frey et al. 2016. Spatial models reveal the microclimatic buffering capacity of old-growth forests. Sci. Adv. 2016; 2:e1501392 22 April 2016.

- **Ecological Considerations**: Observed inter-annual consistency in site-level conditions in Old Growth Forests, which occurred despite substantial differences in annual climatic conditions, lends support to the notion that thermally buffered sites may provide temporally consistent refugia for biodiversity (7).
- **Background**: in heterogeneous mountain landscapes with complex thermal regimes, climate-sensitive species have the potential to disperse to, and persist in, favorable microclimatic conditions

Morelli et al. 2016

- **Study**: Our goals are to: (1) build on recent literature to elaborate the value of climate change refugia as a short- to medium-term management strategy; (2) aid identification of climate change refugia by describing the processes that create them; and (3) introduce a framework for operationalizing the concept of refugia for climate adaptation.
- **Study**: We briefly review the theoretical framework for refugia, based in the Quaternary literature but with application to conservation (also see [7, 8, 9]).
- **Study**: We delineate seven steps for managing refugia (Fig 3, Table 1).
- **Study**: We have outlined the opportunities and challenges for effective implementation of the climate change refugia concept.
- **Background**: Climate Change Refugia (definition): areas relatively buffered from contemporary climate change over time that enable persistence of valued physical, ecological, and socio-cultural resources.
- **Background**: Climate change refugia are at least large enough to sustain a manageable unit of the focal resource, such as a small population or metapopulation [7], rather than smaller, transient micro-environmental “refuges” from exposure and disturbance [9, 18].
- **Background**: A focus on areas resistant to ongoing climate change is increasingly suggested as a potential conservation strategy [4], yet lack of clarity on how to identify and manage these “climate change refugia” hampers practitioners [5].
- **Background**: Populations persisted and survived during the last glacial maximum in habitats where climate change was buffered or compensated, and in regions where suitable climates were displaced toward the equator or to lower elevations relative to their postglacial distribution.
- **Background**: Not only did refugia provide a safe haven during periods of unfavorable climate, but they served as sources for colonization following climate warming [10].

- **Background**: Physically-based definitions of climate refugia emphasize the mechanisms that enable an area to remain buffered from regional influences and usually do not attempt to link refugia to particular ecological components, such as species or habitats [7].
- **Background**: Climate change refugia are characterized by the occurrence of relatively stable local climatic conditions that persist over time, despite change at regional and global scales [22].
- **Background**: strong microclimatic gradients allow for short distance dispersal and movements to compensate for climate changes and thus can act as climate change refugia.
- **Background**: Managing climate change refugia for local persistence of valued resources gains time for systems to adapt and for managers and society to develop longer-term solutions [2].
- **Finding**: Physical characteristics that tend to result in climate refugia:
    - Topographically complex terrain creates varied microclimates and increases the likelihood that current climates will continue to exist nearby
    - Deep snow drifts provide insulation to the surface below and provide water later in the season
    - Valleys that harbor cold air pools and inversions can decouple local climatic conditions from regional circulation patterns
    - Canopy cover can buffer local temperatures maximums and minimums throughout the year
    - Areas near or in large deep lakes or oceans will warm more slowly due to the high heat capacity of water
    - Cold groundwater inputs produce local cold-water refuges in which stream temperature is decoupled from air temperature
    - Poleward-facing slopes and aspects result in shaded areas that buffer solar heating, particularly during the low solar angles of winter and early spring
- **Finding**: Characteristic examples are cold-air pools (CAPs [28]), where temperature inversions are created by concentrated air in valleys and other topographic depressions that is cooler and moister than surrounding uplands. Although most common under clear night skies, still air, and low temperatures, CAPs can become a semi-permanent feature in topographically sheltered areas.
- **Finding**: Persistent seasonal features, such as inland penetration of coastal fog and low stratus clouds caused by offshore upwelling, can also produce large climatic response gradients over short distances [29].
- **Finding**: Wet areas, including wetlands, riparian zones, rock glaciers, and talus slopes (see American pika case study in Fig 2), can act as climate change refugia [30]. In semi-arid and desert regions, groundwater-fed seeps and springs support persistent populations of highly diverse taxa [31].
- **Finding**: Pole-facing slopes generally experience slower hydrologic change [32]. Similarly, deep snow drifts, which can be found in downwind topographic depressions, in granite fissures, or at the base of steep slopes, can serve as important hydrologic reserves. Furthermore, large bodies of water and their surroundings, like coastal areas or deep lakes, are buffered from regional warming because more of the sun's energy is expended in evaporation than in surface heating [7, 33].
- **Finding**: Streams and rivers that are buffered from regional air temperatures via cold groundwater inputs from deep aquifers provide cold, sustained streamflows in regions where water temperatures would otherwise become too warm or streamflows too low during the summer months [37]. Such large, cold, connected river networks are recognized as regional

strongholds for imperiled fish populations facing increasing pressures from climate warming and other stressors [38].

- **Finding**: forest canopies and riparian corridors buffer against climate extremes and variability [44] with consequences for both temperature and water balance.
- **Finding**: Habitat variability (e.g., variable stand densities, forest gaps, evergreen/deciduous mosaics, riparian corridors) can also increase spatial variability in climate, creating shade and allowing for short-distance dispersal and movements to compensate for climate changes.
- **Finding**: Areas that are protected from climate- related disturbance, such as increasingly severe fires and extreme floods, also can be considered climate change refugia [45, 46].
- **Finding**: Ecosystem engineers such as beaver and termites that alter water movement and storage and influence the structure and function of heat exchange processes [47] could also contribute to processes creating and maintaining climate change refugia for other species. For example, deep persistent pools created by beavers buffer aquatic species like trout from extreme drought and effects of wildfire [48].
- **Finding**: Climate change refugia might only be relevant for a certain degree of climatic change, after which conditions in refugia might become climatically stressful for the populations they were designed to protect [29]. Thus, climate change refugia are not necessarily long-term solutions [76]. They function best when coupled with contingency plans, such as tracking geographic shifts in refugial habitats to keep pace with climate change or maintaining genetic material in seed banks, captive propagation, or zoos for future re-introduction.
- **Finding**: Challenges also include questions about the scale at which climate change refugia should be identified and managed, uncertainty about the duration of their effectiveness, and confusion over how to incorporate multiple species or other resources that will respond to climate change in different ways.
- **Finding**: we suggest that climate change refugia will not be appropriate for conserving all resources. Species already limited to extreme environments, such as alpine species restricted to mountain summits, might not be candidates for management with refugia. On the other hand, some species with extensive home ranges could benefit from climate change refugia; the wide-ranging wolverine (Gulo gulo), for example, requiresminimum levels of snowpack for den sites that could potentially be managed [65].
- **Management**: Recommendations for managing climate change refugia:
    - Step 1: the first step of managing climate change refugia is to determine the purpose and scope (Table 1, step 1) by defining the management or conservation target (“valued resource”). The relevant spatial scale can be global, regional, or local
    - Step 2: Assessing vulnerability of the resource to climate change is the next step (Table 1, step 2). Vulnerability assessment considers the sensitivity of a resource and measures its exposure to particular aspects of, as well its adaptive capacity to adjust to, climate change [1, 52].
    - Step 3: Following the vulnerability assessment, management or conservation goals should be reevaluated to ensure they remain attainable [3], including whether refugia management is an effective strategy (Table 1, Step 3). Climate change refugia will be most relevant to resources that are moderately to highly vulnerable to climate change on a regional scale, but for which spatial variability in vulnerability factors suggest local buffering of climate change impacts.
    - Step 4: Where extensive climate and resource data are lacking, first approximations of refugia can be identified based upon the physical and biotic processes that buffer climate change (Fig 1). For example, Ashcroft and colleagues [22] used climatically stable

regions within a topographically diverse landscape to predict regions associated with refugial communities.

    - Other methods recognize climate change refugia based on biological data. Past persistence through climate change might be a clue to locations buffered in the future, either for native species or those that will shift into the area [33]. For example, disjunct populations of cool-temperate plant species (e.g., Tsuga canadensis) are scattered across Ohio, Indiana, Illinois, and Kentucky, apparent relicts of northward postglacial migrations in the late-glacial or early Holocene. The populations are concentrated in unique microhabitats, usually north-facing slopes and shaded ravines.
    - Similarly, relict populations at the rear or trailing edge of a species' range might indicate climate change refugia [59].
    - One can also identify areas of high genetic diversity or persistence for climate vulnerable species or other resources, which might indicate places where populations have persisted owing to climatic stability or high topographic variability.
    - Multiple lines of evidence from combining different approaches can be used to increase confidence in the identification of climate change refugia [63, 64, 69].
    - An essential though rarely accomplished step to use independent data to validate potential climate change refugia by testing predictions for specific taxa or ecological characteristics. The key is to evaluate, as fully as possible, whether a refugial location really meets the needs of the valued resource.
- Step 5: The next step is to prioritize climate change refugia for management. In addition to connectivity, capacity, and size [4, 8, 23, 51, 70], other criteria will be important for prioritization, including representation of valued resources, potential for protecting multiple resources within refugia now and into the future, existing and expected land use change [71], and practical considerations such as the feasibility of management actions and public perspectives.
- Step 6: Once locations are prioritized, management options can be identified (Table 1, step 6). Current suites of management tools and actions will need to be analyzed on a case-by-case basis with the best information of future climate and ecological settings to evaluate long-term benefit.
    - protecting, maintaining, and fostering the features and processes of climate buffering identified in the previous steps could include reducing direct and indirect stressors. For example, removing recreation trails through wet meadows to redirect visitor use improves hydrologic function, increases resilience, and could ultimately protect federally listed wetland species.
    - Active fire and fuel management could be prioritized to protect climate change refugia from, or enhance resilience to, extreme fires that otherwise might damage the ecosystem irreversibly.
    - Similarly, managing groundwater by limiting withdrawals and setting minimum ecological flows is relevant for common conservation practice, but storage, pumping, and other active manipulations may become more important options, despite their associated risks.
    - Unprotected lands identified as climate change refugia could be the focus of acquisitions or easements. If publicly owned, a new area selected for protection specifically for its resistance to climate change could be designated as a climate change refugium via enabling legislation or by another legal or regulatory

        instrument, or as a "climate change refugia emphasis area" in management plans.
    - Step 7: Given the inherent uncertainty in ways that climate change will affect physical resources, habitats, species interactions, and ecosystem functions, adaptively monitoring the effectiveness of identified refugia and realigning locations and management practices accordingly are critical to the climate change refugia conservation cycle (Table 1, step 7). Millar and colleagues [72] recommended flexible approaches that promote reversible and incremental steps and encouraged ongoing learning and modification.
        - Depending on the situation, management actions could focus on improving resistance of refugia (e.g., habitat restoration; [30]) or strategies for assisted migration of prioritized species. Monitoring could also ensure that actions taken, such as prescribed burns and increased connectivity, are not increasing the presence of invasive species.

Olson et al. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou Ecoregion. Nature Areas Journal 31: 65-74.

- **Finding**: They identify a provisional set of 22 highest-priority and 40 high-priority microrefugia that occur mostly outside of existing protected areas and along wetter and lower elevations of the ecoregion
- **Background**: Current anthropogenic stressors are likely compromising the effectiveness of the KS Ecoregion as a refugium for this century's projected changes.
    - Over a century of land use activities (e.g., mining, logging, livestock grazing, damming of rivers, and human-caused alterations of fire) have damaged or destroyed mesic habitats that may have previously functioned as refugia
    - Loss of contiguous habitat along elevational and other environmental gradients
    - Loss and degradation of most of the mature or old-growth forests, particularly mesic lowland and mid-elevation habitats
        - Only about 28% of historic old-growth forests remain
    - Increasing prevalence of invasive plants and pathogens from road-building and land use practices
- **Background**: KS region has acted as biodiversity refuge in the past due to:
    - Special location (latitude and coastal proximity)
    - Rugged terrain
    - Climate stability
    - Complexity of soils and microclimates
- **Background**: The existing protected area system (i.e., National and State Parks, Wilderness Areas, National Monuments, Botanical Areas) is inadequate for ensuring the persistence of most of the ecoregion's vulnerable biodiversity (DellaSala et al. 1999; Noss et al. 1999; Carroll et al. 2010).
    - Existing reserves largely protect higher-elevation communities, while the lower-elevation reserves are limited in their geographic extent, thereby missing many distinct lowland species assemblages and areas that may act as potential microrefugia.
- **Background**: We define microrefugia as sites with cool and moist conditions conducive to the persistence of species vulnerable to climate change.
- **Background**: We define mesorefugia as large areas that contain nested clusters of microrefugia with similar species assemblages that have functioned as a refugium over millennia.

- **Ecological Considerations**: Most of the KS region's biodiversity, endemic species, and species vulnerable to climate change are largely restricted to persistently cool and moist late-successional forest and are:
    - Invertebrates
    - Non-vascular plants
    - Fungi
    - Bryophytes
- **Ecological Considerations**: possible refugia sites for the ecoregion's at-risk endemic serpentine-subtrate flora are sites that will retain wet soil conditions, such as seeps and bogs.
- **Ecological Considerations**: The Russian Wilderness has an extraordinary sympatric assemblage of conifer species whose presence could be due to mesorefugia conditions

Predicted Climate Change Impacts

Anacker, B.L., Gogol-Prokurat, M., Leidholm, K. and S. Schoenig. 2013. Climate change vulnerability assessment of rare plants in California. Madrono 60(3): 193-210.

- **Background**: A changing climate may reduce and extirpate populations (Pounds et al. 2006), cause species to migrate north and upslope (Parmesan 1996; Kelly and Goulden 2008; Loarie et al. 2009), advance flowering times, promote species invasion, increase disturbance (e.g., fire), and cause community reorganization (Walther et al. 2002; Burkett et al. 2005).

Asarian, J. Eli and Jeffrey D. Walker. 2016. Long-term trends in streamflow and precipitation in northwest California and southwest Oregon, 1953-2012. Journal of the American Waters Association, 52 (1): 241-261.

- **Finding**: a few sites (9%) had significant decreasing trends in precipitation
- **Finding**: September precipitation declined at 70% of sites.
- **Finding**: Increased April precipitation in the Upper Rogue Basin and the Upper Klamath Basin
- **Finding**: Decreased January precipitation in the Middle Klamath Basin
- **Finding**: Summer streamflow (June - September) declined at many sites, including 73% of unregulated (non-dam) sites in September
- **Finding**: Groundwater-dominated sites—in comparison to snow- or rain-runoff dominated sites—had a greater percentage of declining trends in streamflow (with precipitation controlled for)
- **Background**: Water availability is an increasing concern for humans and aquatic systems in the West, especially during the hot summer months
- **Background**: Climate is warming, shifting precipitation from snow to rain, reducing snowpack, and causing earlier snowmelt.
- **Background**: In snow-dominated watersheds, the timing of peak streamflow has shifted to earlier in the year.
- **Background**: Summer low-flow levels are likely to decrease as the climate warms
- **Background**: Increased summer temperatures will increase evapotranspiration of natural vegetation, and increase water withdrawals for agriculture and landscaping.

Breining, Greg. 2016. What's a National Park to do about climate change? Ensia Magazine. http://ensia.com/features/whats-a-national-park-to-do-about-climate-change/

- **Background**: Rising temps and changing patterns of precipitation are driving iconic plants and animals out of areas where they have lived for centuries or longer.
- **Background**: National Park Service director Jonathan Jarvis in 2010 called climate change "fundamentally the greatest threat to the integrity of our national parks that we have ever experienced."
- **Background**: precipitation in a warmer world is so hard to predict.

Chmura et al. 2011. Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. Forest Ecology and Management 261: 1121-1142.

- **Background**: Although large natural climatic changes have occurred over centuries to millennia (Jansen et al., 2007), changes of similar magnitude are now projected to occur over decades to years (Meehl et al., 2007; Trenberth et al., 2007). These unprecedented rates of climatic change may profoundly affect the ability of forests to acclimate or adapt to future conditions.

- **Climate Change Impacts**: In the northwestern USA
    - Decrease snowpack
    - Earlier snowmelt
    - Increase summer evapotranspiration
    - Increase the frequency and severity of droughts
    - The effects of CC are generally expected to reduce forest growth and survival
        - However, in some cases, elevated CO^2 and warmer temperatures may have positive effects on growth and productivity where there is adequate moisture or where growth is limited by the cold
    - Predispose forests to disturbance by wildfire, insects, and disease
    - Change forest structure and composition at the landscape scale
- **Climate Change Impacts**: The extent of CC impacts on northwestern US forests will depend upon:
    - The magnitude of Climate Change
    - The ability of individual trees to acclimate
    - The ability of tree populations to adapt *in situ*
    - The ability of tree populations to migrate to suitable habitats
- **Climate Change Impacts**: See Table 1 in paper for a host of effects that increased CO2, increased temperatures, precipitation changes, drought increase, wildfire increase, and disease/insect increases will have on trees.
- **Climate Change Impacts**: Tree growth was generally enhanced in elevated [CO2] in both short- and long-term studies (Ceulemans and Mousseau, 1994; Curtis and Wang, 1998; Norby et al., 1999; Hamilton et al., 2002; Nowak et al., 2004; Ainsworth and Long, 2005; DeLucia et al., 2005; Finzi et al., 2006, but see Körner et al., 2005; Norby et al., 2010)
    - At the individual tree level, increased growth results from physiological adaptations that optimize photosynthetic C acquisition and allocation (Eamus and Jarvis, 1989; Pushnik et al., 1995).
- **Climate Change Impacts**: The leaf area of individual trees and stands (i.e., leaf area index, LAI) may increase under elevated [CO2] (Ceulemans and Mousseau, 1994; Ainsworth and Long, 2005), but the maximum LAI is typically similar in ambient and elevated [CO2] (Norby et al., 2003b; DeLucia et al., 2005).
- **Climate Change Impacts**: Many studies found increases in the production and standing crops of tree roots under elevated [CO2], and increases in the amount and depth of fine-root growth were particularly noticeable (Allen et al., 2000; Tingey et al., 2000; Lukac et al., 2003; Norby et al., 2004; Pritchard et al., 2008, but see Johnson et al., 2006; Bader et al., 2009).
- **Climate Change Impacts**: In separate FACE studies, the deciduous tree Liquidambar styraciflua allocated most of the extra carbon it assimilated in the elevated [CO2] treatment into non-woody fine roots (Norby et al., 2004), whereas the evergreen Pinus taeda allocated most of its additional carbon into woody biomass (Hamilton et al., 2002). Because fine roots have rapid

turnover, these differences may have ramifications for C cycling and overall productivity (DeLucia et al., 2005).

- **Climate Change Impacts**: In the NW, the direct positive effects of warmer temperatures and elevated [CO2] will be realized in only a limited set of environments that do not experience increased droughts, heat stress, or nutrient limitations. Warming-induced decreases in snowpack and increases in evapotranspiration are expected to increase the frequency and intensity of drought stress, with negative consequences for forest growth and health.
- **Climate Change Impacts**: Areas that are moisture-limited are particularly vulnerable. In the NW, this includes low-elevations in the northern Sierra Nevada, Klamath Mountains, Siskyou Mountains, Blue Mountains, Wallowa Mountains, Steens Mountain; Columbia Highlands, northern Rocky Mountains, and eastern foothills of the Cascade Range (Arno, 1979; Franklin and Dyrness, 1988; West and Young, 2000; Littell et al., 2008).
- **Climate Change Impacts**: In areas where limitations by soil moisture and temperature are low (e.g., much of the Coast Range, Olympic Mountains, and mid-elevations in the Cascade Range), future water availability is uncertain because it will depend on the net effects of rainfall, snowfall, snowmelt, surface runoff, subsurface flow, and evapotranspiration.
- **Climate Change Impacts**: Chief concerns are projected increases in droughts, fires, and pest outbreaks, and winter (chilling) temperatures.

Climate Leadership Initiative, National Center for Conservation Science and Policy, Pacific Northwest Research Station. 2008. Preparing for Climate Change in the Rogue River Basin of Southwest Oregon.

- **Climate Change Impacts**
  - **Prediction for Rogue River Basin:** (summary) hotter, drier summers; increasing wildfire risk; reduced snowpack; and rainier, stormier winters
    - projected average temps in the Rogue River Basin may increase 1-3 d F by 2040 and 4-8 d F by 2080 – and summers heat up 7-15 d F by 2080
    - total precipitation may be roughly similar to historic levels but increasingly likely to fall in the mid-winter months rather than spring, summer, and fall
    - rising temps will cause snow to turn to rain at lower elevations and decrease average January snowpack significantly.
    - According to one model, snowpack will decrease by 75% by 2040, and then again by another 75% by 2080 to an insignificant amount
    - Likely to experience more severe storm events, higher and flashier winter and spring runoff events, and more flooding
    - Wet and dry cycles are likely to last longer and be more extreme, leading to periods of deeper drought and periods of more extensive flooding
    - Wildfire: likely a significant increase in the amount of biomass consumed by wildfire
    - **Source**: University of Oregon's Climate Leadership Initiative & National Center for Conservation Science and Policy
    - **Note**: Future forecasts of precipitation in the Rogue River Basin are highly uncertain.

    - Models forecast increased severity and variability of precipitation in Rogue River Basin, which could mean longer and deeper droughts and longer and more severe floods
- **Comparison**: Rogue River Basin could transition into an area with conditions comparable to Sacramento, California

De Frenne et al. 2013

- **Climate Change Impacts**: The thermophilization of vegetation is consistent with the warming climate observed across the regions: the mean rise in Aprilto- September temperatures between the old and recent survey was 0.28 °C·decade−1 (Table S1).

DellaSala et al. 2010. Climate-adapted conservation planning. Powerpoint presentation.

- **Climate Change Impacts by 2075**
  - Winters increase 4-6 degrees F
  - Summers increase 6-10 degrees F
  - Declining snowpack
  - Altered peak stream flows
  - Reduced summer stream flows
  - Precipitation shifting to mid-winter and away from spring-fall
  - Decrease in coastal fog
  - Increase in evapotranspiration

Dugger et al. 2016. The effects of habitat, climate, and Barred Owls on long-term demography of Northern Spotted Owls. The Condor 118: 57-116.

- **Climate Change Impacts**: Climate change is expected to increase the risk of large, high-intensity wildfire in the Pacific Northwest and throughout the western U.S. in general (Westerling et al. 2006, Davis et al. 2011, Stavros et al. 2014).
- **Climate Change Impacts**: In addition, climate change may cause changes in forest tree species composition (Peterson et al. 2014) and even potentially the growth rates of tree species in the Pacific Northwest (Littell et al. 2010, Albright and Peterson 2013).

Grant, Evan H. Campbell and David A. W. Miller, Benedikt R. Schmidt, Michael J. Adams, Staci M. Amburgey, Thierry Chambert, Sam S. Cruickshank, Robert N. Fisher, David M. Green, Blake R. Hossack, Pieter T. J. Johnson, Maxwell B. Joseph, Tracy A. G. Rittenhouse, Maureen E. Ryan, J. Hardin Waddle, Susan C. Walls, Larissa L. Bailey, Gary M. Fellers, Thomas A. Gorman, Andrew M. Ray, David S. Pilliod, Steven J. Price, Daniel Saenz, Walt Sadinski & Erin Muths. Quantitative evidence for the effects of multiple drivers on continental-scale amphibian declines. Scientific Reports, 2016 DOI: 10.1038/srep25625

  - **Climate Change Impacts**: Evidence shows that climate changes are the cause of amphibian declines across the southern USA and the West Coast

Harrison, S., Damschen, E.I. and J.B. Grace. 2010. Ecological contingency in the effects of climate warming on forest herb communities. www.pnas.org/lookup/suppl/doi:10.1073/pnas.1006823107/-/DCSupplemental.

- **Findings**: Our results provide community level validation of predicted nonlinearities in climate change effects.

- **Background**: Upward and poleward shifts of species and vegetation zones are expected under climatic warming, and considerable evidence has been found in support of these broad predictions (1–5).
- **Background:** However, large differences among communities in the magnitude, rate, and direction of responses to climatic warming are also expected, based on factors such as topography and substrate, land use history, and community-level variation in species functional traits (e.g., 6, 7–10).
- **Climate Change Impacts**: One of the earliest and best-known expectations about contingency is that climate change effects should be most pronounced at high elevations where plant growth is most strongly limited by temperature (14), specifically by the length of the snow-free growing season.
    - This expectation is based on studies in the alpine and nival zones of the European Alps and elsewhere, where warming temperatures have been observed to lead to increases in plant productivity and species richness, although with losses of high-elevation specialist species, presumably as the result of competition (e.g., 9, 14–16).
- **Climate Change Impacts:** However, growing evidence also shows severe effects of climatic warming in warm and water-limited biomes, such as the western United States at low to moderate elevations, where enhanced drought stress has led to widespread vegetation die-off (e.g., 2, 17, 18).
    - In fact, physiologically based models predict that a given amount of growing-season warming should reduce plant growth at water-limited low elevations while enhancing it at temperature-limited higher elevations (e.g., 12, 19), a straightforward prediction that accords with data on tree growth rates (11), remotely sensed productivity indices (20), and shifts in flowering phenology (21).
- **Climate Change Impacts**: Mean annual temperatures and mean summer temperatures have increased [in the Klamath-Siskiyous] ≈2 °C since 1948, and snow-water equivalent (the product of snow depth and snow relative density) has declined, although mean and seasonal precipitation have not changed significantly (28–30).
- **Climate Change Impacts**: The primary effect of climatic warming in water-limited environments, in the absence of changes in precipitation, is to exacerbate drought stress (5, 17, 18). Accordingly, we found that Siskiyou low-elevation forest herb communities have shifted toward a greater prevalence of species with small, thick leaves (lower SLA) that are better adapted to dry conditions than species with large, thin leaves (32–34).
- **Climate Change Impacts**: Had our study extended into still higher Siskiyou elevations where there is no forest cover, we would expect to find increases in herb cover and richness similar to those observed in Alpine studies (e.g., 15, 16, 50).
- **Climate Change Impacts**: Water limitation may potentially become more important at progressively higher elevations as the snowpack diminishes or disappears completely.

Lienard, J., Harrison, J. and N. Strigul. 2016. US forest response to climate-related stress: a tolerance perspective. Global Change Biology, doi: 10.1111/gcb.13291

- **Finding**: We estimate that 18% of US ecosystems are vulnerable to drought-related stress over the coming century. Vulnerable areas include mostly the Midwest United States and Northeast United States, as well as high-elevation areas of the Rocky Mountains.
- **Finding**: Some of the climate conditions (and hence drought tolerance characteristics)

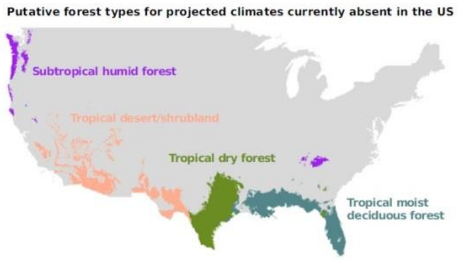


Fig. 4 Putative forest types for which projected future climatic conditions are outside the TDM range in the United States (areas in purple in d and f) using RCP 8.5 as a forcing scenario.

anticipated to occur over the next several decades do not currently exist in the conterminous United States (Williams et al., 2007; Ackerly et al., 2010). The Pacific Northwest's Cascades are anticipated to have a climate similar to China's Fujian Province or Southern Brazil's Parana and Santa Catarina. As all analogs for the projected US Pacific Northwest climate area are far away, it is uncertain what species will migrate to fill the ecological niches created by a changing climate.

Mote et al. 2003. Preparing for climate change: the water, salmon, and forests of the Pacific Northwest. Climate Change 61: 45-88.

- **Climate Change Impacts:** Warmer, drier years, often associated with El Niño events and/or the warm phase of the Pacific Decadal Oscillation, tend to be associated with below-average snowpack, streamflow, and flood risk, below-average salmon survival, below-average forest growth, and above-average risk of forest fire.
- **Climate Change Impacts**: During the 20th century, the PNW experienced a warming of 0.8 ◦C.
  - Using output from eight climate models, we project a further warming of 0.5–2.5 ◦C (central estimate 1.5 ◦C) by the 2020s, 1.5–3.2 ◦C (2.3◦C) by the 2040s, and an increase in precipitation except in summer. The foremost impact of a warming climate will be the reduction of regional snowpack, which presently supplies water for ecosystems and human uses during the dry summers.
- **Climate Change Impacts:** For water resources, all climate scenarios lead (with high confidence) to the large-scale loss of snowpack at moderate elevations by mid-century, bringing large reductions in summer flow in all streams and rivers that depend on snowmelt.
- **Climate Change Impacts**: For forests, the first-order effects of reduced snowpack will enhance establishment and growth at high elevations and increase drought stress at lower elevations, but the effects will depend strongly on the site and moisture conditions of specific stands, and are subject to two important uncertainties: the magnitude and consequences of CO2-induced increases in water-use efficiency, and the capacity for increased seasonal soil-moisture storage, which could allow increased winter rains to offset the increased drought stress from warmer summers.

Myer, G. 2013. The Rogue Basin Action Plan for Resilient Watersheds and Forests in a Changing Climate. Thaler, T., Griffith, G., Perry, A., Crossett, T., Rasker, R. (Eds). Model Forest Policy Program in association with the Southern Oregon Forest Restoration Collaborative, the Cumberland River Compact and Headwaters Economics; Sagle, ID. December, 2013.

- **Findings**: The key risks identified include
  - uncharacteristic impacts of severe wildfire to forest ecosystems;
  - declines in water quantity and quality;
  - risks to the various values (ecosystem services) people receive from the forests.
- **Climate Change Impacts**: Key climate impacts in the Rogue Basin include
  - increase in severity and frequency of wildfires;
  - decreased snowpack and earlier snowmelt affecting water quality and quantity for humans and wildlife;
  - increase severity in droughts and flooding;
  - higher elevation transition from snow to rain;
  - increasing stream temperatures which are already a large issue in the Basin;
  - biogeographic shifts in species' ranges.

  - Average temperatures are expected to rise in the Rogue Basin between 2.3 and 4.5°C (4.3 and 8.2°F) by 2075-2085 (USFS MAPSS data), even if efforts are taken to mitigate climate change.
- **Climate Change Impacts**
  - Snowfall
    - Rising temperatures will likely cause precipitation to fall as rain at lower elevations rather than as snow on peaks so average January snowpack will decrease; by 2035 – 2045 snowpack may be reduced 60 – 65% and by 2075 – 2085 as much as 90%. This will likely reduce run-off during late summer / fall and substantially reduce available irrigation and drinking water.
  - Severe weather
    - Weather variability is likely to increase as both wet and dry cycles are likely to increase in length and severity. Many more days are likely to exceed 900F and 1000F while more heavy rainfall days are likely. More precipitation falling as rain at low elevations rather than snow at high elevations is likely to increased flash flood frequency in Winter and Spring.
  - Wildfires
    - Longer droughts and higher temperatures with more intense heat waves will likely increase substantially the amount of (vegetation) forest lost to wildfire.
  - Vegetation
    - With warming and drying, climatic conditions will likely become more appropriate for deciduous forest communities such as oaks and other hardwoods while conditions for higher elevation spruce/fir/hemlock communities will be severely compromised and those for Douglas-fir will likely be reduced in area. Grassland and scrubland conditions are likely to expand as forest conditions diminish.
  - Native aquatic systems
    - With increases in storms and fires, enhanced soil erosion will likely cause greater stream sediment and mineral build-up. Increased summer air temperatures will elevate water temperatures reducing critical dissolved oxygen concentrations and potentially enhancing bacterial and disease conditions. Reduced snowpack and earlier snowmelt will likely modify current stream flow patterns. With warmer water temperatures earlier aquatic insect emergence is probable, compromising historic food availability pulses for migratory fish. Reduction in conditions for many native fish species may be accompanied by range expansion of non-native species.
  - Native terrestrial systems
    - Probable increase in wildfires and lengthened fire seasons may induce dramatic shifts in vegetation communities towards more fire-adapted associations. Both invasive and non-native species abundances may be enhanced as natives are reduced. Particularly at risk are mature forests and the wildlife species they support as well as amphibians which will have limited dispersal capacity as conditions become dryer. Disruption of synchronicity is likely between insect development and nesting / hatching particularly of migrant bird species. Bark beetle conditions will be enhanced, increasing the threat to native forests.
- **Climate Change Impacts**: Additionally, several studies indicate that climate change is likely to exacerbate forest damages resulting from disease and pests such as the mountain pine beetle.

    - Mountain pine beetle populations are typically held in check by cold winters (EcoNorthwest, 2009). As the frequency of cold winters decreases, the mountain pine beetle's population will no longer be constrained. This could lead to rapid and widespread tree mortality. Furthermore, the mountain pine beetle is now beginning to show a potential to jump to non-pine species if pine is no longer available (EcoNorthwest, 2009). Mountain pine beetles potentially could impact the majority of remaining forest in Oregon. Adding to the problem, stressed trees increase the concentration of amino acids in their tissues, making them more nutritious for herbivorous insects (that are generally nitrogen limited) (Hsiao, 1973). Stress from insects and pathogens coupled with other local stressors such as increased temperatures and decreased soil moisture, will hasten tree mortality.
- **Climate Change Impacts**: Potential ecological implications of these hydrological changes, especially in conjunction with increases in air temperature, earlier snowmelt, and changes in precipitation, could result in shifts in native fish assemblages.
- **Climate Change Impacts**: One of the greatest current and future risks to the water system is stream temperatures. All of the sub basins of the Rogue Basin are over the recommended stream temperatures by ODEQ, and these are projected to increase further in stream temperature.
- **Climate Change Impacts**: Southwestern Oregon is one of the key regions where fire frequency is expected to increase with climate change (Westerling et al. 2006). There has been a six-fold spike in the area of forest burned since 1986 in the Pacific Northwest as compared with the 1970-1986 period (CIER 2007). One can see a notable shift to larger fires in terms of acres burned starting around 1985, with the fires of 2013 (Figure 23) bringing a record number of acres burned for the region in the past 50 years. Forests are expected to continue to have large impacts from increased incidence of fire (CIER 2007). Duration of fires has also increased from 7.5 to 37.1 days since 1986 (CIER 2007). This affects forest, water quality for human use, human health, soil quality, forest productivity, and habitat for a variety of species.
- **Climate Change Impacts**: A primary effect of climatic change in water-limited environments, such as the dry forests of Southwest Oregon, is to exacerbate drought stress.
- **Ecological Considerations**: Analyses of the impact of climate projections on the forests of southern Oregon (e.g. Doppelt et al. 2008) indicate that the Douglas-fir association is likely to diminish but that the ponderosa pine and oak chaparral associations are likely to expand. By way of contrast, the climate envelope analyses of Rehfeldt et al. (2006) that identify where future conditions are likely to be suitable for the success of western tree species indicate that both the Douglas-fir and ponderosa pine are at risk.

Noss, Reed F. 2001. Beyond Kyoto: forest management in a time of rapid climate change. Conservation Biology 15(3): 578-590.

- **Background**: Rapid range shifts in response to warming trends over the last few decades have been documented for a number of species of vertebrates and invertebrates (Wuethrich 2000).
    - For example, in a sample of 35 nonmigratory European butterflies, 63% have shifted their ranges to the north by 35–240 km during this century, whereas only 3% have shifted south (Parmesan et al. 1999).
    - Nevertheless, migration to track a rapidly changing climate may be difficult for species with poor dispersal abilities, such as small forest vertebrates and flightless invertebrates, especially in relatively homogeneous landscapes with few opportunities for short-distance moves into suitable microhabitats.

    - Barriers to movement may be formidable in fragmented landscapes (Noss & Csuti 1997).
- **Background**: Some species may adapt to climate change by in situ evolution. The modern Great Basin (U.S.) flora, for example, appears to consist of a mix of species that migrated northward from Pleistocene refugia in the southern portions of the region, and species that changed little in distribution during the Pleistocene and coped with climate change by genetic adaptation (Nowak et al. 1994).

Olson et al. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou Ecoregion. Nature Areas Journal 31: 65-74.

- **Climate Change Impacts**: Diminishment of fog in KS region (Johnstone and Dawson 2010)

Spittlehouse and Stewart. 2003.

- **Climate Change Impacts**: By the end of the 21st century, the mean annual temperature for western North America could be 2–5°C above the range of temperatures that have occurred over the last 1000 years.
- **Climate Change Impacts**: An increase in winter precipitation and a decrease in summer precipitation may also occur. These changes would significantly affect human society and ecosystems (McCarthy et al. 2001).

Stralberg, D., Jongsomjit, D., Howell, C.A., Snyder, M.A., Alexander, J.D., Wiens, J.A. and T.L. Root. 2009. Re-shuffling of species with climate disruption: a no-analog future for California birds? PLoS ONE 4(9): e6825. doi:10.1371/journal.pone.0006825

- **Climate Change Impacts**: Climate models generally concur in projections of significant warming for California over the next century, with small changes in precipitation but potentially large declines in snow accumulation [22,23].

Climate Change Vulnerability

Anacker, B.L., Gogol-Prokurat, M., Leidholm, K. and S. Schoenig. 2013. Climate change vulnerability assessment of rare plants in California. Madrono 60(3): 193-210.

- Finding: There was no correlation of the CCVI scores with rarity type, suggesting that climate change vulnerability cannot be inferred by simple categorizations based on geographic range and habitat preference.
- Finding: Life history trait assumed to lead to high vulnerability to climate change (table 2):
  - Lower dispersal ability leads to high vulnerability.
  - Narrow historical climate exposure and special microclimatic preferences leads to high vulnerability.
  - Dependence on a particular disturbance regime leads to high vulnerability.
  - Habitat specialization leads to high vulnerability.
  - Dependence on other species (facilitation, pollinators, and seed dispersers) leads to high vulnerability.
  - Genetics: Low genetic diversity leads to high vulnerability.
  - Phenological response: Shorter bloom period leads to high vulnerability.
- Finding: Of the 156 rare plant species assessed, 99 (~2 out of every 3) were determined to be vulnerable (extremely vulnerable, highly vulnerable, or moderately vulnerable) to climate change and 48 were determined to be stable or increasing (presumed stable or increase likely). The distribution of final scores was: extremely vulnerable (n 5 2), highly vulnerable (n 5 40), moderately vulnerable (n 5 57), presumed stable (n 5 32), increase likely (n 5 16), and insufficient evidence (n 5 9).
- Finding: We found the CCVI scores were independent of both California Rare Plant Rank and rarity type. This suggests that the rarest species, such as the California Rare Plant Rank 1B species or habitat specialists with small ranges and small population sizes, are not necessarily the most vulnerable to climate change.
- Management: The information produced in our vulnerability assessments will be useful in identifying the most vulnerable rare plant species to climate change, which can then be carefully monitored.

Olson et al. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou Ecoregion. Nature Areas Journal 31: 65-74.

- Ecological Considerations: the responses of vulnerable taxa to climate change will necessarily be local due to a limited capacity of many species to move to new habitat.
- Ecological Considerations: The region’s endemic serpentine flora is highly vulnerable to projected increases in warming and drying (Damschen et al 2010) and some taxa may only persist within persistently wet pockets and seeps surrounded by late-seral forests (mature and old-growth)

Benefits of Healthy Ecosystems

Asarian, J. Eli and Jeffrey D. Walker. 2016. Long-term trends in streamflow and precipitation in northwest California and southwest Oregon, 1953-2012. Journal of the American Waters Association, 52 (1): 241-261.

- **Finding**: The most pristine surface-runoff-dominated watersheds in the study area showed no decrease in streamflow (with precipitation controlled for) during the summer months
    - **Explanation**: streamflow decreases at other sites are likely due to increased human withdrawals and vegetation changes, and not due to climate factors
    - **In the Future**: Increasing temperatures will increase evapotranspiration and decrease streamflow

Chmura et al. 2011. Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. Forest Ecology and Management 261: 1121-1142.

- **Background**: Ecophysiological processes are the foundation of acclimation and evolutionary adaptation for trees to climate change. Although phenotypic plasticity is substantial for some traits (e.g., timing of bud flush), the existence of among-population genetic variation for bud flush and many other adaptive traits indicates that phenotypic plasticity is insufficient to confer optimal fitness to the range of climates experienced by most species (Rehfeldt et al., 2001; St.Clair and Howe, 2007). Because trees are genetically adapted to their local climates, rapid rates of climate change may challenge the capacity of tree species to adapt in place or migrate to new locations (St.Clair and Howe, 2007; Aitken et al., 2008).
- **Governance**: Northwest forests will continue to be an important part of the regional economy and may play a significant role in carbon (C) sequestration and climate change mitigation (Alig et al., 2006; Krankina and Harmon, 2006).

DellaSala, D.A., Baker, R., Heiken, D., Frissell, C.A., Karr, J.R., Nelson, S.K., Noon, B.R., Olson, D. and Strittholt, J., 2015. Building on Two Decades of Ecosystem Management and Biodiversity Conservation under the Northwest Forest Plan, USA. Forests, 6(9), pp.3326-3352.

- **Background**: Older forests and intact watersheds generally provide a myriad of ecosystem services associated with high levels of biodiversity [77,78]. Some examples of ecosystem services that have benefited from the NWFP include net primary productivity, water quality, recreation such as camping and hunting, salmon productivity, and carbon storage and sequestration. Older forests with high biomass (>200 mg carbon/ha, live above ground biomass of trees) most abundantly provide these services in aggregate primarily on federal lands [79].
- **Background**: The storage of carbon on federal lands is especially noteworthy because the region's high-biomass forests are among the world's most carbon dense forest ecosystems [80,81]. When cut down, these forests quickly release about half their carbon stores as CO2 [82]. Reduced logging levels and increased regrowth under the NWFP has resulted in the regional forests shifting from a net source of CO2 prior to the NWFP to a net sink for carbon during the NWFP time period [83]. While most of the carbon losses on federal lands are the result of forest fires, logging (mostly on nonfederal lands) remains the leading cause of land-use related CO2 emissions [84]. Forests regenerating from natural disturbances including fire also rapidly sequester carbon and can then store it for long periods via succession if undisturbed. By

comparison, logging places forests on short-rotation harvests, thereby precluding long-periods of carbon accumulation [82,83].

Frey et al. 2016. Spatial models reveal the microclimatic buffering capacity of old-growth forests. Sci. Adv. 2016; 2:e1501392 22 April 2016.

- **Finding**: Complex forests do good job of regulating temperatures on the ground… the more structurally complex the forest (more big trees, more vertical layers), the cooler it was, as much as 4.5 degrees F on warm days.
    - Old growth forests also held in heat during cold weather--these forests have a moderating effect on temp extremes.
- **Finding**: Old-growth vegetation appeared to have insulating effect on temperature; max springtime monthly temps decreased by 2.5 degrees C across the old growth gradient (from structurally simple plantations to complex old-growth forests). Overall, these influences of old-growth forests on thermal conditions were consistent between years.
    - These cooling effects across a gradient in forest structure are of similar magnitude to 50-year forecasts of the Intergovernmental Panel on Climate Change and therefore have the potential to mitigate climate warming at local scales.
- **Finding**: Maximum monthly temperatures (C) decreased by 2.5°C (95% confidence interval, 1.7° to 3.2°C) and observed minimum temperatures (D) increased by 0.7°C (0.3° to 1.1°C) across the observed structure gradient from plantation to old-growth forest.
- **Finding**: Sites with old-growth forest traits (for example, taller canopies, higher biomass, and more complex vertical structure) had reduced temperatures and greater temperature stability (fig. S2).
- **Finding**: To our knowledge, this is the first evidence that subtler structural differences within mature forest types (that is, mature plantations versus old-growth forests) mediate under-canopy temperature regimes.

Noss, Reed F. 2001. Beyond Kyoto: forest management in a time of rapid climate change. Conservation Biology 15(3): 578-590.

- **Background**: If educated to understand the multiple benefits of sustaining diverse, healthy, resilient forests, people will place value on protecting these forests.

Strittholt, J.R., DellaSala, D.A. and H. Jiang. 2006. Status of Mature and Old-Growth Forests in the Pacific Northwest. Conservation Biology 20(2): 363-374.

- **Background**: Decades of research in the Pacific Northwest have documented the many values of old-growth forests, including their importance as wildlife habitat, regulation of hydrologic processes, sequestration of carbon, and maintenance of soil and nutrient processes (Norse 1990; Franklin & Spies 1991a; Thomas 1991; NRC 2000; Lindenmayer & Franklin 2002).
- **Background**: The Forest Ecosystem Management Assessment Team (FEMAT 1993) responded to concerns about the management of old-growth forests within the range of the federally threatened Northern Spotted Owl (Strix occidentalis caurina) and determined that approximately 1084 species were associated with older forests, including 10 species on the federal endangered species list.

Management – General

Breining, Greg. 2016. What's a National Park to do about climate change? Ensia Magazine. http://ensia.com/features/whats-a-national-park-to-do-about-climate-change/

- Ecological Considerations: One extreme is to let nature take its course. The other is assisted migration of Joshua trees to suitable areas where they don't exist now. In between might be collecting seeds and planting them in their current range if in the future it becomes too warm for the plants to seed naturally, or controlling invasive species to make life easier for the native ones.
- Management: But to protect other species, such as the bull trout in Glacier, wildlife biologists have taken a step that's radical by the standards of the NPS, which is usually loath to move species: Fishery managers have caught native bull trout and transported them upstream of barrier waterfalls to upper reaches of mountain streams that are both cooler and — so far, anyway — free of marauding lake trout. "We're trying to ensure the genetic lineage of those bull trout that survive in that watershed, so we are moving them up the watershed where historically they never existed," Mow says.
- Management: The whitebark pine is another high-elevation species predicted to disappear from much of its current range within a few decades. Some scientists are already preparing to plant whitebark pine in areas more to the trees' liking in years ahead, a strategy called assisted migration. "In some cases the strategy may be completely hands off, letting nature figure out if it's resilient enough and see how it evolves. On the other end of the scale, the strategy might be assisted migration. Will we be moving plant species hundreds of miles north of their current range as a way of ensuring their survivability?"

Cahall, Rebecca E. and John P. Hayes. 2009. Influences of postfire salvage logging on forest birds in the Eastern Cascades, Oregon, USA. Forest Ecology and Management 257: 1119-1128.

- Management: We suspect that our observations of greater abundances of ground and shrub-nesting species and lower abundances of species associated with snags in the early years following postfire salvage logging are likely to be consistent throughout dry ponderosa pine and Douglas-fir forests in the interior west of North America.
- Management: Salvage logging influenced abundances of cup-nesting and cavity-nesting species. Morissette et al. (2002) similarly found that salvage logging influenced the numbers of cup-nesting birds in boreal forests of mixed-wood and jack pine after fire. The response of cup-nesting forest birds, especially sensitive and of conservation concern, should be considered in addition to the response of cavity-nesting species when implementing management prescriptions of salvage logging.
- Management: The black-backed woodpecker is a species of management concern and is designated as a ''sensitive species'' in Oregon (Oregon Natural Heritage Information Center, 2004) and Idaho (USDI, 2003), and a ''species of concern'' in Montana (Montana Natural Heritage Program and Montana Fish Wildlife and Parks, 2006). Our results support previous conclusions that the blackbacked woodpecker is less abundant in salvaged forests than in unsalvaged forests (Caton, 1996; Saab and Dudley, 1998; Haggard and Gaines, 2001; Hutto and Gallo, 2006; Koivula and Schmiegelow, 2007; Saab et al., 2007); retention of areas of unsalvaged habitat may be of particular importance for this species.
- Management: If the maintenance of native species of bird populations is a goal of forest management, than managers should leave some burned forest for birds that are postfire specialists, particularly forest that is otherwise suitable for salvage. Additionally, as influences of

salvage logging are not limited to cavity-nesting species, the response of cup-nesting birds should also be considered when implementing salvage logging.

Chmura et al. 2011. Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. Forest Ecology and Management 261: 1121-1142.

- Management: Effective approaches to climate adaptation for forests will likely include:
    - Assisted migration of species and populations
    - Forest density management
        - Use of these approaches to increase forest resistance and resilience at the landscape scale requires a better understanding of species adaptations, within-species genetic variation, and the mitigating effects of silvicultural treatments
- Management: Recent discussions of proactive strategies for helping forests adapt to climate change have outlined several common principles, including:
    - assessing risk
    - acknowledging uncertainty
    - making use of adaptive learning
    - developing novel and flexible approaches that can deal with unforeseen problems
        - Sources: (Ledig and Kitzmiller, 1992; Spittlehouse and Stewart, 2003; Ohlson et al., 2005; Spittlehouse, 2005; Millar et al., 2007).
- Management: Climate change opportunities include increased growth in areas that are currently cold-limited, and CO2 fertilization which may have net positive effects, or help ameliorate stresses resulting from climate change.
- Management: To effectively respond to climate change, land managers need spatially explicit assessments of forest vulnerability that provide combined, integrated assessments of all threats and opportunities. This information could be used to target areas for enhanced monitoring, gene conservation, silvicultural treatments to increase forest resistance or resilience, or priority harvest.
- Management: Managers should seek to lessen vulnerabilities by paying attention to key stages of forest development, and by sustaining or enhancing traits that promote adaptability. Trees are most vulnerable during the regeneration phase (reviewed in van Mantgem et al., 2006; Nitschke and Innes, 2008).
- Management: the effects of climate change on the fitness of naturally regenerated stands are probably underestimated, and provenance tests that assess climatic effects on the regeneration phase are sorely needed. Once trees become established, they are generally more resistant to climatic influences. For example, recently germinated seedlings are more susceptible to damage from heat, frost, damping-off fungi, and the drying of the soil surface (Hermann and Chicote, 1965), but may be less susceptible to certain pests (e.g., bark beetles) and competition for limiting resources
- Management: Various genetic strategies could be used to help forests adapt to climate change, including assisted migration, traditional or molecular breeding, and gene conservation. Existing

trees may be able to resist, tolerate, or acclimate to modest changes in climate, but phenotypic plasticity will probably be insufficient in the long-term (Jump and Pe˜nuelas, 2005).

  - Management: Genetic variation among populations can provide adaptability to the more extreme, long-term climatic changes. Knowledge of population-level variation in adaptive traits has been used to develop seed transfer guidelines designed to prevent the use of maladapted seed sources (cf. Campbell, 1974; Rehfeldt, 1987). More recently, field and nursery provenance tests have been used to assess the adaptability of species and populations to new climates (Matyas, 1994; Schmidtling, 1994; Rehfeldt et al., 2001; St.Clair and Howe, 2007).

- Management: We should be able to lessen the adverse effects of climate change using within-species assisted migration, which is the purposeful movement of species or populations to areas where they are expected to be better adapted in the future (McLachlan et al., 2007; O'Neill et al., 2008). Despite the promise of this approach, comprehensive studies of adaptive genetic variation are rare in non-commercial and non-threatened tree species, shrubs, and other plant groups.
- Management: Any forest attribute or management practice that increases stress will also increase forest vulnerability to future climates. Vulnerable stands are those that are comprised of species or seed sources that are maladapted to future conditions, overstocked, or have high levels of competing vegetation. Based on the knowledge of expected impacts of climate change, foresters should employ genetic and silvicultural management options that target the most vulnerable sites, life stages, traits and processes to increase forest adaptability.

Climate Leadership Initiative, National Center for Conservation Science and Policy, Pacific Northwest Research Station. 2008. Preparing for Climate Change in the Rogue River Basin of Southwest Oregon.

- Management: Recommendations to prepare aquatic and terrestrial systems for climate change:
  - Terrestrial systems
    - Protect and restore ecosystem function, structure, and genetic diversity
      - To enable organisms to withstand and adapt to climate stressors
    - Use fire strategically to reduce the likelihood of severe fire, and then replant with a diverse array of native species
    - Apply ecologically-appropriate fuels reductions (where needed)
    - Protect remaining intact habitats, especially
      - Old growth
      - Roadless areas
      - Corridor connections (to aid wildlife migration)
    - Protected areas should be expanded longitudinally and latitudinally
      - To allow species to shift ranges
    - Identify, protect, and restore land and stream reaches that provide critical ecosystem services
    - Translocate native species when they cannot do this for themselves, due to habitat fragmentation or too-swift changes in climate
  - Aquatic and Terrestrial Systems
    - Reduce existing stressors

        - Habitat fragmentation
        - Erosion from resource extraction and roads
        - Air and water pollution and contamination
        - The loss of keystone species
        - Invasive species
        - Conversion of natural habitats to urban and suburban
- Management: Forest management recommendations
    - Build resistance and resiliency through greater structural and genetic vegetation diversity
    - Manage forests with longer harvest rotations to sequester more carbon, and may acquire credits in a cap and trade system
- **Governance** recommendations
    - Reorient management plans to focus on "future range of climate variability"
    - Use "scenario planning" methods to identify and plan for climate futures
    - Increase public understanding of the likely consequences of climate change

Damschen, E.I., Harrison, S., Ackerly, D.D., Fernandez-Going, B.M. and B.L. Anacker. 2012. Endemic plant communities on special soils: early victims or hardy survivors of climate change? Journal of Ecology 100: 1122-1130.

- **Background**: One of the greatest challenges that ecologists and land managers face today is anticipating how climate change will affect the diversity and composition of ecological communities to develop effective strategies for adaptation and mitigation (e.g. Burkett et al. 2005; Glick, Stein & Edelson 2011; Klausmeyer et al. 2011).

DellaSala et al. 2010. Climate-adapted conservation planning. Powerpoint presentation.

- Management: Reserve design
    - Robust reserve design = microfeguia + connectivity – land use stressors
    - Current protection (in 2010) of 13% of KS Region would need to increase to 50%
- Management: Goals for reserves in a changing climate
    - Represent plant communities in well-distributed reserves
    - Maintain focal species and special elements
    - Maintain key processes (fire, hydrology, evolutionary hot spots)
    - Provide for resilient ecosystem properties
    - Identify and protect microrefugia
        - Coastal influence
        - Higher precipitation
        - Middle elevations
        - Vegetation stability
        - North-facing slopes
    - Identify critical links, connectivity among microrefugia, and among elevational gradients
- Management: For microrefugia and connectivity
    - Intact old forest blocks spanning elevation zones are needed to connect refugia
- Management: Reduce non-climate stressors
    - Livestock
    - Invasives
    - Logging of old forests
    - Habitat fragmentation

    - Floodplain/coastal development
    - Flooding
    - Over allocation of water
    - Species declines
    - Energy development
    - Human footprint
    - Disease
    - Overfishing
    - Inappropriate fire management
- Management: old forest protection = carbon storage

DellaSala, D.A., Baker, R., Heiken, D., Frissell, C.A., Karr, J.R., Nelson, S.K., Noon, B.R., Olson, D. and Strittholt, J., 2015. Building on Two Decades of Ecosystem Management and Biodiversity Conservation under the Northwest Forest Plan, USA. Forests, 6(9), pp.3326-3352.

- **Background**: Conservation scientists have long-recognized that effective conservation planning involves two complementary approaches: a coarse filter consisting of representative reserve networks, and fine filter that includes local protections for species outside reserves [18,19]. FEMAT [2] emphasized the need for a large, interconnected reserve network as fundamental to biodiversity conservation [1,20,21]
- **Background**: conservation biology principles guided the design of the NWFP [2]:
    - Species that are widely distributed are less prone to extinction than those with more restricted ranges because local population dynamics are more independent [31]. Large patches of habitat supporting many individuals are more likely to sustain those populations than small patches because larger populations are less subject to demographic and environmental stochasticity [32,33].
    - Populations residing in habitat patches in proximity are less extinction prone than those in widely separated patches because the processes of dispersal and recolonization are facilitated [34].
    - The extent to which the landscape matrix among habitat patches (supporting local populations of the focal species) resembles suitable habitat, the greater the connectivity among local populations leading to lower extinction risks [35].
    - Sustaining a species over the long-term requires that demographic processes be evaluated at three key spatial scales: territory, local population, and metapopulation [36].
- **Background**: Improvements to the NWFP's ecosystem and conservation focus are especially relevant today given: (1) the spotted owls' precarious status, including increased competition with barred owls; (2) continuing declines in murrelet populations; (3) other at-risk species recently proposed for listing (e.g., Pacific fisher Martes pennanti, North Oregon Coast Range distinct population segment of the red tree vole Arborimus longicaudus); (4) numerous forest associated invertebrates and lesser known species with restricted ranges that are vulnerable to extinction as a result of climate change [24]; and (5) additional ESU's of Pacific salmon that have been listed with none recovered to the point of delisting. Recent and ongoing land-use stressors acting alone or in concert, especially on nonfederal lands, also need to be reduced along with improved forest management practices and stepped up conservation efforts (Table 4).
- Finding: Table 4 provides specific suggestions for improving conservation impact of Northwest Forest Plan: page 3340.
- Management: We urge federal land managers to:

  - (1) protect all remaining late-successional/old-growth forests;
  - (2) identify climate refugia for at-risk species;
  - (3) maintain or increase stream buffers and landscape connectivity;
  - (4) decommission and repair failing roads to improve water quality;
  - (5) reduce fire risk in fire-prone tree plantations;
  - (6) prevent logging after fires in areas of high conservation value.
- **Management**: As forest plan revisions go forward in the region, the reserve network needs to be expanded in response to increasing land-use stressors to ecosystems and at-risk species, and to provide for a more robust conservation framework in response to climate change.
- **Management**: Livestock grazing in combination with climate change is also now the biggest impact to biodiversity on federal lands that needs to be offset by new protections such as large blocks of ungrazed areas [88].
- **Management**: Regional carbon storage capacity can be increased if managers both protect carbon stores in older high biomass forests and allow young forests to re-grow for longer periods [83,84]. Managing for high-biomass forests is also associated with the multifunctionality of ecosystems because carbon dense forests are associated with high levels of biodiversity and numerous other ecosystem services [79].

DellaSala, Dominick A. 2016 White Paper. Do mountain pine beetle outbreaks increase the risk of high-severity fires in Western forests: a summary of recent field studies. Geos Institute.

- **Background**: Thus, the effect of fires on susceptibility to outbreaks may be contingent on current and future climate influences on beetle populations and tree resistances. Occurrence of large severe bark beetle outbreaks also may deplete tree host populations that then reduce the probability of subsequent outbreaks for 70 years or more4. For example, under a weather scenario of future dry climate, reduction of host tree populations may lower the probability of subsequent bark beetle outbreaks in some forest types
- **Background**: In general, the major results of roads on the terrestrial environment include increases in forest fragmentation and disruption of the natural movement of species across the landscape. Aquatic systems are impacted through disruption of natural infiltration of water into the soil and increased runoff to streams. While proper road engineering can help mitigate some negative effects, it does not mitigate the overall impact of roads on hydrologic processes, water flow, and fragmentation of wildlife habitat by roads that act as chronic stressors to ecosystems. Roads also increase human-caused fire ignitions due to greater access during fire season.

Frey et al. 2016. Spatial models reveal the microclimatic buffering capacity of old-growth forests. Sci. Adv. 2016; 2:e1501392 22 April 2016.

- **Background**: Given that old-growth forests continue to decline globally (23) and that plantations continue to proliferate (24), understanding microclimatic impacts is of great conservation importance.
- **Management**: Management strategies to conserve old-growth characteristics and to curb current rates of primary forest loss could maintain microrefugia, enhancing biodiversity persistence in mountainous systems under climate warming.
- **Management**: Our findings indicate that management practices that result in single-species, even-aged plantations are likely to reduce the thermal buffering capacity of forest sites, potentially limiting the availability of favorable microclimates for some species.

- Management: In jurisdictions where biodiversity maintenance is the goal, conservation and restoration of structures associated with old-growth forests are more likely to sustain favorable microclimates (35) and to reduce climate change impacts on temperature-sensitive species.
- Management: Recent work shows that the understory microclimate differences documented here could be highly relevant to biodiversity conservation in temperate forests; cooler forest types have attenuated the widespread loss of cool-adapted understory plant species (13) and have promoted tree recruitment (36). Amphibians, lizards, insects, and even large mammals are shown to take advantage of microclimate conditions when regional climate moves beyond the range of thermal preferences (5, 37, 38).
  - **Caveat**: Our findings apply to species inhabiting forest understory, and cannot speak to canopy-occurring species.
- Management: because older seral stages provide the highest levels of buffering, management options may be limited for species inhabiting early successional forests (42), unless they are able to take advantage of the microclimatic buffering of older forests or cooler microclimates that are near old-forest edges (34).
  - Currently, early seral species are of high conservation concern in the Pacific Northwest, largely as a result of habitat loss (42); given that early seral forests may not have equivalent thermal refuges, we predict synergistic negative effects on these species when combined with climate.
- Management: By conserving or creating forest conditions that buffer organisms from the impacts of regional warming and/or slow the rate at which organisms must adapt to a changing climate, it may be possible to ameliorate some of the severe negative effects of regional warming.

Grant, Evan H. Campbell and David A. W. Miller, Benedikt R. Schmidt, Michael J. Adams, Staci M. Amburgey, Thierry Chambert, Sam S. Cruickshank, Robert N. Fisher, David M. Green, Blake R. Hossack, Pieter T. J. Johnson, Maxwell B. Joseph, Tracy A. G. Rittenhouse, Maureen E. Ryan, J. Hardin Waddle, Susan C. Walls, Larissa L. Bailey, Gary M. Fellers, Thomas A. Gorman, Andrew M. Ray, David S. Pilliod, Steven J. Price, Daniel Saenz, Walt Sadinski & Erin Muths. Quantitative evidence for the effects of multiple drivers on continental-scale amphibian declines. Scientific Reports, 2016 DOI: 10.1038/srep25625

- Management: "Implementing conservation plans at a local level will be key in stopping amphibian population losses, since global efforts to reduce or lessen threats have been elusive," said Evan Grant, a USGS research wildlife biologist who led the study published in Scientific Reports today.
  - "This research changes the way we need to think about amphibian conservation by showing that local action needs to be part of the global response to amphibian declines, despite remaining questions in what is causing local extinctions."

Gunderson, Lance H. 2000. Ecological resilience—in theory and application. Annual Review of Ecology and Systematics 31: 425-439.

- **Background**: Adaptive Management
  - Integrative and holistic, searching for simple structures and relationships that explain much of nature's complexity
  - Assumes surprises are inevitable, that knowledge will always be incomplete, and that human interaction with ecosystems will always be evolving

    - Natural resources being managed will always change, so humans must respond by adjusting and conforming as situations change
    - Views management policies as hypotheses
    - Develop and evaluate hypotheses around a set of desired system outcomes
- **Management**: In practice, maintaining a capacity for renewal in a dynamic environment provides an ecological buffer that protects the system from the failure of management actions that are taken based upon incomplete understanding, and it allows managers to affordably learn and change.
- **Management**: When faced with shifting stability domains and resulting crises, management options fall into one of three general classes of response.
    - The first is to do nothing and wait to see if the system will return to some acceptable state. One consequence of this option is that the social benefits of the desired state are foregone while waiting to see if the system will return to the desired state.
    - The second option is to actively manage the system and try to return the system to a desirable stability domain.
    - The third option is to admit that the system is irreversibly changed, and hence the only strategy is to adapt to the new, altered system.
- **Management**: In order to add resilience to managed systems, at least three strategies are employed:
    - increasing the buffering capacity of the system
    - managing for processes at multiple scales
    - nurturing sources of renewal (18).
- **Governance**: Institutions (defined broadly as the set of rules and structures that allow people to organize for collective action) can add resilience to a system
    - Learning, trust and engagement are key components of social resilience.
    - Social learning is facilitated by recognition of uncertainties, monitoring and evaluation by stakeholders.
    - The most difficult issues to deal with are those whose consequences will be realized 10 to 50 years in the future over broad scales.

Halofsky et al. 2011. Mixed-severity fire regimes: lessons and hypotheses from the Klamath-Siskiyou Ecoregion. Ecosphere 2(4): 1-19.

- **Management**: Of high management relevance, northern spotted owls and California spotted owls (S. o. occidentalis) may also utilize the M-S mosaic. In the Klamath-Siskiyou region, Northern Spotted Owl fitness is higher in landscapes containing a mixture of old forest and younger brushy vegetation (Franklin et al. 2000), suggesting that in this part of its range, the spotted owl is well suited to a M-S fire regime.
    - However, in the short term, a large extent of high-severity fire within owl territories may provoke negative short-term responses (e.g., displacement, lower survival). While partially confounded by salvage logging, Clark et al. (in press) found that survival of northern spotted owls within fires was lower than in adjacent unburned habitat in the initial years (1–4 yrs post-fire) following high-severity fire.
- **Management**: studies in the Klamath-Siskiyou region suggest that some common postfire management actions—such as tree planting, snag removal, and vegetation control—may not always be needed to meet the management objectives of providing wildlife habitat, promoting forest regeneration, and reducing fire hazard (Donato et al. 2006, Lopez Ortiz 2007, Shatford et al. 2007, Thompson et al. 2007, Kayes 2008).

Halofsky et al. 2016. Developing and Implementing Climate Change Adaptation Options in Forest Ecosystems: A Case Study in Southwestern Oregon, USA. Forests 7: 268.

- **Study**: We developed an approach to facilitate development and implementation of climate change adaptation options in forest management
- **Study**: This approach, applied in a southwestern Oregon study region, involved establishment of a science–manager partnership, a science-based assessment of forest and woodland vulnerabilities to climate change, climate change education in multiple formats, hands-on development of adaptation options, and application of tools to incorporate climate change in planned projects.
- **Background**: Climate Change-related changes to SW Oregon will likely be driven mainly by wildfire and drought
- **Background**: Currently, most federal agencies have broad-scale strategic plans that describe approaches and priorities for climate change in general, and for adaptation in particular, and several departments and agencies have built on initial strategic documents to increase capacity and develop more detailed plans for assessing vulnerabilities and adapting management to climate change [14].
    - For example, the U.S. Forest Service has a national climate change office, a roadmap that guides response to climate change, a scorecard that tracks accomplishments in ten areas, and climate change coordinators at the regional and national forest levels.
- **Background**: Much of the progress in climate change adaptation in natural resource management to date has been accomplished through collaboration between scientists and resource managers [14,15,18–21].
- **The Klamath-Siskiyou**: Diverse floras from several western U.S. floristic provinces intermingle in the complex environmental and geomorphological gradients that characterize the landscape. These complex gradients have allowed for persistence of localized climatic conditions, or climate refugia, amid broader climatic changes in the past.
- **Climate Impacts**: Trends of increasing temperatures, changing precipitation patterns, and increasing extreme events such as drought and fire are expected to continue in this century, driving changes in forest ecosystems [10,11].
- **Finding**: Engaging managers throughout the project increased ownership of the process and outcomes, as well as the applicability of the adaptation options to on-the-ground actions.
- **Finding**: Science–management partnerships can effectively incorporate evolving science, regardless of the socio-political environment, and facilitate timely progress in adaptation to climate change.
- **Findings**: Through this approach, we improved local manager understanding of the potential effects of climate change in southwestern Oregon, and enabled evaluation of proposed management activities in the context of climatic stressors.

Harrison, S., Damschen, E.I. and J.B. Grace. 2010. Ecological contingency in the effects of climate warming on forest herb communities. www.pnas.org/lookup/suppl/doi:10.1073/pnas.1006823107/-/DCSupplemental.

- **Management**: Anticipating ecological contingency in responses to climate change is especially critical for managers of natural resources, who are well aware of the potential for major nonlinearities ("surprises") in community change and of the particular difficulty of making predictions for physically and biotically complex landscapes (e.g., 11–13).

Heller and Zavaleta. 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. Biological Conservation 142: 14-32.

- **Study**: Scholarly articles recommending measures to adapt conservation to climate change have proliferated over the last 22 years. We systematically reviewed this literature to explore what potential solutions it has identified and what consensus and direction it provides to cope with climate change.
- **Study**: We recorded 524 recommendations from 113 papers, published in 57 different source journals and three books
- **Background**: Landscapes outside of protected areas are hostile to the survival of many species due to human infrastructure and associated stressors, such as invasive species, hunting, cars, and environmental toxins. Such fragmentation directly limits species migration and gene flow.
- **Background**: Further, despite widespread favor for ecological networks, assessment of their effectiveness remains in its infancy. Similarly, the field of corridor ecology, while recognized as integral to conservation practice in fragmented landscapes for years, is still young (see Hilty et al., 2006). Some authors warn of a significant need for more empirical data to support the effectiveness of corridors, optimize their spatial arrangement, and minimize risks of increased transmission of disease or invasive species before the conservation community embraces corridors uniformly as the tool to combat biodiversity loss in the face of global climate change (Graham, 1988; Halpin, 1997; Scott and Lemieux, 2005; Williams et al., 2005).
- **Background**: A second popular recommendation for improving landscape connectivity is to change how we manage the matrix (Da Fonseca et al., 2005; Eeley et al., 1999; Lovejoy, 2005). Many authors advocate creating buffer zones around reserves (Rank 8) or flexible landuse zoning at reserve boundaries to allow for land swaps in the future as species distributions shift (Rank 14). Others recommend urban planning and zoning to avoid climate-related risks (Rank 14). In general, enlisting people and human communities to 'soften' landuse through sustainable or less damaging practices (e.g. low intensity forestry or alternatives to building sea walls) (Rank 9) and to restore habitat (Rank 9) will facilitate species movement and persistence in the future.
- **Background**: Despite wide acknowledgement, these connectivity strategies were among the most poorly developed recommendations, limited mainly to very general actions (e.g. ''build flexibility'', ''manage the matrix'', ''modify land use practices'') without identification of kinds of actors that might need to be involved (e.g. reserve managers, policymakers, individuals) or information gaps. Land use reform likely needs to bring together local governments, urban planners, community groups and conservation organizations and to involve high degrees of coordination across multiple jurisdictions to provide landscape cohesion (Press et al., 1995). Substantial work to flesh out this process, as well as to guide information acquisition, is needed before new forms of management across land use types can be implemented.
- **Finding**: Most common climate change adaptation recommendation from review of 112 scholarly articles: (1) increase connectivity (recommended in 24/112 articles); (2) integrate climate change into planning exercises (19/112 articles); (3) mitigate other threats (e.g., invasive species, fragmentation, pollution, etc.); etc. etc.
- **Finding**: To improve landscape connectivity, so that species can move, is the most frequent recommendation for climate change adaptation in the literature reviewed here (Rank 1).
  - There was little guidance in this literature set for corridor implementation beyond common-sense reasoning, however.
- **Findings**: Several consistent recommendations emerge for action at diverse spatial scales, requiring leadership by diverse actors.

- **Findings**: Broadly, adaptation requires improved regional institutional coordination, expanded spatial and temporal perspective, incorporation of climate change scenarios into all planning and action, and greater effort to address multiple threats and global change drivers simultaneously in ways that are responsive to and inclusive of human communities.
- **Finding**: However, in the case of many recommendations the how, by whom, and under what conditions they can be implemented is not specified. We synthesize recommendations with respect to three likely conservation pathways: regional planning; site-scale management; and modification of existing conservation plans.
- **Finding**: We identify major gaps, including the need for (1) more specific, operational examples of adaptation principles that are consistent with unavoidable uncertainty about the future; (2) a practical adaptation planning process to guide selection and integration of recommendations into existing policies and programs; and (3) greater integration of social science into an endeavor that, although dominated by ecology, increasingly recommends extension beyond reserves and into human-occupied landscapes.
- **Finding**: About 70% of recommendations were classified as general principles under our classification scheme rather than specific, actionable strategies or tactics (Fig. 1).
- **Finding**: Widespread calls exist for immediate action to adapt conservation practice to ongoing climate change in order to ensure the persistence of many species and related ecosystem services. However, the majority of recommendations in the published journal literature lack sufficient specificity to direct this action.
- **Finding**: Recommendations to date also largely neglect social science and are overwhelmingly focused on ecological data (Fig. 4c). This bias is alarming given the obvious importance of human behavior and preferences in determining conservation outcomes (Watson, 2005) and the increasingly important role of multi-use public and private lands in conservation practice.

Myer, G. 2013. The Rogue Basin Action Plan for Resilient Watersheds and Forests in a Changing Climate. Thaler, T., Griffith, G., Perry, A., Crossett, T., Rasker, R. (Eds). Model Forest Policy Program in association with the Southern Oregon Forest Restoration Collaborative, the Cumberland River Compact and Headwaters Economics; Sagle, ID. December, 2013.

- **Management**: Key solutions and opportunities identified are:
    - an opportunity to utilize SOFRC's integrated forest restoration approach and incorporate ecosystem services in multi-party collaborative processes to move projects forward while meeting objectives of federal agencies;
    - the opportunity to restore natural forest structure, function, and fire regimes;
    - an opportunity to provide alternative management recommendations, supported by a variety of partners, that could increase resiliency and resistance to the impacts of climate change while providing economic benefits and a potential solution to the current land management issues present in the Rogue Basin.
- **Management**: Broad goals include:
    - Manage risk and reduce uncharacteristic impacts of wildfire
    - Ensure the highest possible water quantity and quality
    - Use an ecosystem services approach to incorporate values into planning outcomes and provide economic rationale for restoration/resilience focused management
- **Management**: The Southern Oregon Forest Restoration Collaborative and partners have been working to develop a common sense strategy and analytical framework to identify forest restoration need and opportunity in the Rogue Basin. Broad goals for the strategy include:
    - restore a diverse mosaic of healthy, resilient forests;

  - conserve habitat with special attention to species and risk;
  - support regional forest products and associated workforce capacity (SOFRC, 2013).
- **Background**: Collaboration on forest restoration has been critically important in building shared understanding and community support for management to address current conditions, and promote forest health and resilience in southwest Oregon. On-the-ground projects including the Medford District Secretarial Pilot Project and Ashland Forest Resiliency Project have helped to advance stakeholder understanding and support.
- **Ecological Considerations**: Ecologically speaking, forest density, species conversion to shade tolerant trees, degraded aquatic habitat, and increased fuel loads are the primary stressors on forested lands. Primary solutions are landscape planning, forest density reductions, and the reintroduction of large-scale fire (both prescribed and from natural ignitions).
- **Management**: A critical strategy is to restore fire's role in maintaining resilient, healthy forest ecosystems capable of adapting to environmental disturbances.
  - This will involve thinning the forest in identified priority areas, promoting shade-intolerant species and returning spatial heterogeneity through gap creation, and appropriate fire use.
- **Management**: A second strategy is to identify those forest communities most at-risk, buffer them from the more direct impacts of climate change (i.e., severe fire), and ensure that corridors are open for species migration and community adaptation to future climate.
- **Management**: A third strategy is to prioritize riparian restoration efforts to enhance water quality and quantity.
- **Management**: Uncertainty underlines the need for caution in forest management and the need for an adaptive management framework for management to maintain forest health in the face of climate change (Lawler et al. 2010).
- **Management**: Primary strategies to adapt forests to future threats include reducing competition and promoting drought and fire tolerant species (Millar et al 2007; Joyce et al. 2009; Allen et al. 2010, Lawler et al. 2010, Spies et al. 2010, Peterson et al. 2011, Franklin and Johnson 2012). Specifically that means reducing numbers of shade tolerant tree species (e.g. white fir) and regenerating tree species like ponderosa pine that are shade intolerant but resistant to drought and fire (North et al. 2012).
- **Management**: Since major fire events can devastate forests and release vast amounts of carbon, managing our forests to reduce the likelihood of such events constitutes a sound policy in support of carbon sequestration, particularly when such activities are conducted conservatively, in an adaptive management framework (Millar et al. 2007, Lawler et al 2010, Spies et al. 2010, Peterson et al. 2011) and scaled to historical and likely future fire return intervals (Hurteau & Brooks 2011).
- **Management**: Our greatest challenge is our capacity to effectively create change that will minimize the negative impacts and risk of landscape-scale, stand-replacing fires.
- **Management**: Beechie at al. (2012) conducted a literature review to determine strategies most likely to ameliorate stream flow and temperature changes and increase habitat for salmon. They determined the most effective measures to be: restoring floodplain connectivity, restoring stream flow regimes, and restoring channels. The restoration of stream complexity and connectivity will improve salmon spawning habitat and allow for aquatic animal movement to new areas if needed, and the restoration of riparian corridors will provide a safe migratory route for land animals as well (Beechie et al. 2012).
  - Restoration should include identifying and protecting thermal refugia provided by ground-water and tributary inflows,

    - improving or decommissioning roads to reduce temperature impacts and soil erosion,
    - restoring vegetation in riparian zones that provide shade and complex habitat (Mantua 2010).
    - Zoning ordinances to discourage development and/or agriculture within (and immediately adjacent to) riparian areas should also be developed and incorporated into local land use planning.
- Management: Reducing out-of-stream withdrawals during periods of low streamflow and high temperature can help mitigate stream temperature increases (Mantua 2010).
- Management: Restoration and maintenance of riparian corridors, stream complexity and connectivity to floodplains can address many of the stressors both present and projected in the Rogue Basin. Planting native shade trees and restoring riparian buffers help to protect against higher water temperatures, filter pollutants from entering the stream, increase aquifer storage capacity, reduce erosion, increase stream bank stability, mitigate storm flows and nutrient loading downstream, restore natural floodplains for both flood and drought mitigation, and can reduce risks to salmon habitat by providing refuge from high flow events.

Noss, Reed F. 2001. Beyond Kyoto: forest management in a time of rapid climate change. Conservation Biology 15(3): 578-590.

- **Background**: Adaptation of species to climate change can occur through phenotypic plasticity, evolution, or migration to suitable sites, with the latter probably the most common response in the past.
- **Background**: The challenge for conservationists is not to prevent change. It is to keep rates, scales, and intensities of change in ecosystems within the historic range of variability for those systems—or, at least, to come close. Conservationists must also develop strategies to mitigate the effects of inevitable changes that fall outside the historic range of variability.
- Management: Among the land-use and management practices likely to maintain forest biodiversity and ecological functions during climate change are
    - (1) representing forest types across environmental gradients in reserves;
        - Because we do not know precisely which forest types will be most sensitive, maintaining a full spectrum of types in protected areas will help assure
        - Ideally, reserves will span uninterrupted environmental gradients and allow dispersal of organisms to favorable microsites that some resistant and resilient types persist.
    - (2) protecting climatic refugia at multiple scales;
        - It makes abundant sense to identify past climatic refugia wherever possible and protect these areas so that they can again function as refugia during present and future climate change (Eeley et al. 1999).
        - Climatic refugia at much smaller scales also can be important for maintaining species assemblages vastly different from those adapted to the dominant regional climate.
        - If climatic refugia at all spatial scales can be identified and protected, persisting populations may be able to recolonize the surrounding landscape when conditions favorable for their survival and reproduction return.
    - (3) protecting primary forests;
        - Old-growth forests are predicted to possess considerable inertia in the face of climate change (Franklin et al. 1991). Mature trees can survive long periods of unfavorable climate, remaining "several centuries after climatic deterioration

    makes local conditions unsuitable for seedling establishment" (Brubaker 1986). This inertia could be a significant mechanism for ecological resistance.
    - In forest types where the dominant trees live for hundreds or thousands of years, stands protected from catastrophic disturbance might persist through a few centuries of unfavorable climate, to reproduce again when favorable conditions return.
    - Because the intensity and rate of change will be buffered in forest interiors, maintaining large patches of oldgrowth forest is a sensible strategy for maintaining biodiversity during rapid climate change.
  - (4) avoiding fragmentation and providing connectivity, especially parallel to climatic gradients;
    - Fragmentation may threaten biodiversity during climate change through several mechanisms, most notably edge effects and isolation of habitat patches.
    - With progressive fragmentation of a landscape, the ratio of edge to interior habitat increases, until the inertia characteristic of mature forests is broken. Fragmented forests will likely demonstrate less resistance and resilience to climate
    - Another potentially serious impact of fragmentation is its likely effect on species migration. By increasing the isolation of habitats, fragmentation is expected to interfere with the ability of species to track shifting climatic conditions over space and time.change than intact forests.
    - Connectivity is the antithesis of fragmentation. Maintaining habitat linkages parallel to climatic gradients and minimizing artificial barriers is a prudent strategy under any climate- change scenario (Hobbs & Hopkins 1991; Noss1993).
    - Elevational corridors, which span a broader climatic gradient over a shorter distance, may better promote migration in mountainous terrain (Noss 1993; Bennett 1999).
    - In designing linkages, several considerations should be kept in mind:
      - (1) A full range of geological substrates and soil types should be included in linkages because some plant species are exacting in their requirements.
      - (2) Many species have mutualistic or other dependencies on other species, such that migration of assemblages of co-adapted species will be required (Bennett 1999).
      - (3) Because movement routes probably will vary among species, protecting broad linkages rather than narrow corridors is advised.
      - (4) As suggested by Collingham and Huntley (2000), a mixed strategy of corridors and small stepping-stone habitats is desirable to address the distinct dispersal characteristics of different species.
      - Roads are major agents of fragmentation (Noss & Cooperrider 1994; Baker & Knight 2000). In the context of climate change, roads pose two problems: they restrict the dispersal of less mobile species while they encourage the dispersal of invasive exotics.
      - Closing unnecessary roads and providing wildlife crossings on roads with heavy traffic might mitigate some of these effects (Noss 1993; Clevenger & Waltho 2000).

- (5) providing buffer zones for adjustment of reserve boundaries;
    - With changing climate, buffer zones have the potential to provide for shifting populations as conditions inside reserves become unsuitable. For this strategy to work, buffer zones must be large. If incentives can be provided to managers outside reserves to manage their lands sensitively, species will have a better chance of shifting distributions in response to climate change than if land-use adjacent to reserves is intense.
- (6) practicing low-intensity forestry and preventing conversion of natural forests to plantations;
    - Forestry that minimizes soil disturbance (hence reducing invasion of exotic pests, loss of carbon from soil, and potential loss of mycorrhizae; Perry 1994), size of canopy openings (Whitmore 1998), and removal of biomass will do more to promote the resistance and resilience of forests to climate change than intensive logging (Amaranthus 1998).
    - Rapid recovery of host plants after logging appears essential for maintaining obligate mycorrhizal fungi and other soil microbes. Herbicide treatments and other intensive "vegetation management" can destroy this linkage (Perry et al. 1990; Perry 1994;
    - Simplistic carbon accounting ignores the tremendous releases of carbon that occur when forests are disturbed by logging and related activities such as site preparation and vegetation management (Perry 1994; Schulze et al. 2000). It ignores the fate of woody debris and soil organic carbon during forest conversion (Cooper 1983; German Advisory Council on Global Change 1998). Typically, respiration from the decomposition of dead biomass in logged forests exceeds net primary production of the regrowth (Schulze et al. 2000).
    - From the standpoint of maintaining biodiversity during climate change, conversion of natural forests to plantations cannot be justified. Tree plantations around the world, especially exotic monocultures, have less biodiversity than natural forests in the same regions (Hunter 1990; Noss & Cooperrider 1994; Perry 1994). Plantations are often markedly less resistant to disturbances such as fire and more subject to pest outbreaks than natural forests (Schowalter 1989; Perry 1994).
- (7) maintaining natural fire regimes;
    - How fire should be managed in response to climate change is a complex issue and the appropriate policy response is not straightforward.
    - A mixed strategy, in which managers let many natural fires burn, protect (to the extent possible) old growth from stand-replacing fires, and manage other stands by prescribed burning and understory thinning to reduce the risk of high-intensity fire, may be the optimal approach.
- (8) maintaining diverse gene pools;
    - Reforestation, rather than relying on local seed sources (which under relatively stable climatic conditions would be an appropriate strategy), should incorporate individuals from a wide range of localities, but should emphasize sources at lower elevations or latitudes (Bawa & Dayanandan
- (9) identifying and protecting functional groups and keystone species.
    - For many forests, one can only guess which species (e.g., top predators) might be of unusually high ecological importance. Efforts should be made to identify such species, functional groups, and processes for all forest types and other

    ecosystems; then, management must be aimed at maintaining these components in natural patterns of abundance and distribution.1998; Ravindranath & Sukumar 1998).

- Management: Good forest management in a time of rapidly changing climate differs little from good forest management under more static conditions, but there is increased emphasis on protecting climatic refugia and providing connectivity.
- Management: To protect forests from the harmful effects of climate change, we must first mitigate the proximate threats of habitat destruction, fragmentation, and degradation.

Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T. and P.B. Moyle. 2006. Managing fire-prone forests in the western United States. Frontiers in Ecology and Environment 4(9): 481-487.

- **Background**: True ecological restoration requires the maintenance of ecological processes, native species composition, and forest structure at both stand and landscape scales.
- Finding: A common-sense conservation goal is to achieve forests that are low maintenance and require minimal repeated treatment. With time, in a landscape of sufficient size, the right end of the restoration continuum (Figure 4) could be reached, where natural fire maintains the system in the desired state.
- Management: Although many forests will require continued management, a common sense conservation goal is to achieve forests that are low maintenance and require minimal repeated treatment
- Management: Restoration of ponderosa pine and dry, mixed-conifer forests (ie guiding their composition, structure, and function to a condition within the historical range of variability) is often desirable (Figure 3) and can involve active techniques such as thinning of small trees and prescribed burning or passive management such as allowing natural fires to burn and removing livestock (Allen et al. 2002; Brown et al. 2004; Schoennagel et al. 2004).
    - Large wildland landscapes are especially well-suited to passive restoration (Nossetal. 2006b).
- Management: In forests characterized by low-severity fire regimes, restoration varies along a continuum from restoring structure (eg reducing densities of small trees and increasing the density of large trees) to restoring the processes (eg low severity fire, competition between grasses and tree seedlings) that create and maintain that structure (Figure 4).
- Management: The following are some of our key findings that relate to decisions about fire management.
    - (1) Fire exclusion and other human activities led to significant deviations from historical variability in some, but not all, forests. Restoration treatments are warranted, sometimes urgently, only where such activities have resulted in major alterations in ecosystem structure, function, or composition.
    - (2) Fire exclusion has had little effect on fuels or forest structure in forests characterized by high severity (stand replacement) fire. High severity fires are relatively infrequent, occurring at intervals of one to many centuries, whereas active fire exclusion, especially in remote forests, began only decades ago. Because fuel structures or tree densities are usually within the historical range of variability, active restoration is ecologically inappropriate in these forests.
    - (3) Restoration of dry ponderosa pine and dry mixed-conifer forests - where low severity fires were historically most common - is ecologically appropriate on many sites. Active (eg mechanical thinning of small stems, prescribed fire) or passive (eg wildland fire use, livestock removal) management can restore stand densities to the levels that existed

prior to fire exclusion, livestock grazing, logging, and plantation establishment. Retention of old live trees, large snags, and large logs in restoration treatments is critical. Also, restoring other key components of these ecosystems, such as native understory plants, is essential for full recovery of natural conditions, including the characteristic fire regime.

  - (4) Scientific understanding of mixed severity fire regimes is limited, making it difficult to provide defensible guidelines for restoration. These are often complex landscape mosaics; it is therefore necessary to plan and conduct activities at large spatial scales. Where sufficient ecological and fire-history information is available, a combination of thinning and prescribed fire may be useful in restoration. Nevertheless, only portions of these landscapes may warrant treatment.
  - (5) Restoration plans should systematically incorporate fire to maintain restored forests. Forests are dynamic; therefore, any restoration program must provide for sustained fire management to maintain the desired condition. Low-maintenance forests, which can often be achieved through managed natural fire, are an appropriate restoration goal in many cases; where this is not possible, prescribed fire should mimic the characteristic fire regime as closely as possible. Because fire regimes vary tremendously on a regional scale, managers should allow for a range of fire severities.
  - (6) Species closely associated with late- or early-successional conditions in fire-prone landscapes need special management consideration. For example, managed forests are often fragmented by periodic logging and road-building, or consist only of stands of trees too small or too open to meet the needs of late-successional dependent species, such as the spotted owl (Strix occidentalis).
- Management: A generalized policy of fire suppression is inappropriate given the documented negative ecological impacts of fire suppression during the 20th century
- Management: Our findings indicate that allowing fires to serve their natural role is ecologically beneficial.
- Management: Although fire must be managed when close to human infrastructure, in many wilderness areas, national parks, and large areas of public land there is opportunity to increase the use of wildland fire. Such management benefits species that require the shifting mosaics of post-fire habitats found in natural landscapes (Smucker et al 2005).
- Management: Furthermore, fire suppression may be ecologically warranted in some cases, particularly where special values are at risk. For example, it may be appropriate
  - where habitat of critically imperiled species could be lost,
  - where uncharacteristic fuel accumulations have created the potential for a fire outside the historical range of variability,
  - where high severity fires are not now viewed as ecologically desirable (eg old-growth forests in the Pacific Northwest).
- Management: Ecologists should be included on fire management teams to ensure that decisions consider the ecological costs and benefits of management actions.
- Management: Our key findings on post-fire management are as follows.
  - First, post-burn landscapes have substantial capacity for natural recovery. Re-establishment of forest following stand-replacement fire occurs at widely varying rates; this allows ecologically critical, early-successional habitat to persist for various periods of time.
  - Second, post-fire (salvage) logging does not contribute to ecological recovery; rather, it negatively affects recovery processes, with the intensity of impacts depending upon the

nature of the logging activity (Lindenmayer et al. 2004). Post-fire logging in naturally disturbed forest landscapes generally has no direct ecological benefits and many potential negative impacts (Beschta et al. 2004; Donato et al. 2006; Lindenmayer and Noss 2006). Trees that survive fire for even a short time are critical as seed sources and as habitat that sustains biodiversity both above- and below ground. Dead wood, including large snags and logs, rivals live trees in ecological importance. Removal of structural legacies, both living and dead, is inconsistent with scientific understanding of natural disturbance regimes and short- and long-term regeneration processes.

    - Third, in forests subjected to severe fire and post-fire logging, streams and other aquatic ecosystems will take longer to return to historical conditions or may switch to a different (and often less desirable) state altogether (Karr et al 2004). Following a severe fire, the biggest impacts on aquatic ecosystems are often excessive sedimentation, caused by runoff from roads, which may continue for years.
    - Fourth, post-fire seeding of non-native plants is often ineffective at reducing soil erosion and generally damages natural ecological values, for example by reducing tree regeneration and the recovery of native plant cover and biodiversity (Beyers 2004). Non-native plants typically compete with native species, reducing both native plant diversity and cover (Keeley et al 2006).
    - Fifth, the ecological importance of biological legacies and of uncommon, structurally complex early-successional stands argues against actions to achieve rapid and complete reforestation. Re-establishing fully stocked stands on sites characterized by low severity fire may actually increase the severity of fire because of fuel loadings outside the historical range of variability.
    - Finally, species dependent on habitat conditions created by high severity fire, with abundant standing dead trees, require substantial areas to be protected from post-fire logging (Hutto 1995).

Olson et al. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou Ecoregion. Nature Areas Journal 31: 65-74.

- Management: Important actions (note: these are *core-planning elements!*) to alleviate climate change impacts on biodiversity
    - Reduce non-climate stressors
    - Secure protection for large, complex landscapes
    - Immediately protect a network of climate change microrefugia, particularly:
        - Old growth and intact forests
            - On north-facing slopes
            - In canyon bottoms
            - At lower and middle elevations
            - In wetter coastal mountains
            - Along elevational gradients
                - **Explanation**: such areas provide local opportunities for vulnerable species to persist within the ecoregion
- Management: Reducing non-climate stressors
    - Reducing non-climate stressors across the landscape (e.g., road-building, mining) is *the single most important action* that land managers can take to help the regional biota and ecosystems persist in the face of climate change

    - The release from stressors should be strategically targeted to critical core habitats, old-growth forest microrefugia, and adaptation corridors along environmental gradients
    - The release of strategic areas from land use stressors would need to allow mature forests to once again dominate the landscape
- Management: Undertake ecologically based restoration in degraded areas
- Management: Conservation groups in the KS Region have identified two high-priority areas for protection
  - A 243,000 ha land bridge known as the proposed Siskiyou Crest National Monument
  - A 445,000 ha proposed Siskiyou Wild Rivers National Salmon and Botanical Area
    - Protection of these areas will greatly improve the chances for persistence of a large portion of the ecoregion's terrestrial and freshwater biota even with uncertainty of coming temperature and precipitation changes
- Management: Although the long-term efficacy of microrefugia is still uncertain (Carroll et al. 2010; Dobrowski et al. 2010), especially if they remain embedded within largely degraded landscapes, it remains a prudent, bet-hedging strategy in the face of uncertainty to protect a network of microrefugia representative of the ecoregion's distinct species assemblages.
- Management: Site features for effective microrefugia in the KSE include
  - north-facing slopes, valley bottoms and steep canyons, and sinks and basins because they are shadier and exist where cool air predictably pools in the lower sites (Dobrowski et al. 2010).
  - Forests with a northeast- and north-facing aspect also have a lower frequency of wildfires that can alter the capacity of habitats to retain cool and moist conditions (Taylor and Skinner 2003; Alexander et al. 2006).
  - Habitat types that will function well as microrefugia for climate change-sensitive species include late-seral forests, although the greater litter, understory vegetation, and canopy complexity and biomass of old-growth forests (> 150 yrs) makes them superior at retaining moisture (Chen et al. 1999).
  - Late-seral forests that occur in areas with high-precipitation and fog, such as in coastal mountains (Loarie et al. 2008; Ackerly et al. 2010; Carroll et al. 2010) or other areas that experience significant orographic precipitation (e.g., > 1143 mm annual precipitation) will, on average, be better able to retain more moisture and cooler conditions than lower precipitation zones. This is due to more abundant water and greater canopy, understory vegetation, litter biomass, and complexity in these forests.
- Management: for ensuring a robust reserve design that is responsive to climate change, it is prudent to secure priority old-growth forest microrefugia as swiftly as possible while the more time-consuming and uncertain task of conserving larger landscapes continues.
- Management: Targeted surveys of old-growth forest invertebrates and non-vascular plants are needed to improve our understanding of the distribution of distinct assemblages in order to refine the location of mesorefugia and better design representative networks of microrefugia.
- Management: see paper for more detailed information about locations of proposed microrefugia and protected areas

Peterson, G., Allen, C.R. and C.S. Holling. 1998. Ecological resilience, biodiversity, and scale. Ecosystems 1: 6-18.

- Management: Management of natural resources often produces high short-term yields and, either purposefully or unintentionally, creates ecosystems that are less variable and diverse over space and time. Management channels ecological productivity into a reduced number of ecological functions and eliminates ecological functions at many scales. This simplification reduces cross-scale resilience, leaving systems increasingly vulnerable to biophysical, economic, or social events that otherwise could have been absorbed—disease, weather anomalies, or market fluctuations.

- **Management**: The distribution of functional diversity within and across scales allows regeneration and renewal to occur following ecological disruption over a wide range of scales. The consequences of species loss may not be immediately visible, but species loss decreases ecological resilience to disturbance or disruption. It produces ecosystems that are more vulnerable to ecological collapse and reduces the variety of possible alternative ecological organizations.

Sarr, D.A., Hibbs, D.E., Shatford, J.P.A. and R. Momsen. 2011. Influences of life history, environmental gradients, and disturbance on riparian tree regeneration in Western Oregon. Forest Ecology and Management 261: 1241-1253.

- **Management**: Management or restoration of riparian forests, therefore, requires knowledge of site conditions, the life history of the riparian trees present, and in particular an understanding of the species' environmental tolerances, disturbance responses, and competitive abilities relative to one another.
- **Management**: What can a riparian forest manager learn from this study of natural tree regeneration? First, that there is no blueprint for riparian restoration. Riparian environments in western Oregon show great variation from place to place, with corresponding changes in the regeneration behavior of the majority of species present. Because these mountain riparian forests are embedded in the upland watersheds, they are closely coupled to regional climate patterns (Sarr and Hibbs, 2007a,b), and they also contain many upland trees mixed with the familiar "riparian" trees we associate with alluvial rivers.
- **Management**: Second, because the riparian forests in all the watersheds we studied contain a rich array of tree species, a manager interested in riparian forest establishment has excellent opportunities to match one or more of the native species with local riparian conditions. Challenges will vary by locale. Across the dry to wet gradient we studied, drought and competition appear to shift in importance as the primary constraints on the frequency and abundance of the species in the regeneration layer. In the drier climates of the Applegate and South Umpqua watersheds, summer drought is a major factor. Sarr and Hibbs (2007b) demonstrated that the streamside to hillslope gradient in the drier watersheds is associated with much greater changes in summer plant moisture stress than in the wetter watersheds. Consequently, selection of species with a range of drought tolerances will be necessary for riparian restoration, and survival of naturally regenerating and planted seedlings is likely to be quite sensitive to height above the stream channel, aspect, and soil depth.
    - Seedlings of species in the Alnus Group, in particular, are likely to survive only at lowest microelevations adjacent to the active stream channel. Species in the Acer and Tsuga Groups are also most likely to regenerate and thrive in lower topographic positions such as floodplain terraces, and perhaps lower north facing slopes, with species in the latter group likely to benefit from filtered shade. Drought adapted species in the Pseudotsuga, and Quercus Groups, although not typically considered riparian, compose a large proportion of the biomass and the natural regeneration in such dry forests, and should be considered in restoration projects.
- **Management**: In contrast, in the wetter climates of the McKenzie and especially Alsea watersheds, summer drought is less of a concern, but variation in light availability and soils may

nonetheless drive some topographic segregation of species. Vigorous growth of understory vegetation, especially clonal shrubs, probably will limit the success of slow growing or shade intolerant species. Generally, the conditions in the wettest watershed strongly favor dominance by the Alnus Group near streams and in disturbed areas and by the Tsuga Group in older forest settings or less frequently disturbed upper floodplains and hillslopes. Slower growing species in the Acer, Pseudotsuga, and Quercus Groups are unlikely to regenerate in such forests without sizable disturbance gaps, and may not be suitable at all in some settings.

- Management: Third, managers pursuing conifer establishment in riparian forests, which is a common riparian restoration goal in the Pacific Northwest (Stolnack and Naiman, 2010), will need to recognize the important variation in life history traits of the common riparian conifer species. Two of the conifers in the Tsuga Group, T. heterophylla and T. brevifolia appear to demonstrate continuous regeneration under conifer canopies, and retention of mature seed trees should be adequate to foster regeneration of these two species in northwest and southwest Oregon riparian forests, respectively.
- Management: The remaining conifer species in this study, especially those in the Pseudotsuga and Quercus Groups, tended to regenerate in midslope and hillslope positions in gap environments. This suggests that their regeneration is strongly influence by upland disturbance regimes, such as fire.

Stralberg, D., Jongsomjit, D., Howell, C.A., Snyder, M.A., Alexander, J.D., Wiens, J.A. and T.L. Root. 2009. Re-shuffling of species with climate disruption: a no-analog future for California birds? PLoS ONE 4(9): e6825. doi:10.1371/journal.pone.0006825

- Management: The likely emergence of novel, no-analog communities over the coming decades presents enormous conservation and management challenges. These challenges will be exacerbated in the high proportion of landscapes that are dominated by intensive human management [46,47], where it will be more difficult for species to move to new climatically suitable areas.
- Management: Managers and conservationists will be faced with difficult choices about how, where, and on which species to prioritize their efforts and investments. Traditional management approaches that focus on maintaining the status quo will not likely be successful; novel approaches will be needed to manage novel communities [48]. Adaptive management will become even more important as conservation targets shift and new ones emerge in unanticipated ways. Successful adaptive management will depend on rapid transfer of information from the scientific community to resource managers so that decisions can be made quickly.

Strittholt, J.R. and D.A. DellaSala. 2001. Importance of roadless areas in biodiversity conservation in forested ecosystems: case study of the Klamath-Siskiyou Ecoregion of the United States. Conservation Biology 15(6): 1742-1754.

- Management: On numerous scientific grounds, our analyses strongly support protecting roadless areas in the Klamath-Siskiyou ecoregion. Roadless areas contained many known locations of species of concern, including rare and endangered species, many more than could be explained by additional land area alone, and the contribution by small roadless areas was noteworthy.

Strittholt, J.R., DellaSala, D.A. and H. Jiang. 2006. Status of Mature and Old-Growth Forests in the Pacific Northwest. Conservation Biology 20(2): 363-374.

- Management: Strengthening protection requirements for the LSRs and including IRAs, however, can greatly improve the functionality of the reserve network. This combination of increased LSR and IRA protections would add 1.3 million ha of old conifer forest to the reserve network, increasing the total protection of older forests to 2,533,456 ha (or 69% of the old forest on public lands) and, because these areas are close to existing protected areas, increasing functional connectivity across the region as well.
- Management: the reserve network can be managed more effectively to accommodate largescale disturbances by (1) increasing the redundancy and connectivity of reserves by protecting remaining older forests, (2) increasing the size of the reserves to withstand large disturbances (although this may not be practical because many large fires eclipse the size of individual reserves), and (3) building fire resiliency into the reserves through restorative actions. Reducing fuel loads in fire-suppressed forests through low-density thinning (small trees and ladder fuels) and using prescribed burning are ways to increase resiliency (Brown et al. 2004; Spies et al. 2006).
- Management: If all the remaining old growth on public land were protected, roughly 21% of the historical area of old growth would not be subjected to industrial development. And although 21% seems like a luxury compared with many regions, it still may be insufficient to maintain all of the old-growth forest values present in the region.
    - This research and the growing public interest in protecting older forests support the conservation need to set aside old-growth forests on federal lands and to manage the maturing conifer forest to reach old-growth condition to ensure that the many biological values associated with older forests are maintained in perpetuity.

Welsh, Jr., H.H. and A.J. Lind. 2002. Multiscale habitat relationships of stream amphibians in the Klamath-Siskiyou Region of California and Oregon. Journal of Wildlife Management 66(3): 581-602.

- Management: Based on our research, we expect D. tenebrosus to continue to be widely distributed and abundant, while A. truei likely will continue to decline across the landscapes of the KS Region (and the greater Pacific Northwest) in response to these relatively new, more intensive anthropogenic disturbance regimes (e.g., Corn and Bury 1989, Dupuis and Steventon 1999, Welsh 2000

Management – Fuels and Fire

Campbell, John L., Mark E. Harmon, and Stephen R. Mitchell. 2011. Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? Frontiers in Ecology and the Environment 10.2: 83-90.

- **Background**: Various levels of tree removal, often paired with prescribed burning, are a management tool commonly used in fire-prone forests to reduce fuel quantity, fuel continuity, and the associated risk of high-severity forest fire.
    - Collectively referred to as “fuel-reduction treatments”, such practices are increasingly used across semiarid forests of the western US, where a century of fire suppression has allowed fuels to accumulate to levels deemed unacceptably hazardous.
    - The efficacy of fuel-reduction treatments in temporarily reducing fire hazard in forests is generally accepted (Agee and Skinner 2005; Ager et al. 2007; Stephens et al. 2009a) and, depending on the prescription, may serve additional management objectives, including the restoration of native species composition, protection from insect and pathogen outbreaks, and provision of wood products and associated employment opportunities.
- **Background**: Furthermore, Hurteau and North (2010) reported that fire-suppressed control plots deposited as much C over 7 years as did comparable thinned plots.
- **Background**: There is a strong consensus that large portions of forests in the western US have suffered both structurally and compositionally from a century of fire exclusion and that certain fuel-reduction treatments, including the thinning of live trees and prescribed burning, can be effective tools for restoring historical functionality and fire resilience to these ecosystems (Hurteau et al. 2010; Meigs and Campbell 2010). Furthermore, by reducing the likelihood of high-severity wildfire, fuel-reduction treatments can improve public safety and reduce threats to the resources provided by mature forests.
- **Finding**: Carbon (C) losses incurred with fuel removal generally exceed what is protected from combustion should the treated area burn
- **Finding**: Even among fire-prone forests, one must treat about ten locations to influence future fire behavior in a single location
- **Finding**: It has been suggested that thinning trees and other fuel-reduction practices aimed at reducing the probability of high-severity forest fire are consistent with efforts to keep carbon (C) sequestered in terrestrial pools, and that such practices should therefore be rewarded rather than penalized in C-accounting schemes. By evaluating how fuel treatments, wildfire, and their interactions affect forest C stocks across a wide range of spatial and temporal scales, we conclude that this is extremely unlikely.
- **Finding**: Our review reveals high C losses associated with fuel treatment, only modest differences in the combustive losses associated with high-severity fire and the low-severity fire that fuel treatment is meant to encourage, and a low likelihood that treated forests will be exposed to fire.
- **Finding**: Although fuel-reduction treatments may be necessary to restore historical functionality to fire-suppressed ecosystems, we found little credible evidence that such efforts have the added benefit of increasing terrestrial C stocks.
- **Finding**: A review of fuel-reduction treatments carried out in semiarid conifer forests in the western US reveals that aboveground C losses associated with treatment averaged approximately 10%, 30%, and 50% for prescribed fire only, thinning only, and thinning followed by prescribed fire, respectively (WebTable 1). By comparison, wildfires burning over comparable

fire-suppressed forests consume an average 12–22% of the aboveground C (total fire-wide averages reported by Campbell et al. [2007] and Meigs et al. [2009], respectively).

- **Finding**: Mitchell et al. (2009) simulated wildfire combustion following a wide range of fuel-reduction treatments for three climatically distinct conifer forest types in Oregon. As illustrated in Figure 2, fuel treatments were effective in reducing combustion in a subsequent wildfire, and the greater the treatment intensity, the greater the reduction in future combustion. However, even in the mature, firesuppressed ponderosa pine (Pinus ponderosa) forest, protecting one unit of C from wildfire combustion typically came at the cost of removing three units of C in treatment. The reason for this is simple: the efficacy of fuel reduction treatments in reducing future wildfire emissions comes in large part by removing or combusting surface fuels ahead of time.
- **Finding**: Presuming that maximum steady-state C stocks are not dictated entirely by permanent site qualities and depend, at least in some part, on the nature and timing of disturbance, it is conceivable that prescriptions such as fuel reduction and prescribed fire could eventually elevate (or reduce) C stocks at a single location slightly beyond what they would be under a different disturbance regime (Hurteau et al. 2010). However, exactly how stable or self-reinforcing this alternate state is remains unknown.
- **Finding**: Only when treatment, wildfire, or their interaction leads to changes in maximum biomass potential (ie system state change) can fuel treatment profoundly influence C storage.
- **Finding**: Model simulations support the notion that forests subjected to fuel-reduction treatments experience less pyrogenic emissions when subsequently exposed to wildfires. However, across a range of treatment intensities, the amount of C removed in treatment was typically three times that saved by altering fire behavior (Figure 2).
- **Finding**: Fire-spread simulations suggest that strategic application of fuel-reduction treatments on as little as 1% of a landscape annually can reduce the area subject to severe wildfire by 50% over a 20-year period. Even so, the protection of one hectare of forest from wildfire required the treatment of 10 hectares, owing not to the low efficacy of treatment but rather to the rarity of severe wildfire events (Figure 3).
- **Finding**: It is reasonable to expect that after a forest-replacing fire, the decomposition of fire-killed trees exceeds NPP, driving NEP below zero. By contrast, the deliberate removal of necromass in fuel-reduction treatments could result in a period of elevated NEP. However, despite marked differences in post-disturbance NEP, it is possible for average C stocks to be identical for these two disturbance types (Figure 4).
- **Finding**: The degree to which fuel management could possibly lead to increased C storage over space and time is contingent on the capacity of such treatments to increase maximum achievable biomass through mechanisms such as decreased non-fire mortality or the protection from losses in soil fertility that are sometimes associated with the highest-severity fires (Figure 6).
- **Management**: A full accounting of C would also include the fossil- fuel costs of conducting fuel treatments, the longevity of forest products removed in fuel treatments, and the ability of fuel treatments to produce renewable “bioenergy”, potentially offsetting combustion of fossil fuels.
    - First, the fossil-fuel costs of conducting fuel treatments are relatively small, ranging from 1–3% of the aboveground C stock (Finkral and Evans 2008; North et al. 2009; Stephens et al. 2009b).
    - Second, only a small fraction of forest products ever enters “permanent” product stocks; this is especially true for the smaller-diameter trees typically removed during fuel treatments. Primarily, half-lives of forest products (7–70 years) are not significantly

    - different than the half-life of the same biomass left in forests (Krankina and Harmon 2006).
    - Third, the capacity of forest biofuels to offset C emissions from fossil-fuel consumption is greatly constrained by both transportation logistics and the lower energy output per unit C emitted as compared with fossil fuel (Marland and Schlamadinger 1997; Law and Harmon 2011).

Chmura et al. 2011. Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. Forest Ecology and Management 261: 1121-1142.

- Management: other silvicultural approaches can be used to enhance forest growth and vigor, increase resistance and resilience, and sustain ecosystem services. As part of this strategy, managers should consider potential changes in the type, frequency, and extent of disturbance (Dale et al., 2001; Millar et al., 2007; Joyce et al., 2008, 2009; Peterson et al., in press; Littell et al., in review).
    - Overall, density management should be the most effective approach because of its ability to lessen drought stress, fire risk, and predisposition to insects and disease. In addition to reducing the demand for water and nutrients, thinning can modify stand structures and species assemblages to reduce the risk of fires and insect infestations.
    - Treatments should be applied carefully to avoid physical damage to remaining trees, soil compaction and fuel build-up.
    - Prescribed fires can be used as a thinning tool, or to decrease surface fuels; and if treatments are sufficiently large and strategically arrayed, they can be used to modify disturbance at the landscape level.
    - Furthermore, post-fire reforestation will provide many opportunities to alter species and within-species genetic composition.

DellaSala, Dominick A. 2016 White Paper. Do mountain pine beetle outbreaks increase the risk of high-severity fires in Western forests: a summary of recent field studies. Geos Institute.

- Finding: In terms of the effects of thinning and logging on mountain pine beetle outbreaks, the studies show mixed effects on reducing tree mortality before outbreaks at the stand level, no effect during outbreaks of landscape scales, and substantial impacts of post-fire logging on resilience of forests to natural disturbances, including the potential for logging and road building to increase future fire risk and severity.
    - Many studies recommend treating the home-ignition zone, 100-200-ft from a home structure outward, and building with fire-resistant materials as proven fire-risk reduction methods.
    - Focusing on defensible space requires treating a narrow zone nearest homes totaling ~12,282 square miles in 13 states.
    - Treating forests in the backcountry, or outside of this zone, is costly and does nothing to stop insect outbreaks, diverting limited resources away from incentivizing and creating defensible space.
- Finding: Studies that have looked directly at thinning effects on tree vigor in Douglas-fir and ponderosa pine forests show mixed results7. While some researchers have found thinning reduces beetle susceptibility in forest stands when there is not an outbreak, others have found that bark beetles do not preferentially infest trees with declining growth. Under some

circumstances, thinning may alleviate tree stress at the stand level but does not mitigate susceptibility against extensive or severe outbreaks7.

  - Specifically, while thinning can maintain adequate growing space and resources, there is accumulating evidence that suggests tree injury, soil compaction, and temporary stress caused by thinning may increase susceptibility of remaining trees to bark beetles and forest pathogens that invade weakened trees7.

- **Finding**: There is general scientific agreement that forest thinning cannot effectively stop outbreaks once a large-scale (landscape) insect infestation has started. Most "control efforts" involving thinning have had little effect on the final size of outbreaks and can do more harm than good7. This is because once an extensive outbreak has started, active management is unlikely to stop it as beetles overwhelm host resistance to outbreaks. Thinning large areas also can have major consequences (impacts) to soils, water quality (e.g. from soil runoff), wildlife, recreation, and other forest values8.
- **Finding**: Post-disturbance logging is common practice in forests that removes trees or other biomass to produce timber. By reducing habitat for species that specialize by feeding on insects, post-disturbance logging can actually inadvertently lead to greater insect activity.
- **Management**: We recommend that priority be given to limited removal of hazardous trees within the immediate road prism and campgrounds to prevent potential loss of life from falling dead trees overtime. Moreover, in order to reduce existing and future risks of fire, it is prudent to concentrate fuel reduction activities within a defensible space of 100-200 foot zone around homes as this method has been shown to be most effective in reducing a home's ignitability (Fig. 3)10.
- **Management**: Since beetle outbreaks and fires are both linked to global warming, prudent policies first and foremost would focus rapidly reducing greenhouse gas emissions rather than having a preoccupation with the effect of warming – outbreaks and fires. Logging to contain outbreaks or fire events simply does not work, is an expensive and ineffective use of taxpayer resources, and comes with significant costs to ecosystems that are otherwise quite resilient to natural disturbance events13.

DellaSala et al. 2016. In Review. (To be added…)

- **Note from Dominick—May 2016**: In the coming months, Geos Institute will be working with partners in keeping logging ridders off fire legislation in the Senate. We also have a new paper in review that shows forests with lower levels of protection (more logging) are burning more severely than those that are strictly protected as parks and wilderness areas. This is another key assumption being made by members of Congress seeking to overturn forest protections based on the refuted assumption that protected forests burn more severely when, in fact, the opposite is true!

Fontaine, J.B., Donato, D.C., Robinson, W.D., Law, B.E. and J.B. Kauffman. 2009. Bird communities following high-severity fire: response to single and repeat fires in a mixed-evergreen forest, Oregon, USA. Forest Ecology and Management 257: 1496-1504.

- **Management**: In our study of high-severity wildfire, many species were significantly associated with mature forests but a greater number were associated with early seral post-fire habitats. The high number of indicator species, and similar species richness suggest that early seral conditions created by wildfire are integral to maintaining
- **Management**: In our study, the repeat burn (15 year interval) possessed a unique bird community characterized by both shrub-associated and open-habitat associated bird species

with species richness and density comparable to unburned forest. Given the historic regime of frequent mixed severity fire, this habitat type has likely occurred on the landscape in the past. Recognition of the importance of a variety of early seral habitats as well as late-seral forests will likely bolster the maintenance of regional avian biodiversity.

- Management: Taken together – the lack of a negative impact of repeated high-severity fire on bird species richness, the unique composition of early seral bird communities, and the association of broad-leaved vegetation with bird abundance and traits – our study suggests that land managers faced with competing goals and limited resources could consider allowing naturally generated early seral conditions to persist for a period in some places, rather than focusing on rapid establishment of conifers and/or closed forest. Extended periods of early successional conditions in the Klamath- Siskiyou ecoregion likely would benefit a broad suite of species and complement regional biodiversity within a landscape mosaic.

Harrison, S., Damschen, E.I. and J.B. Grace. 2010. Ecological contingency in the effects of climate warming on forest herb communities. www.pnas.org/lookup/suppl/doi:10.1073/pnas.1006823107/-/DCSupplemental.

- Management: the main effect of logging on herbs may be to reduce the abundances of species with modes of persistence, dispersal, and regeneration that are ill-adapted to recovery from heavy disturbance (e.g., 31, 53, 54), and this effect acts largely independently of climatic limiting factors.

Odion, D.C., Frost, E.J., Strittholt, J.R., Jiang, H., DellaSala, D. and M.A. Moritz. 2004. Patterns of fire severity and forest conditions in the western Klamath Mountains, California. Conservation Biology 18: 927-936.

- **Background**: Forestry practices other than fire exclusion also may influence fire regimes. Even-aged silviculture can increase fire hazard by creating more combustible fuel complexes (Perry 1994; Weatherspoon & Skinner 1995).
- Management: We concluded that fuel buildup in the absence of fire did not cause increased fire severity as hypothesized. Instead, fuel that is receptive to combustion may decrease in the long absence of fire in the closed forests of our study area, which will favor the fire regime that has maintained these forests. However, plantations are now found in one-third of the roaded landscape. Together with warming climate, this may increase the size and severity of future fires, favoring further establishment of structurally and biologically simple plantations.
- Management: In our study area, harvest treatments to reduce fire severity based on a model of fuel build-up in the absence of fire would be misdirected because long-unburned areas exhibited the lowest fire severity. Moreover, these treatments may be ecologically detrimental because stand- replacing or stand-thinning fire plays a key role in the regeneration of Douglas-fir and most other conifers and natural vegetation in our study area (Wills & Stuart 1994, Thornburgh 1995). Other elements of biodiversity may depend on these fire effects and the habitat heterogeneity that results. There are also more immediate biological consequences of harvest treatments-for example, to understory plants, soil organisms, and aquatic resources. The potential for these treatments to spread exotic forest diseases and plants also needs to be addressed.
- Management: Conversely, fuel treatments that reduce fire severity in portions of the landscape where human activities have increased available fuel will address the problem of un- naturally high fire severity. Not only have we found high fire severity in plantations, but, working in the

same region, Key (2000) also found that plantations and adjacent vegetation burned more severely than natural forests (see also Weatherspoon & Skinner 1995).

- **Management**: Naturally ignited wildfires in the Klamath-Siskiyou region shape vegetation patterns that underlie biodiversity and are in alignment with the current climate. These fires are difficult for society to accommodate because they may burn for long periods, including when weather is extreme. Conservation objectives are affected by the need to protect people and property from such fires. In a de- tailed analysis of potential solutions to balancing the goals of human protection and conservation, modification of the edges of the built environment to slow or stop fire has been emphasized (Bradstock & Gill 2001). Treating the home-ignition zone as described by Cohen (2000) can almost eliminate the possibility of homes burning in wildfires. This would increase fire-management options and perhaps ultimately further conservation goals in the Klamath-Siskiyou ecoregion.

Odion, D.C., Moritz, M.A. and D.A. DellaSala. 2010. Alternative community states maintained by fire in the Klamath Mountains, USA. Journal of Ecology 98: 96-105.

- **Management**: There are several reasons why forests in the study region become less pyrogenic with Time Since Fire and with stand age. Understorey shrubs and small conifers are increasingly excluded by the forest canopy (Azuma, Donnegan & Gedney 2004). Closed forests also have a microclimate that is less favourable to fire (Countryman 1955). Larger trees and fallen logs act as heat sinks during fires (Azuma, Donnegan & Gedney 2004).
- **Management**: However, our results conflict with assumptions regarding fire-prone forested landscapes of the study region (Spies et al. 2006) and western United States of America that fire exclusion leads to more pyrogenic forests, increasing the probability of high-severity fire. Current management based on these prevailing views, such as thinning forest stands, constructing fuelbreaks and establishing plantations after fire, does not address the rapid decrease in fire-dependent sclerophyll vegetation and changes to forests that are caused by fire exclusion in the study region.

Skinner, C.N., Taylor, A.H. and J.K. Agee. 2006. Chapter 9: Klamath Mountains Bioregion; In: Fire in California's Bioregions.

- **Management**: Recent studies suggest that vegetation patterns and conditions generated by pre–fire-suppression fire regimes (Taylor and Skinner 1998, 2003) may be advantageous for wildlife species of concern such as the northern spotted owl (Strix occidentalis caurina) (Franklin et al. 2000) and several species of butterflies (Huntzinger 2003).
- **Management**: Hardwoods, especially oaks, provide important habitat elements for many species of wildlife. As a result, managers may use prescribed fire to inhibit conifer encroachment into oak stands as well as to improve acorn crops (Skinner 1995b).
- **Management**: Quantities of large woody material for standards and guidelines were developed from contemporary old-growth forests that had experienced many decades of fire suppression. These quantities of woody material were probably unusually high compared to typical pre–fire-suppression values. Consequently, a management emphasis on meeting or exceeding standards and guidelines for dead woody material has and will increase fire hazard over time and threatens the very habitat the standards and guidelines were designed to improve (Skinner 2002b).
- **Management**: Though there is much current discussion of the need for restoring fire as an ecological process, or at least creating stand structures that would help reduce the general intensity of fires to more historical levels, there are many competing social/political concerns

and objectives (e.g., fine filter approaches to managing wildlife habitat and air quality) that make doing anything problematic (Agee 2003).

Strittholt, J.R., DellaSala, D.A. and H. Jiang. 2006. Status of Mature and Old-Growth Forests in the Pacific Northwest. Conservation Biology 20(2): 363-374.

- **Background**: salvage logging obscures the distinction between timber production and old-growth forest protection because this activity is virtually always damaging to regenerative processes following fire (Lindenmayer et al. 2004).

Welsh, Jr., H.H. and A.J. Lind. 2002. Multiscale habitat relationships of stream amphibians in the Klamath-Siskiyou Region of California and Oregon. Journal of Wildlife Management 66(3): 581-602.

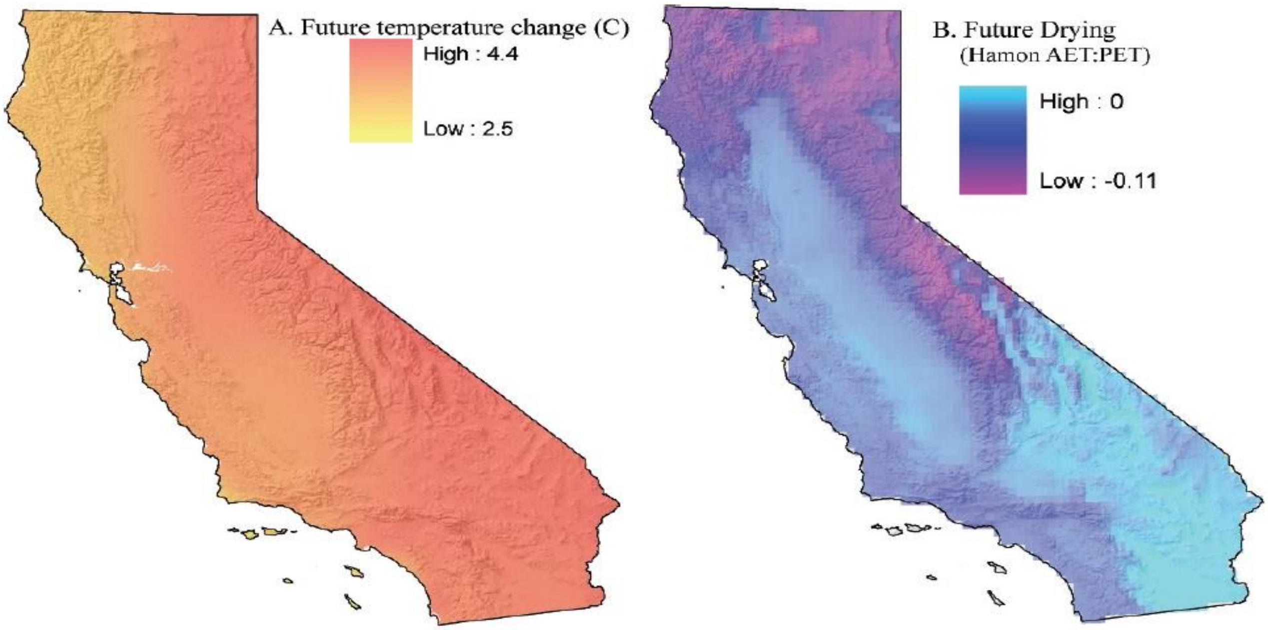
- **Management**: Timber harvesting near streams can have a profound effect on the nature and availability of substrate interstices (Waters 1995), which are important microhabitat for tailed frogs (Welsh and Ollivier 1998). Depending on the competency of the bedrock materials, stream conditions can change dramatically following nearby tree removal (Waters 1995).
- **Management**: In the case of A. truei, although present in some streams in younger forests (e.g., Diller and Wallace 1999, Aubry 2000, Wilkins and Peterson 2000), their populations often are reduced or eliminated by timber harvest and related activities through direct perturbations to the forest and stream environment. Given that habitat conditions for A. truei are optimized in late-seral forests (Corn and Bury 1989; Welsh 1990, 1993; Welsh and Lind 1991), the long-term viability of this frog throughout the region of our study probably is linked to the presence and spatial accessibility of these forests and the interior microclimatic conditions they provide.

Anacker and Harrison. 2012.

- **Finding**: Our results are consistent with the notion that benign climates (i.e., high rainfall and less extreme temperatures) promote the persistence of small populations with novel adaptations (i.e., endemics)
- **Management**: This provides evidence that the benign climates of microrefugia (high rainfall and less extreme temperatures) are more likely than other locations to promote the persistence of small populations of endemic species.

Anacker et al. 2013.

- **Study**: We assessed the vulnerability to climate change of 156 rare plant species. The species were selected from the 1625 rare species in California to comprise eight rarity types, classified according to range size, population size, and habitat specificity. For each of the 156 species, we first assigned a climate change vulnerability score using life history attributes and species distribution models, as specified by the Climate Change Vulnerability Index (CCVI) of NatureServe. The resulting CCVI scores were extremely vulnerable (n 5 2), highly vulnerable (n 5 40), moderately vulnerable (n 5 57), presumed stable (n 5 32), increase likely (n 5 16), and insufficient evidence (n 5 9).



- **Background**: A changing climate may reduce and extirpate populations (Pounds et al. 2006), cause species to migrate north and upslope (Parmesan 1996; Kelly and Goulden 2008; Loarie et al. 2009), advance flowering times, promote species invasion, increase disturbance (e.g., fire), and cause community reorganization (Walther et al. 2002; Burkett et al. 2005).
- **Background**: By identifying species or habitats most at risk from effects of climate change, conservation and management efforts can be targeted to reduce these impacts, such as by protecting existing habitat or through assisted migration (Hunter 2007; McLachlan et al. 2007).
- **Background**: topographically complex landscapes may provide refugia or paths for movement to more suitable areas under changing temperature and moisture regimes (Hunter et al. 1988; Beier and Brost 2010).
- **Background**: Further, assessments of geophysical diversity (i.e., the number of bedrock types) may be a useful alternative to species-level assessments, since high levels of geological diversity are often associated with habitat heterogeneity and species diversity (Anderson and Ferree 2010).

- **Background**: A leading example of combining species traits and SDMs into a single vulnerability analysis comes from NatureServe (Arlington, VA), a nonprofit organization whose mission is to provide the scientific basis for effective conservation action. NatureServe developed the Climate Change Vulnerability Index (CCVI) to serve as a standardized methodology for assessing vulnerability to climate change at the species level (Young et al. 2012).
- **Finding**: There was no correlation of the CCVI scores with rarity type, suggesting that climate change vulnerability cannot be inferred by simple categorizations based on geographic range and habitat preference.
- **Finding**: 60 of the 156 species were predicted to have declines in climatic suitability, regardless of modeling technique.
- **Finding**: Species in topographically dissected landscapes may be less vulnerable to climate change because they can find suitable climates locally as climate changes.
- **Finding**: Life history trait assumed to lead to high vulnerability to climate change (table 2):
    - Lower dispersal ability leads to high vulnerability.
    - Narrow historical climate exposure and special microclimatic preferences leads to high vulnerability.
    - Dependence on a specific disturbance regime Dependence on a particular disturbance regime leads to high vulnerability.
    - Habitat specialization leads to high vulnerability.
    - Dependence on other species (facilitation, pollinators, and seed dispersers) leads to high vulnerability.
    - Genetics Low genetic diversity leads to high vulnerability.
    - Phenological response Shorter bloom period leads to high vulnerability.
- **Finding**: Of the 156 species assessed, 99 were determined to be vulnerable (extremely vulnerable, highly vulnerable, or moderately vulnerable) to climate change and 48 were determined to be stable or increasing (presumed stable or increase likely). The distribution of final scores was: extremely vulnerable (n 5 2), highly vulnerable (n 5 40), moderately vulnerable (n 5 57), presumed stable (n 5 32), increase likely (n 5 16), and insufficient evidence (n 5 9).
- **Finding**: Topographic complexity was not significantly related to California Rare Plant Rank, but was significantly related to rarity type (P , 0.001), where habitat specialists occurred in locations with higher topographic
- **Finding**: For 99 of the 156 species, the ability to migrate to track shifting climate will likely be impeded by man-made barriers. This may reflect the fact that many rare species are concentrated in coastal areas, where population density and associated fragmentation are extremely high (e.g., the San Francisco Bay Area and Los Angeles) (Stein et al. 2000).complexity than habitat generalists.
- **Finding**: We found the CCVI scores were independent of both California Rare Plant Rank and rarity type. This suggests that the rarest species, such as the California Rare Plant Rank 1B species or habitat specialists with small ranges and small population sizes, are not necessarily the most vulnerable to climate change.

- **Management**: The information produced in our vulnerability assessments will be useful in identifying the most vulnerable rare plant species to climate change, which can then be carefully monitored.
- **Management**: Viewing multiple sources of information together, including the CCVI vulnerability score, rarity ranking, topographic complexity, and a range of SDM results may give a broader picture of the overall vulnerability of a rare plant species to climate change.

Asarian and Walker. 2016.

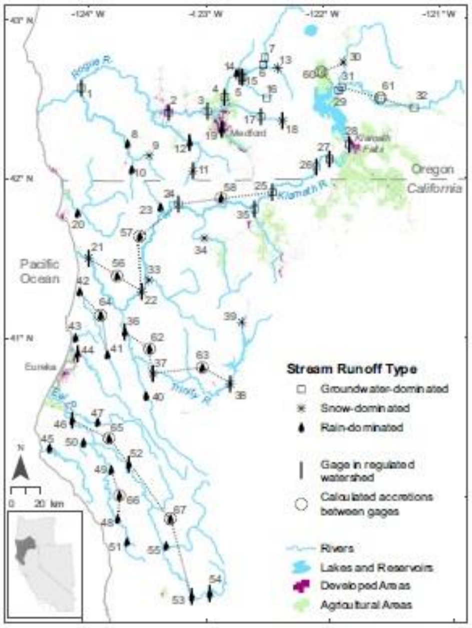


FIGURE 1. Map Showing the Location and Runoff Type for the 55 Streamflow Gages and the 12 Calculated Accretions Used in This Study. See Tables 1 and 2 for a key to site number labels. Developed and agricultural areas (Fry *et al.*, 2011) are shown as indicators of hydrologic alteration.

- Study: assessed long-term (1953-2012) trends in streamflow and precipitation in northern California and southern Oregon at 26 sites regulated by dams and at 41 "unregulated" sites (see map on right).
- Study: The study area was chosen to coincide with the range of the Southern Oregon/Northern California Coast Evolutionary Significant Unit of coho salmon.
- Finding: a few sites (9%) had significant decreasing trends in precipitation
- Finding: September precipitation declined at 70% of sites.
- Finding: Increased April precipitation in the Upper Rogue Basin and the Upper Klamath Basin
- Finding: Decreased January precipitation in the Middle Klamath Basin
- Finding: Summer streamflow (June - September) declined at many sites, including 73% of unregulated (non-dam) sites in September
- Finding: Groundwater-dominated sites—in comparison to snow- or rain-runoff dominated sites—had a greater percentage of declining trends in streamflow (with precipitation controlled for)
- Finding: The most pristine surface-runoff-dominated watersheds in the study area showed no decrease in streamflow (with precipitation controlled for) during the summer months
    - **Explanation**: streamflow decreases at other sites are likely due to increased human withdrawals and vegetation changes, and not due to climate factors
    - **In the Future**: Increasing temperatures will increase evapotranspiration and decrease streamflow
- **Background**: Water availability is an increasing concern for humans and aquatic systems in the West, especially during the hot summer months
- **Background**: Climate is warming, shifting precipitation from snow to rain, reducing snowpack, and causing earlier snowmelt.
- **Background**: In snow-dominated watersheds, the timing of peak streamflow has shifted to earlier in the year.
- **Background**: Summer low-flow levels are likely to decrease as the climate warms
- **Background**: Increased summer temperatures will increase evapotranspiration of natural vegetation, and increase water withdrawals for agriculture and landscaping.
- **Background**: The conventional approach to increasing summer water supply is construction of new dams and reservoirs.

    - But dams have profound effects on river ecosystems, impeding species migration and affecting sediment dynamics
- **Background**: Dams have been identified as a primary cause of declining salmonid populations within the study area.
- **Ecological Considerations**: Declining streamflows—which occurred primarily at regulated (dam) sites in the fall and winter and at unregulated (non-dam) sites in the summer and fall—is a troubling indicator for the future of anadromous salmonid fisheries within the study area.
    - Decreasing summer streamflow reduces the quality and quantity of pools available where juvenile fish can survive during the dry summer months
    - Declining fall streamflow could affect migration and spawning of adult salmonids, which use flow increases as migratory cues and as a means to enter small streams
- **Management to Increase Streamflows**: A program to equip rural residences with tanks to store spring and winter runoff for summer use has reduced summer water withdrawals and resulted in measurable increases in summer low flows in the Mattole River at the south end of the study area.
- **Management to Increase Streamflows**: Increase the capacity of the landscape to store water by reconnecting floodplains and raising groundwater tables, including the use of native beavers and beaver dam analogs.
- **Management to Increase Streamflows**: Decrease human consumption of water.

Ayram et al. 2016.

- **Study**: This paper presents a review of the literature based on 162 publications from 2000 to 2013, in which we evaluated the current state and recent advances in the integration of landscape connectivity in the identification and planning of conservation areas.
- **Study**: The literature review and data analysis were based on a database organized into five categories: General information, study areas, research objectives, research methods in connectivity studies, and integration of connectivity with conservation.
- **Background**: The study of landscape connectivity in conservation has increased considerably since the early part of the 21st century. While the implications of landscape connectivity are self-evident for conservation, they are also important for physical geography since a proper understanding of landscape patterns and processes allows for better landscape management practices, which are at the core of geography.
- **Background**: Connectivity is a key factor in indicating the ecological effects of environmental change. For example, protected areas cannot meet their conservation goals if they do not have functional linkages between them that allow ecological processes like gene flow, migration, re-colonization of areas with threatened populations, and, most importantly, the possibility by individuals and populations to adapt to climate change (Rudnick et al., 2012).
- **Background**: The definition of landscape connectivity includes two fundamental concepts: a) structural connectivity, corresponding to spatial relationships (continuity and adjacency) between the structural elements of the landscape (e.g. Forest patches), which is independent on the ecological characteristics of the species (Taylor et al., 2006; Tischendorf and Fahrig, 2000), and b) functional connectivity, which refers to landscape features that facilitate or impede the movement of species between habitat patches (Taylor, 1993; Taylor et al., 2006).
- **Finding**: We found a substantial increase in the number of publications relating to connectivity and conservation from 2008 to 2013. Least cost analysis was the method most commonly applied.
- **Finding**: We found no implementation of landscape connectivity proposals generated by the studies (e.g. potential corridors) into real landscape elements to ensure the permanence and functionality of ecosystems.
- **Finding**: The last decade showed a notable increase in the number of publications that incorporate habitat connectivity in conservation analyses, indicating that there is an expanding research interest in this topic.
- **Finding**: Least cost analysis was the most utilized method in connectivity analyses (see Figure 7). This approach assumes that the ability of focal species to disperse results from the characteristics of the landscape matrix facilitating or impeding their mobility between patches (Adriaensen et al., 2003).

Batabyal. 1998.

- **<u>Background</u>**: The resilience of ecological functions in ecosystems is generally an increasing function of the number of substitute species that can perform those functions.

Bottom et al. 2009.

- **Study**: In this special feature introduction, we explore several key attributes of ecosystem resilience that have been overlooked by traditional salmon management approaches.
- **Background**: The resilience of ecosystem services has been linked to the diversity of species within functional groups —i.e., sets of organisms that support similar ecosystem processes (Walker et al. 1999, Carpenter et al. 2006)—and to the diversity within species and populations (Luck et al. 2003).
- **Background**: In an open letter to the Oregon State legislature in 1875, U.S. Commissioner of Fish and Fisheries Spencer Baird predicted that Columbia River salmon would suffer a similar fate to eastern salmon for the same reasons: habitat loss, excessive harvest, and dams and other impediments to fish migration.
    - The Commissioner enthusiastically endorsed hatchery technology as the means to maintain a stable salmon supply and to avoid the highly unpopular regulatory alternatives. Numerous state and federal fishery management agencies were established thereafter, and Baird's simple formula—artificial fish propagation to compensate for habitat loss and intensive harvest—was institutionalized, setting the priorities for U.S. fishery management for the next century (Bottom 1997).
- **Background**: The history of Pacific salmon conservation is a classic case of "command-and-control" management of renewable resources (Holling and Meffe 1996). Fishery management developed from an agricultural model of conservation (Bottom 1997). It devised methods to stabilize fish production at optimum levels by controlling or removing presumed limitations to survival and yield. Biologists selected salmon spawning partners and controlled rearing conditions in hatcheries; dictated the sizes, times, and locations for releasing hatchery fish; established predator control programs to eliminate threats from other fishes, birds, and mammals; and regulated harvest levels to achieve the maximum yield.
- **Background:** Throughout the western United States, approximately 29% of nearly 1400 historical salmonid populations (including the five species listed above and pink salmon, O. gorbuscha) are now extinct (Gustafson et al. 2007), and 27 salmonid stock groups are formally listed as threatened or endangered (http://www.nwr.noaa.gov/ESA-Salmon-Listings/).
- **Background**: We define resilience as the amount of disturbance that an ecosystem can accommodate without shifting to a different regime or stability domain as characterized by a fundamentally different structure, function, and feedback mechanisms (Walker et al. 2004).
- **Background:** Salmon ecosystems are defined by the long chain of freshwater, estuarine, and marine habitats that individuals in a population must navigate to complete their anadromous life cycles. Salmon may spawn and rear in a diversity of freshwater habitats from small headwater streams and lakes to larger rivers and estuaries, and feed for months or years in coastal and open marine waters of the North Pacific Ocean (Fig. 1).

- **Background**: Regime shifts often are attributed to human actions that have undermined ecosystem resilience (Folke et al. 2004).
- **Background**: Paleoecological studies have documented large fluctuations in abundance and shifts in the dominance of pelagic marine fish species in the North Pacific well before intensive fisheries had any impact on fish stocks (Soutar and Isaacs 1969, 1974). A 2200-year reconstruction of Alaska sockeye salmon abundances demonstrated dramatic jumps from high to low productivity that lasted for centuries even without any anthropogenic influence (Finney et al. 2002).
- **Background**: Salmon populations are directly responsible for conveying three of the four categories of ecosystem services defined by the Millennium Ecosystem Assessment (2005): provisioning, cultural, and supporting (Fig. 2).
  - In the last two decades, ecological studies have detailed many ecosystem supporting services also provided by salmon populations. Salmon are the principal food item of many terrestrial wildlife species (Willson and Halupka 1995, Merz and Moyle 2006) and a source of marine-derived nutrients to coastal lakes and streams (Bilby et al. 1996, Cederholm et al. 1999, Finney et al. 2000). They act as watershed engineers that structure streambed habitats and alter sediment composition during spawning (Schindler et al. 2003).
  - Ecosystem provisioning, cultural, and regulating services ultimately may depend on the supporting services of salmon populations that drive nutrient and energy flows in coastal watersheds.
  - Salmon carcasses, eggs, and sperm left behind after spawning deliver a continuous flow of nutrients and energy from the ocean to small coastal streams, rivers, and lakes.
  - Predation by terrestrial scavengers and nutrient uptake by riparian vegetation transfers marine-derived nutrients to terrestrial plants and animals.
  - Marine-derived nutrients from salmon even provide direct economic benefits through nutrient inputs to agricultural crops in fields near salmon rivers (Merz and Moyle 2006).
  - The growth of riparian trees that shade freshwater systems, regulate stream temperatures, and provide in-stream habitat structure may at least partially depend on healthy salmon populations (Helfield and Naiman 2001, Naiman et al. 2002).
- **Background**: Salmon also are sensitive indicators of regulating services in coastal watersheds. Because the environmental tolerances of salmon species are relatively narrow and habitat requirements at each life stage are very specific, populations are sensitive to water quality and habitat structure throughout a watershed. Thus, many of the same habitats that support robust salmon populations—functional wetlands and floodplains and intact riparian systems, for example—also support regulating ecosystem services (e.g., water purification, flood control, and temperature regulation) that benefit people (Fig. 2).
- **Background**: By one estimate, only 6%–7% of the historical subsidy of marine-derived nitrogen and phosphorous now reaches rivers across the Pacific Northwest (due to salmon population declines) (Gresh et al. 2000).

- **Ecological Considerations**: Because salmon convey important provisioning, cultural, and supporting services to their local watersheds, widespread population decline has undermined both human well-being and ecosystem resilience.
- **Ecological Considerations**: Healthy salmon ecosystems will provide important ecosystem services, including those clean water, ample stream flows, functional wetlands and floodplains, intact riparian systems, and abundant fish populations.
- **Ecological Considerations**: Widespread salmon decline may affect regional biodiversity of terrestrial-dependent wildlife species (Willson and Halupka 1995).
    - Others hypothesize that disruption of the marine feedback loop to coastal rivers could cause a downward spiral in freshwater ecosystems and a shift to a persistent low-productivity regime that is resistant to salmon recovery (Gresh et al. 2000, Schindler et al. 2003).
- **Management**: Strengthening resilience of salmon ecosystems will require expanding habitat opportunities for salmon populations to express their maximum life-history variation.
- **Management**: because ecosystems have limits in their capacities to reorganize and repair themselves following disturbance, human actions must work within the resilient capacities of salmon to avoid placing important ecosystem services at risk. A resilience-based management approach, therefore, seeks to strengthen the self-repairing capacity of ecosystems to support the services that people value.
- **Management**: Warming of the world's oceans, reduced snow packs, and other effects of global climate change are creating new uncertainties about the adaptive capacities of salmon populations in the region (Mote et al. 2003). Such trends suggest a need to strengthen ecosystem resilience as a strategy to cope with unpredictable social–ecological changes (Carpenter and Folke 2006).
- **Management**: Resilience perspective argues for a more explicit accounting of all of the salmon ecosystem services that natural-resource management programs influence and hope to maintain (Carpenter et al. 2001).

Breining, Greg. 2016. Ensia article: "What's a National Park to do about Climate Change"

http://ensia.com/features/whats-a-national-park-to-do-about-climate-change/

- **Background**: Rising temps and changing patterns of precipitation are driving iconic plants and animals out of areas where they have lived for centuries or longer.
- **Background**: National Park Service director Jonathan Jarvis in 2010 called climate change "fundamentally the greatest threat to the integrity of our national parks that we have ever experienced."
- **Background**: The loss of glaciers is doing more than stripping the identity of Glacier National Park. It also means the loss of a reliable snowpack and meltwater upon which both humans and animals depend.
- **Background**: precipitation in a warmer world is so hard to predict.
- **Background**: the NPS goal was to preserve "a vignette of primitive America." But the challenges of climate change have forced the park service to restate its goal to "steward NPS resources for continuous change that is not yet fully understood" — a phrase neither as evocative nor as reassuring.
- **Background**: But park managers also realize that the wild, open spaces many parks offer will have value even in a changing world. Perhaps *especially* in a changing world.
- **Governance:** Yet such a strategy will require a far greater land base than the national parks alone: Mow says Glacier is working with more than 30 land-management partners in the U.S. and Canada to plot a strategy for species that might lose out to a warmer climate.
- **Governance**: Rather than trying to predict the climate future of a particular park — warmer temperatures are a near certainty, but changes in precipitation are much harder to predict — Schuurman encourages parks staff to anticipate several plausible "scenarios" to better grasp what kinds of problems they might be facing. "Scenarios are a good way to help people let go of the idea that the future will be like the past," he says.
- **Governance**: In many cases, Schuurman says, park management will involve triage, and in many cases, simply "letting go." Even then, he says, "the parks won't cease to exist."
- **Ecological Considerations**: The needs of humans aren't the only concern as Glacier warms.
  - Wolverines den in deep snow to give birth. "They're a great sentinel species of cold climates," says Mow. With less cold and snow, he says, they have an uncertain future in the park.
  - Mountain goats, another iconic Glacier species, bed down on lingering snowpack to cool off in summer. "The areas where you're accustomed to seeing goats wandering around, snow is not there," says Mow.
  - Pikas — the diminutive, rotund relatives of rabbits that live in rocks at high altitude — appear to be retreating to higher altitudes as climate warms. But the

    animals can retreat only so far on the mountaintops. Pikas have already vanished from some southern parks, including Zion and Bryce Canyon in Utah.
    - Losing a reliable source of icy meltwater would threaten the western glacier stonefly known solely in a small area of Glacier National Park, where "it's uniquely adapted to stream waters that are fed by melting glaciers," says Mow.
    - Losing a steady supply of cold runoff also affects the bull trout, a native sportfish that is fighting a two-front war in Glacier, as in much of the West. On the one hand, loss of snowpack is raising stream temperatures where this heat-intolerant fish lives.
- Ecological Considerations: At Isle Royale National Park in Lake Superior, both moose and wolves gained access decades ago by walking 15 miles or so over winter lake ice. Now the wolf population, which once numbered as high as 50, has dwindled to two and is probably doomed because of inbreeding. The opportunities for new wolves to cross the ice and replenish the populations are fewer as warmer winters mean fewer occasions when the lake is frozen. The park is studying its options, from translocating new breeding pairs of wolves to the island to start a new population, to letting moose overtake the island habitat unchecked by a predator.
- Ecological Considerations: One extreme is to let nature take its course. The other is assisted migration of Joshua trees to suitable areas where they don't exist now. In between might be collecting seeds and planting them in their current range if in the future it becomes too warm for the plants to seed naturally, or controlling invasive species to make life easier for the native ones.
- Ecological Considerations: An even hotter climate will threaten endemic species that are closely tied to the park's scarce water, such as five species of pupfish and a number of riparian insects. "All of them would be highly at risk of extinction," says Hoines.
- Management: But to protect other species, such as the bull trout in Glacier, wildlife biologists have taken a step that's radical by the standards of the NPS, which is usually loath to move species: Fishery managers have caught native bull trout and transported them upstream of barrier waterfalls to upper reaches of mountain streams that are both cooler and — so far, anyway — free of marauding lake trout. "We're trying to ensure the genetic lineage of those bull trout that survive in that watershed, so we are moving them up the watershed where historically they never existed," Mow says.
- Management: The whitebark pine is another high-elevation species predicted to disappear from much of its current range within a few decades. Some scientists are already preparing to plant whitebark pine in areas more to the trees' liking in years ahead, a strategy called assisted migration. "In some cases the strategy may be completely hands off, letting nature figure out if it's resilient enough and see how it evolves. On the other end of the scale, the strategy might be assisted migration. Will we be moving plant species hundreds of miles north of their current range as a way of ensuring their survivability?"
- Management: Survey wildlife during the next year and compare the diversity they find to that recorded by surveys taken between 1908 and 1945. But an inventory is just a

first step, says Hoines. Much tougher is figuring out how to respond to climate threats. “It truly is on a wait-and-see basis,” he says.

Cahall and Hayes. 2009.

- **Study**: We compared densities and relative abundances of forest birds after fire in unsalvaged stands and stands subjected to one of two intensities of salvage logging (moderate, 30 snags retained per ha and heavy, 5–6 snags retained per ha) in mixed-conifer forests in central Oregon.
- **Study**: We evaluated three hypotheses concerning the influence of different intensities of salvage on densities or relative abundances of sixteen species of birds, and two hypotheses concerning the influence of time since salvage logging on relative abundances or densities of birds.
- **Study**: We also examined the relationship between vegetation and abundances of each bird species.
- **Ecological Considerations**: Cavity-nesting birds (Hutto, 1995; Saab and Dudley, 1998; Kotliar et al., 2002), aerial insectivores (Hutto, 1995; Caton, 1996; Kotliar et al., 2002), and ground- and shrub-foraging birds (Bock and Lynch, 1970; Caton, 1996) often increase in abundance following fire, and burned forests may be necessary for the persistence of some species of birds (Raphael and White, 1984; Raphael et al., 1987; Hutto, 1995; Murphy and Lehnhausen, 1998; Hobson and Schieck, 1999; Hoyt and Hannon, 2002).
- **Ecological Considerations**: The abundance and characteristics of snags (Everett et al., 2000; Smith, 2000), abundance of insect prey (Muona and Rutanen, 1994; Rasmussen et al., 1996; McHugh et al., 2003), and characteristics of the forest floor and herbaceous and shrub communities (Kauffman, 1990; Agee, 1993; Smith, 2000) following stand-replacing fire are important habitat elements contributing to responses of wildlife to postfire conditions.
- **Ecological Considerations**: The black-backed woodpecker is closely associated with burned forests, and abundances typically dramatically increase after fire (Blackford, 1955; Hutto, 1995; Murphy and Lehnhausen, 1998; Dixon and Saab, 2000), and as a consequence are of particular conservation concern (USDI, 2003; Oregon Natural Heritage Information Center, 2004; Montana Natural Heritage Program and Montana Fish Wildlife and Parks, 2006). Our findings of lower numbers in salvaged stands are consistent with those of other studies that have demonstrated negative effects of salvage logging on the black-backed woodpecker (Caton, 1996; Hutto and Gallo, 2006; Koivula and Schmiegelow, 2007; Saab et al., 2007), even in partially salvaged stands (Saab and Dudley, 1998; Haggard and Gaines, 2001).
- **Ecological Considerations**: Similarly, numbers of the hairy woodpecker appear to be negatively influenced by salvage logging at both intensities considered in our study, consistent with findings in other regions where near complete removal of snags occurred (Caton, 1996; Saab and Dudley, 1998; Haggard and Gaines, 2001; Hutto and Gallo, 2006; Koivula and Schmiegelow, 2007; Saab et al., 2007). Yet, findings for response of the hairy woodpecker to partial salvage logging relative to unsalvaged and complete salvage have been mixed (Saab and Dudley, 1998; Haggard and Gaines, 2001;

Saab et al., 2007), suggesting that further investigation of different salvage intensities are necessary to better understand the response of the hairy woodpecker.

- **Finding**: We did not detect significant differences among treatments in densities or relative abundances for eight (of sixteen) species and one genus of birds.
- **Finding**: We detected significant differences for seven species, though the patterns differed among species.
    - Relative abundances or densities of the black-backed woodpecker (Picoides arcticus), hairy woodpecker (P. villosus), brown creeper (Certhia americana), western wood-pewee (Contopus sordidulus) and yellow-rumped warbler (Dendroica coronata) were lower in the heavy and moderate salvage treatment compared to the unsalvaged treatment
    - Densities of the dark-eyed junco (Junco hyemalis) and fox sparrow (Passerella iliaca) were greater in the moderately and heavily salvaged stands than in the unsalvaged treatment.
    - We detected significant differences between years for four species of birds.
- **Finding**: Our findings suggest that both cavity-nesting and cup-nesting species respond to salvage logging, and that some species respond uniquely to habitat features influenced by salvage logging.
- **Finding**: For species that responded negatively to salvage logging, the moderate salvage intensity did not appear to mitigate the negative influence of salvage logging.
- **Finding**: Areas of unlogged burned forest appear to provide important habitat for some species of birds following forest fires. Our findings parallel those of other recent studies of these species, suggesting robust patterns that transcend particular locations.
- **Finding**: Densities of the fox sparrow were strongly positively correlated with volume of shrubs which increased with decreasing density of snags. The fox sparrow selects brushy habitat (Austin, 1968; Weckstein et al., 2002), and densities of the fox sparrow increase as shrub density increases following fire (Bock and Lynch, 1970; Raphael et al., 1987). Changes in shrub volume in the salvaged stands may have been an underlying mechanism for observed differences in densities of the fox sparrow.
- **Management**: We suspect that our observations of greater abundances of ground and shrub-nesting species and lower abundances of species associated with snags in the early years following postfire salvage logging are likely to be consistent throughout dry ponderosa pine and Douglas-fir forests in the interior west of North America.
- **Management**: Salvage logging influenced abundances of cup-nesting and cavity-nesting species. Morissette et al. (2002) similarly found that salvage logging influenced the numbers of cup-nesting birds in boreal forests of mixed-wood and jack pine after fire. The response of cup-nesting forest birds, especially sensitive and of conservation concern, should be considered in addition to the response of cavity-nesting species when implementing management prescriptions of salvage logging.
- **Management**: The black-backed woodpecker is a species of management concern and is designated as a ‘‘sensitive species’’ in Oregon (Oregon Natural Heritage Information Center, 2004) and Idaho (USDI, 2003), and a ‘‘species of concern’’ in Montana (Montana Natural Heritage Program and Montana Fish Wildlife and Parks, 2006). Our results

support previous conclusions that the blackbacked woodpecker is less abundant in salvaged forests than in unsalvaged forests (Caton, 1996; Saab and Dudley, 1998; Haggard and Gaines, 2001; Hutto and Gallo, 2006; Koivula and Schmiegelow, 2007; Saab et al., 2007); retention of areas of unsalvaged habitat may be of particular importance for this species.

- **Management**: If the maintenance of native species of bird populations is a goal of forest management, than managers should leave some burned forest for birds that are postfire specialists, particularly forest that is otherwise suitable for salvage. Additionally, as influences of salvage logging are not limited to cavity-nesting species, the response of cup-nesting birds should also be considered when implementing salvage logging.

Campbell et al. 2011.

- **Study**: In this paper, we combine empirical data from various fire-prone, semiarid conifer forests of the western US (where issues of wildfire and fuel management are most relevant) with basic principles of forest growth, mortality, decomposition, and combustion. Our goal is to provide a complete picture of how fuel treatments and wildfires affect aboveground forest C stocks by examining these disturbance events (1) for a single forest patch, (2) across an entire forest landscape, (3) after a single disturbance, and (4) over multiple disturbances.
- **Study**: The empirical data used in this paper derive from semiarid, fire-prone conifer forests of the western US, which are largely composed of pine, true fir (Abies spp), and Douglas fir. These are the forests where management agencies are weighing the costs and benefits of up-scaling fuel-reduction treatments.
- **Background**: Various levels of tree removal, often paired with prescribed burning, are a management tool commonly used in fire-prone forests to reduce fuel quantity, fuel continuity, and the associated risk of high-severity forest fire.
    - Collectively referred to as “fuel-reduction treatments”, such practices are increasingly used across semiarid forests of the western US, where a century of fire suppression has allowed fuels to accumulate to levels deemed unacceptably hazardous.
    - The efficacy of fuel-reduction treatments in temporarily reducing fire hazard in forests is generally accepted (Agee and Skinner 2005; Ager et al. 2007; Stephens et al. 2009a) and, depending on the prescription, may serve additional management objectives, including the restoration of native species composition, protection from insect and pathogen outbreaks, and provision of wood products and associated employment opportunities.
- **Background**: four of the most pressing environmental and societal concerns facing forest managers in this region today – namely, fire hazard, economic stimulus, socalled forest health, and climate-change mitigation.
- **Background**: The amount of biomass combusted in a high-severity crown fire is unquestionably greater than the amount combusted in a low-severity surface fire. The difference, however, is smaller than that suggested by some authors (eg Hurteau et al. 2008).
    - Even under the most extreme fuel-moisture conditions, the water content of live wood frequently prohibits combustion beyond surface char; this is evident in the retention of even the smallest canopy branches after high-severity burns (Campbell et al. 2007).
    - Moreover, the consumption of fine surface fuels (ie leaf litter, fallen branches, and understory vegetation), though variable, can be high even in low-severity burns.
- **Background**: Campbell et al. (2007) found that patches of mature mixed-conifer forest in southwestern Oregon that were subject to low-severity fire (ie 0–10% overstory

mortality) released 70% as much C per unit area as did locations experiencing high-severity fire (ie > 80% overstory mortality).

  - When scaled over an entire wildfire perimeter, the importance of high-severity fire in driving pyrogenic emissions is further diminished because crown fires are generally patchy while surface fires are nearly ubiquitous (Meigs et al. 2009).

- **Background**: A study conducted by North et al. (2007) in the Sierra Nevada found that net losses in large-diameter trees between 1865 and 2007 were more than compensated for by the infilling of small-diameter trees, such that total live-wood volume remained unchanged over this period of fire suppression.
- **Background**: Furthermore, Hurteau and North (2010) reported that fire-suppressed control plots deposited as much C over 7 years as did comparable thinned plots.
- **Background**: There is a strong consensus that large portions of forests in the western US have suffered both structurally and compositionally from a century of fire exclusion and that certain fuel-reduction treatments, including the thinning of live trees and prescribed burning, can be effective tools for restoring historical functionality and fire resilience to these ecosystems (Hurteau et al. 2010; Meigs and Campbell 2010). Furthermore, by reducing the likelihood of high-severity wildfire, fuel-reduction treatments can improve public safety and reduce threats to the resources provided by mature forests.
- **Finding**: Carbon (C) losses incurred with fuel removal generally exceed what is protected from combustion should the treated area burn
- **Finding**: Even among fire-prone forests, one must treat about ten locations to influence future fire behavior in a single location
- **Finding**: Over multiple fire cycles, forests that burn less often store more C than forests that burn more often
- **Finding**: It has been suggested that thinning trees and other fuel-reduction practices aimed at reducing the probability of high-severity forest fire are consistent with efforts to keep carbon (C) sequestered in terrestrial pools, and that such practices should therefore be rewarded rather than penalized in C-accounting schemes. By evaluating how fuel treatments, wildfire, and their interactions affect forest C stocks across a wide range of spatial and temporal scales, we conclude that this is extremely unlikely.
- **Finding**: Our review reveals high C losses associated with fuel treatment, only modest differences in the combustive losses associated with high-severity fire and the low-severity fire that fuel treatment is meant to encourage, and a low likelihood that treated forests will be exposed to fire.
- **Finding**: Although fuel-reduction treatments may be necessary to restore historical functionality to fire-suppressed ecosystems, we found little credible evidence that such efforts have the added benefit of increasing terrestrial C stocks.
- **Finding**: According to Campbell et al. (2007), less than 20% of the estimated 3.8 teragrams of C released to the atmosphere by the 2002 Biscuit Fire in the Siskiyou National Forest of southern Oregon and northern California (Figure 1) arose from overstory combustion.

  - Simply put, because most pyrogenic emissions arise from the combustion of surface fuels, and most of the area within a typical wildfire experiences surface-fuel combustion, efforts to minimize overstory fire mortality and subsequent necromass decay are limited in their ability to reduce fire-wide pyrogenic emissions.
- **Finding**: A review of fuel-reduction treatments carried out in semiarid conifer forests in the western US reveals that aboveground C losses associated with treatment averaged approximately 10%, 30%, and 50% for prescribed fire only, thinning only, and thinning followed by prescribed fire, respectively (WebTable 1). By comparison, wildfires burning over comparable fire-suppressed forests consume an average 12–22% of the aboveground C (total fire-wide averages reported by Campbell et al. [2007] and Meigs et al. [2009], respectively).
- **Finding**: Mitchell et al. (2009) simulated wildfire combustion following a wide range of fuel-reduction treatments for three climatically distinct conifer forest types in Oregon. As illustrated in Figure 2, fuel treatments were effective in reducing combustion in a subsequent wildfire, and the greater the treatment intensity, the greater the reduction in future combustion. However, even in the mature, firesuppressed ponderosa pine (Pinus ponderosa) forest, protecting one unit of C from wildfire combustion typically came at the cost of removing three units of C in treatment. The reason for this is simple: the efficacy of fuelreduction treatments in reducing future wildfire emissions comes in large part by removing or combusting surface fuels ahead of time.
- **Finding**: It is reasonable to expect that in the first decade or two after a forest-replacing fire, the decomposition of firekilled trees may exceed the net primary production (NPP) of re-establishing vegetation, thus driving net ecosystem production (NEP) below zero.
- **Finding**: Presuming that maximum steady-state C stocks are not dictated entirely by permanent site qualities and depend, at least in some part, on the nature and timing of disturbance, it is conceivable that prescriptions such as fuel reduction and prescribed fire could eventually elevate (or reduce) C stocks at a single location slightly beyond what they would be under a different disturbance regime (Hurteau et al. 2010). However, exactly how stable or self-reinforcing this alternate state is remains unknown.
- **Finding**: Only when treatment, wildfire, or their interaction leads to changes in maximum biomass potential (ie system state change) can fuel treatment profoundly influence C storage.
- **Finding**: Empirical evidence shows that most pyrogenic C emissions arise from the combustion of surface fuels, and because surface fuel is combusted in almost all fire types, high-severity wildfires burn only 30% more biomass than do the low-severity fires that fuel treatment is intended to promote (Figure 1).
- **Finding**: Model simulations support the notion that forests subjected to fuel-reduction treatments experience less pyrogenic emissions when subsequently exposed to wildfires. However, across a range of treatment intensities, the amount of C removed in treatment was typically three times that saved by altering fire behavior (Figure 2).
- **Finding**: Fire-spread simulations suggest that strategic application of fuel-reduction treatments on as little as 1% of a landscape annually can reduce the area subject to

severe wildfire by 50% over a 20-year period. Even so, the protection of one hectare of forest from wildfire required the treatment of 10 hectares, owing not to the low efficacy of treatment but rather to the rarity of severe wildfire events (Figure 3).

- Finding: It is reasonable to expect that after a forest-replacing fire, the decomposition of fire-killed trees exceeds NPP, driving NEP below zero. By contrast, the deliberate removal of necromass in fuel-reduction treatments could result in a period of elevated NEP. However, despite marked differences in post-disturbance NEP, it is possible for average C stocks to be identical for these two disturbance types (Figure 4).
- Finding: Long-term simulations of forest growth, decomposition, and combustion illustrate how, despite a negative feedback between fire frequency and fuel-driven severity, a regime of low-frequency, high-severity fire stores more C over time than a regime of high-frequency, low-severity fire (Figure 5).
- Finding: The degree to which fuel management could possibly lead to increased C storage over space and time is contingent on the capacity of such treatments to increase maximum achievable biomass through mechanisms such as decreased non-fire mortality or the protection from losses in soil fertility that are sometimes associated with the highest-severity fires (Figure 6).
- Management: A full accounting of C would also include the fossil- fuel costs of conducting fuel treatments, the longevity of forest products removed in fuel treatments, and the ability of fuel treatments to produce renewable “bioenergy”, potentially offsetting combustion of fossil fuels.
  - First, the fossil-fuel costs of conducting fuel treatments are relatively small, ranging from 1–3% of the aboveground C stock (Finkral and Evans 2008; North et al. 2009; Stephens et al. 2009b).
  - Second, only a small fraction of forest products ever enters “permanent” product stocks; this is especially true for the smaller-diameter trees typically removed during fuel treatments. Primarily, half-lives of forest products (7–70 years) are not significantly different than the half-life of the same biomass left in forests (Krankina and Harmon 2006).
  - Third, the capacity of forest biofuels to offset C emissions from fossil-fuel consumption is greatly constrained by both transportation logistics and the lower energy output per unit C emitted as compared with fossil fuel (Marland and Schlamadinger 1997; Law and Harmon 2011).

Chmura et al. 2011.

- **Study**: Review study containing lots and lots of minutiae around how plants respond physiologically to increases in temperature, CO2, etc.
- **Study**: A premise of this review is that the persistence and integrity of forests depend on the acclimation and adaptation of forest trees to future climates. In this review, we identify critical processes, traits and attributes that will underpin this adaptation. Specifically, we (1) review the ecophysiological foundations of forest growth, reproduction and mortality in relation to elevated [CO2], warmer temperatures, changes in precipitation, and droughts; emphasizing interactions among these factors, and how they interact with disturbances, such as fire, insects and diseases; and (2) identify key adaptations and processes underpinning tree tolerance and resistanceto anticipated stresses. It will be important to consider these adaptations when managers design strategies to help forests to adapt to future climates. We center our attention on forests of the NW – the states of Washington, Oregon, Idaho, the northern parts of California, and western parts of Montana.
- **Background**: Although large natural climatic changes have occurred over centuries to millennia (Jansen et al., 2007), changes of similar magnitude are now projected to occur over decades to years (Meehl et al., 2007; Trenberth et al., 2007). These unprecedented rates of climatic change may profoundly affect the ability of forests to acclimate or adapt to future conditions.
- **Background**: Forests in the northwestern U.S. (NW) are distinct among the Northern Hemisphere temperate forests in their species composition and high productivity (Waring and Franklin, 1979). Composed mostly of conifers, these forests are adapted to the wet/mild winters and warm-dry summers typical of the region (Franklin and Halpern, 2000). There are steep climatic gradients associated with elevation, latitude, distance from the ocean, and proximity to the mostly north–south mountain ranges. Complex topography contributes to substantial climatic variability at a fine scale, often resulting in mosaics of vegetation types within small geographic areas.
- **Background**: Ecophysiological processes are the foundation of acclimation and evolutionary adaptation for trees to climate change. Although phenotypic plasticity is substantial for some traits (e.g., timing of bud flush), the existence of among-population genetic variation for bud flush andmanyother adaptive traits indicates that phenotypic plasticity is insufficient to confer optimal fitness to the range of climates experienced by most species (Rehfeldt et al., 2001; St.Clair and Howe, 2007). Because trees are genetically adapted to their local climates, rapid rates of climate change may challenge the capacity of tree species to adapt in place or migrate to new locations (St.Clair and Howe, 2007; Aitken et al., 2008).

- **Governance**: Northwest forests will continue to be an important part of the regional economy and may play a significant role in carbon (C) sequestration and climate change mitigation (Alig et al., 2006; Krankina and Harmon, 2006).
- **Climate Change Impacts**: In the northwestern USA
    - Decrease snowpack
    - Earlier snowmelt
    - Increase summer evapotranspiration
    - Increase the frequency and severity of droughts
    - The effects of CC are generally expected to reduce forest growth and survival
        - However, in some cases, elevated CO^2 and warmer temperatures may have positive effects on growth and productivity where there is adequate moisture or where growth is limited by the cold
    - Predispose forests to disturbance by wildfire, insects, and disease
    - Change forest structure and composition at the landscape scale
- **Climate Change Impacts**: The extent of CC impacts on northwestern US forests will depend upon:
    - The magnitude of Climate Change
    - The ability of individual trees to acclimate
    - The ability of tree populations to adapt *in situ*
    - The ability of tree populations to migrate to suitable habitats
- **Climate Change Impacts**: See Table 1 in paper for a host of effects that increased CO2, increased temperatures, precipitation changes, drought increase, wildfire increase, and disease/insect increases will have on trees.
- **Climate Change Impacts**: Tree growth was generally enhanced in elevated [CO2] in both short- and long-term studies (Ceulemans and Mousseau, 1994; Curtis and Wang, 1998; Norby et al., 1999; Hamilton et al., 2002; Nowak et al., 2004; Ainsworth and Long, 2005; DeLucia et al., 2005; Finzi et al., 2006, but see Körner et al., 2005; Norby et al., 2010)
    - At the individual tree level, increased growth results from physiological adaptations that optimize photosynthetic C acquisition and allocation (Eamus and Jarvis, 1989; Pushnik et al., 1995).
- **Climate Change Impacts**: The leaf area of individual trees and stands (i.e., leaf area index, LAI) may increase under elevated [CO2] (Ceulemans and Mousseau, 1994; Ainsworth and Long, 2005), but the maximum LAI is typically similar in ambient and elevated [CO2] (Norby et al., 2003b; DeLucia et al., 2005).
- **Climate Change Impacts**: Many studies found increases in the production and standing crops of tree roots under elevated [CO2], and increases in the amount and depth of fine-root growth were particularly noticeable (Allen et al., 2000; Tingey et al., 2000; Lukac et

al., 2003; Norby et al., 2004; Pritchard et al., 2008, but see Johnson et al., 2006; Bader et al., 2009).

- **Climate Change Impacts**: In separate FACE studies, the deciduous tree Liquidambar styraciflua allocated most of the extra carbon it assimilated in the elevated [CO2] treatment into non-woody fine roots (Norby et al., 2004), whereas the evergreen Pinus taeda allocated most of its additional carbon into woody biomass (Hamilton et al., 2002). Because fine roots have rapid turnover, these differences may have ramifications for C cycling and overall productivity (DeLucia et al., 2005).
- **Climate Change Impacts**: In the NW, the direct positive effects of warmer temperatures and elevated [CO2] will be realized in only a limited set of environments that do not experience increased droughts, heat stress, or nutrient limitations. Warming-induced decreases in snowpack and increases in evapotranspiration are expected to increase the frequency and intensity of drought stress, with negative consequences for forest growth and health.
- **Climate Change Impacts**: Areas that are moisture-limited are particularly vulnerable. In the NW, this includes low-elevations in the northern Sierra Nevada, Klamath Mountains, Siskyou Mountains, Blue Mountains, Wallowa Mountains, Steens Mountain; Columbia Highlands, northern Rocky Mountains, and eastern foothills of the Cascade Range (Arno, 1979; Franklin and Dyrness, 1988; West and Young, 2000; Littell et al., 2008).
- **Climate Change Impacts**: In areas where limitations by soil moisture and temperature are low (e.g., much of the Coast Range, Olympic Mountains, and mid-elevations in the Cascade Range), future water availability is uncertain because it will depend on the net effects of rainfall, snowfall, snowmelt, surface runoff, subsurface flow, and evapotranspiration.
- **Climate Change Impacts**: Chief concerns are projected increases in droughts, fires, and pest outbreaks, and winter (chilling) temperatures.
- **Ecological Considerations**: In a P. menziesii mesocosm experiment, warming affected seasonal growth patterns and seedling height, but stem diameter, whole seedling biomass, and biomass allocation were unaffected by warming, [CO2], or their interaction (Olszyk et al., 1998a,b, 2003).
- **Ecological Considerations**: Elevated [CO2] directly affects plant physiological processes. Most trees are C3 plants in which CO2 and oxygen (O2) compete for the active site of the primary enzyme involved in photosynthesis, Rubisco.WhenCO2 is used as the substrate,CO2 assimilation occurs via photosynthesis (Ps), but when O2 is the substrate, CO2 is produced as an outcome of photorespiration. Elevated [CO2] increases the CO2 concentration in leaves and at the active sites of Rubisco, and can enhance light-saturated photosynthetic rates in woody plants by 2–280%, depending on species and

environmental conditions (Curtis and Wang, 1998; Norby et al., 1999;Nowaket al., 2004; Ainsworth and Rogers, 2007).

- **Ecological Considerations**: Overall, our understanding of respiration at the cellular level is incomplete, and we cannot use information at the cellular level to predict the effects of elevated [CO2] on respiration of whole-trees or ecosystems (Drake et al., 1999; Valentini et al., 2000).
- **Ecological Considerations**: Nutrient availability, particularly nitrogen (N), may determine whether forests benefit from elevated [CO2] because there may be little response on nutrient-poor sites (Table 1; Curtis and Wang, 1998; Oren et al., 2001; McCarthy et al., 2010). Furthermore, increases in C assimilation may increase the demand for N to support additional plant growth, and increase the sequestration of C and N into long-lived pools (e.g., plant biomass and soil organic matter). This may lead to a subsequent decline in growth due to “progressive nitrogen limitation” (Luo et al., 2004).
- **Ecological Considerations**: Warmer temperatures tend to enhance plant biochemical and physiological processes as long as optimum temperatures are not exceeded and moisture is adequate.
- **Ecological Considerations**: Elevated concentration of atmospheric carbon dioxide – [CO2], generally warmer temperatures, and changing precipitation regimes will affect the exchange of energy, carbon, water and nutrients between forests and the environment, leading to changes in forest growth, survival and structure. Interactions with biotic and abiotic disturbance agents will also shape future forests.
- **Management**: To facilitate forest acclimation and adaptation, decision-makers need to understand the potential ecophysiological responses of trees and forests to climate change.
- **Management**: Effective approaches to climate adaptation for forests will likely include:
  - Assisted migration of species and populations
  - Forest density management
    - Use of these approaches to increase forest resistance and resilience at the landscape scale requires a better understanding of species adaptations, within-species genetic variation, and the mitigating effects of silvicultural treatments
- **Management**: Recent discussions of proactive strategies for helping forests adapt to climate change have outlined several common principles, including:
  - assessing risk
  - acknowledging uncertainty
  - making use of adaptive learning
  - developing novel and flexible approaches that can deal with unforeseen problems

- Sources: (Ledig and Kitzmiller, 1992; Spittlehouse and Stewart, 2003; Ohlson et al., 2005; Spittlehouse, 2005; Millar et al., 2007).

- Management: Climate change opportunities include increased growth in areas that are currently cold-limited, and CO2 fertilization which may have net positive effects, or help ameliorate stresses resulting from climate change.
- Management: To effectively respond to climate change, land managers need spatially explicit assessments of forest vulnerability that provide combined, integrated assessments of all threats and opportunities. This information could be used to target areas for enhanced monitoring, gene conservation, silvicultural treatments to increase forest resistance or resilience, or priority harvest.
- Management: Managers should seek to lessen vulnerabilities by paying attention to key stages of forest development, and by sustaining or enhancing traits that promote adaptability. Trees are most vulnerable during the regeneration phase (reviewed in van Mantgem et al., 2006; Nitschke and Innes, 2008).
- Management: the effects of climate change on the fitness of naturally regenerated stands are probably underestimated, and provenance tests that assess climatic effects on the regeneration phase are sorely needed. Once trees become established, they are generally more resistant to climatic influences. For example, recently germinated seedlings are more susceptible to damage from heat, frost, damping-off fungi, and the drying of the soil surface (Hermann and Chicote, 1965), but may be less susceptible to certain pests (e.g., bark beetles) and competition for limiting resources
- Management: Various genetic strategies could be used to help forests adapt to climate change, including assisted migration, traditional or molecular breeding, and gene conservation. Existing trees may be able to resist, tolerate, or acclimate to modest changes in climate, but phenotypic plasticity will probably be insufficient in the long-term (Jump and Pe˜nuelas, 2005).
    - Management: Genetic variation among populations can provide adaptability to the more extreme, long-term climatic changes. Knowledge of population-level variation in adaptive traits has been used to develop seed transfer guidelines designed to prevent the use of maladapted seed sources (cf. Campbell, 1974; Rehfeldt, 1987). More recently, field and nursery provenance tests have been used to assess the adaptability of species and populations to new climates (Matyas, 1994; Schmidtling, 1994; Rehfeldt et al., 2001; St.Clair and Howe, 2007).
- Management: We should be able to lessen the adverse effects of climate change using within-species assisted migration, which is the purposeful movement of species or populations to areas where they are expected to be better adapted in the future (McLachlan et al., 2007; O’Neill et al., 2008). Despite the promise of this approach,

comprehensive studies of adaptive genetic variation are rare in non-commercial and non-threatened tree species, shrubs, and other plant groups.

- Management: other silvicultural approaches can be used to enhance forest growth and vigor, increase resistance and resilience, and sustain ecosystem services. As part of this strategy, managers should consider potential changes in the type, frequency, and extent of disturbance (Dale et al., 2001; Millar et al., 2007; Joyce et al., 2008, 2009; Peterson et al., in press; Littell et al., in review).
    - Overall, density management should be the most effective approach because of its ability to lessen drought stress, fire risk, and predisposition to insects and disease. In addition to reducing the demand for water and nutrients, thinning can modify stand structures and species assemblages to reduce the risk of fires and insect infestations.
    - Treatments should be applied carefully to avoid physical damage to remaining trees, soil compaction and fuel build-up.
    - Prescribed fires can be used as a thinning tool, or to decrease surface fuels; and if treatments are sufficiently large and strategically arrayed, they can be used to modify disturbance at the landscape level.
    - Furthermore, post-fire reforestation will providemanyopportunities to alter species and within-species genetic composition.
- Management: Any forest attribute or management practice that increases stress will also increase forest vulnerability to future climates. Vulnerable stands are those that are comprised of species or seed sources that are maladapted to future conditions, overstocked, or have high levels of competing vegetation. Based on the knowledge of expected impacts of climate change, foresters should employ genetic and silvicultural management options that target the most vulnerable sites, life stages, traits and processes to increase forest adaptability.

Climate Leadership Initiative et al. 2008.

- **Climate Change Impacts**
    - **Prediction for Rogue River Basin:** (summary) hotter, drier summers; increasing wildfire risk; reduced snowpack; and rainier, stormier winters
        - projected average temps in the Rogue River Basin may increase 1-3 d F by 2040 and 4-8 d F by 2080 – and summers heat up 7-15 d F by 2080
        - total precipitation may be roughly similar to historic levels but increasingly likely to fall in the mid-winter months rather than spring, summer, and fall
        - rising temps will cause snow to turn to rain at lower elevations and decrease average January snowpack significantly.
        - According to one model, snowpack will decrease by 75% by 2040, and then again by another 75% by 2080 to an insignificant amount
        - Likely to experience more severe storm events, higher and flashier winter and spring runoff events, and more flooding
        - Wet and dry cycles are likely to last longer and be more extreme, leading to periods of deeper drought and periods of more extensive flooding
        - Wildfire: likely a significant increase in the amount of biomass consumed by wildfire
        - **Source**: University of Oregon's Climate Leadership Initiative & National Center for Conservation Science and Policy
        - **Note**: Future forecasts of precipitation in the Rogue River Basin are highly uncertain.
        - Models forecast increased severity and variability of precipitation in Rogue River Basin, which could mean longer and deeper droughts and longer and more severe floods
- **Comparison**: Rogue River Basin could transition into an area with conditions comparable to Sacramento, California
- **Ecological Considerations**: valuable species at risk to fire: Port Orford Cedar, Brewer's Oak, Marbled Murrelet, northern spotted owl, fisher.
- **Ecological Considerations** for aquatic and terrestrial species in Rogue Basin:
    - Threats to recruitment and survival of native fish
        - Increased storms and wildfires will increase sediment loads, nutrient loads, persistent organic pollutants, and other contaminants entering Rogue River and its tributaries
        - Hotter weather will increase water temperatures
        - Possible disconnection between timing of fish life stages and availability of primary foods due to shifts in timing of stream flows and emergence of aquatic invertebrates
        - Warmer water temperatures and extended low summer base flows extending well past the summer months are likely to decrease dissolved oxygen, produce more disease, and create conditions lethal to native fish

    - Threats to terrestrial vegetation
        - Drought-stressed vegetation could be more susceptible to insect outbreaks and disease
        - Stressed and dying vegetation will allow larger and more frequent fires
        - Rapid climate shifts in concert with existing habitat fragmentation will make it difficult for some native vegetation to adjust and disperse
    - Threats to terrestrial animals
        - Rapid climate shifts in concert with existing habitat fragmentation will make it difficult for some native animals to adjust and disperse
    - Threats to long-distance avian migrants
        - Changes to timing of flowering and insect emergences could result in lowered access to primary foods
    - Threats to amphibians
        - Increased drying of the environment combined with low mobility of many amphibians could cause amphibian populations to decrease
    - Threats to high elevation wildlife and plants
        - Available habitat may become reduced leading to population reductions
    - Threats to all wildlife
        - Diseases and disease vectors are expected to increase with warmer temperatures
        - Wildlife under stress from climate change and/or other stressors will be more susceptible to disease
        - Conditions may become more favorable for some exotic, invasive species
- **Management**: Recommendations to prepare aquatic and terrestrial systems for climate change:
    - Aquatic systems
        - Restore and maintain stream complexity and connectivity
            - To improve spawning habitat
            - To allow movement to new areas if others become too warm
        - Restore and maintain critical landscapes
            - High elevation riparian areas
            - Floodplains
            - Tributary junctions
            - North-facing streams
            - Stream reaches with gravels and topographic complexity
        - Manage fisheries to protect genetic diversity and life history diversity
    - Terrestrial systems
        - Protect and restore ecosystem function, structure, and genetic diversity
            - To enable organisms to withstand and adapt to climate stressors
        - Use fire strategically to reduce the likelihood of severe fire, and then replant with a diverse array of native species
        - Apply ecologically-appropriate fuels reductions (where needed)
        - Protect remaining intact habitats, especially

            - Old growth
            - Roadless areas
            - Corridor connections (to aid wildlife migration)
        - Protected areas should be expanded longitudinally and latitudinally
            - To allow species to shift ranges
        - Identify, protect, and restore land and stream reaches that provide critical ecosystem services
        - Translocate native species when they cannot do this for themselves, due to habitat fragmentation or too-swift changes in climate
    - Aquatic and Terrestrial Systems
        - Reduce existing stressors
            - Habitat fragmentation
            - Erosion from resource extraction and roads
            - Air and water pollution and contamination
            - The loss of keystone species
            - Invasive species
            - Conversion of natural habitats to urban and suburban
- **Management:** Forest management recommendations
    - Build resistance and resiliency through greater structural and genetic vegetation diversity
    - Manage forests with longer harvest rotations to sequester more carbon, and may acquire credits in a cap and trade system
- **Governance** recommendations
    - Reorient management plans to focus on “future range of climate variability”
    - Use “scenario planning” methods to identify and plan for climate futures
    - Increase public understanding of the likely consequences of climate change

DellaSalla et al. 2016. In Review

- **Note from Dominick—May 2016**: In the coming months, Geos Institute will be working with partners in keeping logging ridders off fire legislation in the Senate. We also have a new paper in review that shows forests with lower levels of protection (more logging) are burning more severely than those that are strictly protected as parks and wilderness areas. This is another key assumption being made by members of Congress seeking to overturn forest protections based on the refuted assumption that protected forests burn more severely when, in fact, the opposite is true!

Cushman et al. 2013.

- **Study**: The goal of this chapter is to describe the state of the art in quantitative corridor and connectivity modelling. We will review several critical issues in modelling, and provide expert guidance and examples to help practitioners implement effective programmes to preserve, enhance or create connectivity among wildlife populations.
- **Background**: The ability of individual animals to move across complex landscapes is critical for maintaining regional populations in the short term (Fahrig 2003; Cushman 2006), and for species to shift their geographic range in response to climate change (Heller & Zavaleta 2009).
- **Background**: Habitat fragmentation decreases dispersal success (Gibbs 1998), increases mortality (Fahrig et al. 1995) and reduces genetic diversity (Reh & Seitz 1990; Wilson & Provan 2003). Local populations may decline if immigration is prevented (Brown & Kodric-Brown 1977; Harrison 1991) and may prevent recolonization following local extinction (Semlitsch & Bodie 1998).

Damschen et al. 2012.

- **Study**: Here, we ask how plant communities on serpentine (ultramafic) soils will be affected by climate change, relative to those on less extreme soils
- **Background**: Predicting and mitigating climate change effects on ecological communities is a tremendous challenge. Little attention has been given to how endemic-rich communities on isolated patches of low-nutrient soil (e.g. serpentine) will respond to climate change.
- **Background**: One of the greatest challenges that ecologists and land managers face today is anticipating how climate change will affect the diversity and composition of ecological communities to develop effective strategies for adaptation and mitigation (e.g. Burkett et al. 2005; Glick, Stein & Edelson 2011; Klausmeyer et al. 2011).
- **Background**: Plant communities found on patches of unusual bedrock and soil types, such as serpentine, gypsum, limestone, dolomite and shale (i.e. 'special soil', 'azonal', or 'low nutrient' communities), contain many endemic species and make large contributions to regional floristic diversity.
    - For example, in California, 35% of the state's 1742 rare plant species occur on special substrates (Skinner & Pavlik 1994).
- **Background**: Plant communities on special soils have two distinctive attributes that may cause them to respond uniquely to climate change.
    - First, they are often found in discrete outcrops making them more spatially isolated from one another than 'normal' soils that tend to be more contiguous (hereafter, we refer to this set of considerations as 'spatial factors'). For example, serpentine outcrops across the world are seldomfound in outcrops of more than a few hundred square kilometres, with some notable exceptions including New Caledonia; southern Oregon, USA; Sulawesi; and eastern Cuba (Brooks 1987). This spatial isolation maymake itmuchmore difficult for species to successfully migrate under climate change.
    - Second, because these communities are on unproductive substrates, they may differ from communities on 'normal soils' in terms of limiting resources, functional traits, and the relative importance of disturbance, competition and other ecological processes (hereafter, we refer to these as 'non-spatial factors').
        - Plants in these special soil habitats often have traits associated with tolerance of drought and nutrient limitation [e.g. small stature, low-specific leaf area (SLA), high allocation to roots relative to shoots] because nutrient availability is limited, water can be scarce, and soils may have additional unusual chemistries (e.g. presence of heavy metals or particularly acidic or basic pH).
        - Special soil communities are more strongly water limited than others; therefore, they may be especially responsive to changes in available precipitation.

    - On the other hand, because plants on special soils already have adaptations for stress tolerance, they may be particularly well suited to withstand climatic changes.
- **Background**: Serpentinite and peridotite (collectively called ultramafic or simply serpentine) rocks are found throughout the world, primarily where oceanic crust and mantle have been exposed on continents (Alexander et al. 2006). Soils weathered from these rocks are extremely magnesium-rich and calcium-poor compared with most other soils and are also typically low in macronutrients (especially P and K) and sometimes also high in heavy metals (Ni, Cr, Co) (Alexander et al. 2006). In many cases, these soils have very high rock fragment content, leading to a scarcity of available water (Alexander et al. 2006). Sparse canopy cover may also contribute to high temperature and low moisture near the ground surface.
- **Background**: On limestone soils, Grime et al. (2000, 2008) experimentally manipulated temperature and precipitation and measured the effects on grassland communities in two settings: Buxton, UK, an unproductive limestone grassland, and Wytham, UK, an early successional productive limestone grassland. Over a 5-year period (Grime et al. 2000), the composition of the unproductive grassland changed considerably less in response to treatments than the productive grassland, and even after 13 years, changes in the unproductive grassland were strikingly small (Grime et al. 2008). This response was attributed in part to a suite of stresstolerant functional traits shared by the species on the unproductive site and in part to the potential for individuals at the unproductive site to move among microhabitats determined by soil depth, allowing them to persist through climatic changes (Fridley et al. 2011).
- **Background**: On gypsum soils, Matesanz, Escudero & Valladares (2009) experimentally manipulated rainfall and measured the effects on a specialist shrub species, Centaurea hyssopifolia, across habitats that varied in, among other factors, their 'quality' as measured by plant cover and soil nutrient content. In poor quality habitat, reduced rainfall led to greater advancement of flowering and dispersal times, greater reduction in growth rate and greater increase in the fractions of senescent leaves, compared with individuals under similar rainfall treatment in higher-quality habitat.
- **Background**: Taken together, the above two studies suggest that climate change effects may be buffered by the community-level properties of plants on low-nutrient soils, but individual species may suffer stronger effects of climate change on low-nutrient soils than high-fertility soils.
- **Background**: In a study of chaparral and oak woodland in northern California, Harrison (1997) found that elevational and coast-to-inland gradients had no effect on local diversity on serpentine soils. However, local diversity on non-serpentine sedimentary soils decreased with distance inland, increased with elevation and slope interacted with both of these effects. These results indicate that local diversity on sedimentary soils is greater in favorable climates and is more variable along climatic gradients than on serpentine soils.
- **Background**: Using the fossil pollen record in six lakes, Briles et al. (2011) compared woody vegetation change during the Holocene on serpentine and non-serpentine soils

(granitic) in the Klamath- Siskiyou Mountains. They found that shrub and tree abundances were less variable on serpentine in comparison to granitic substrates in response to the past 15 000 years of climatic variability. On serpentine, the relative abundances of the dominant species were altered, but there was little change in species composition. Briles et al. (2011) conclude that trees and shrubs on serpentine soils were able to persist under a range of past climate conditions for the same reasons that they can tolerate nutrient deficiencies and high heavy-metal concentrations. They caution against generalizing these results to all plant species responses to future climate change in that the paleorecord lacks the ability to detect many species-level responses, particularly for herbs.

- **Background**: Fernandez-Going, Anacker & Harrison (in press) compared temporal variability in diversity over 10 years for serpentine and non-serpentine grasslands in northern California, USA. They found that variability in species richness and composition in response to annual variation in precipitation was lower on serpentine than on non-serpentine soils. They also found that serpentine communities were less functionally diverse and had greater numbers of species with stress-tolerant traits (short stature, low-SLA, low foliar C⁄N ratio) than non-serpentine communities.
- **Background**: Damschen, Harrison & Grace (2010) examined long-term vegetation change in the Klamath-Siskiyou Mountains, Oregon, USA, using a historical data set originally collected by Robert Whittaker from 1949 to 1951 (Whittaker 1960). Whittaker sampled vegetation to determine how community composition changed along environmental gradients including elevation, topography and soil type.
    - Since that time, the region has shown an increase in mean annual temperatures of c. 2 ————————C (Damschen, Harrison&Grace 2010).
    - In 2007, these communities were resampled to examine change over time on serpentine and non-serpentine soils. Cover of nearly all herb species either declined or remained the same on both serpentine and non-serpentine soils.
    - Species with functional traits associated with cool and moist habitats (i.e. high specific leaf areas (SLA), northern biogeographic affinities) declined more than those with opposite traits.
    - As a result, species composition of a given site today resembles that of a warmer (more southerly) topographical position in Whittaker's time.
    - The observed shifts in plant species richness and cover were of greater magnitude for serpentine vs. non-serpentine soils, but changes in functional traits and species composition were similar between soils.
    - Serpentine endemics also showed greater declines in cover than soil generalists.
    - These results suggest that herbaceous communities on serpentine have been as strongly affected by a warming climate as communities on non-serpentine soils.
- Finding: Other qualitative observations from the literature on the biogeography of serpentine plants likewise support the interpretation that the composition of non-serpentine communities may show greater variation over climate gradients than serpentine communities (Rune 1953; Whittaker 1960; Kruckeberg 1984; Brooks 1987; Borhidi 1991; see review in Harrison, Damschen & Going 2009).

- **Finding**: A surprising result of our models (See Fig. 2 and Appendix S1 in Supporting Information for model results) under the no-dispersal scenario was that species do not disproportionately suffer habitat loss as a result of being confined to serpentine. This implies that serpentine soils are just as abundant at higher elevations and higher latitudes where suitable climatic conditions are predicted to occur in the future, as in the geographical regions where the species exist now.

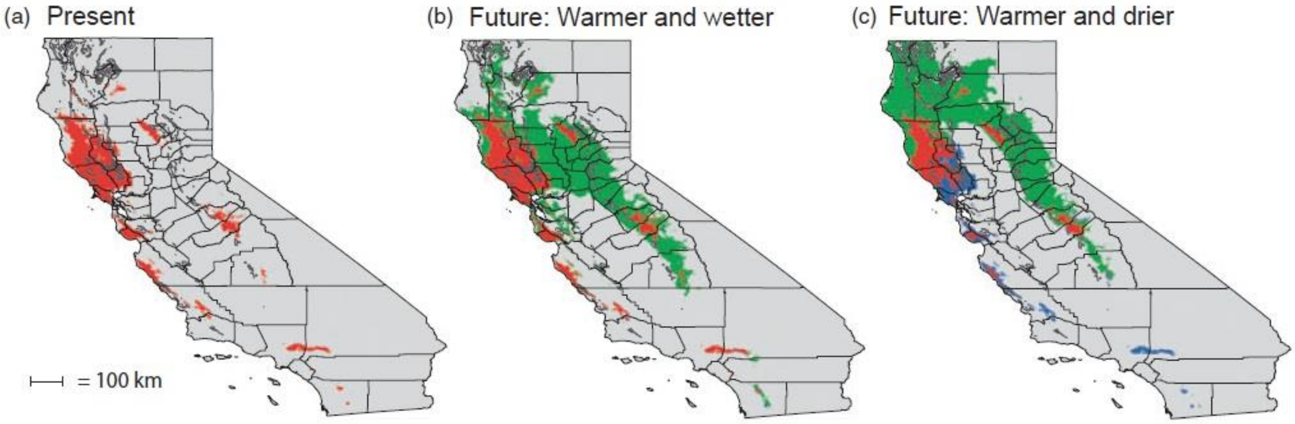


Fig. 2. The (a) current range, (b) future range assuming a warmer and wetter climate and (c) future range assuming a warmer and drier climate for *Ceanothus jepsonii*, one of 12 species examined. In panel a, Red is the species range at present. In panels b and c, Red is the area of overlap between present and future ranges, Blue is the area that is lost due to climate change and Green is the area that is gained due to climate change. Serpentine outcrops and county boundaries are outlined in black. See Appendix S1 for maps of the remaining 11 species.

- **Finding**: Under the scenario that included dispersal, we found that to colonize the nearest serpentine patch in their newly suitable range from a patch within their current climate envelope, the 12 species had to make minimum initial dispersal distances averaging 596 m for the warmer–wetter and 1891 m for the warmer–drier climate projection models.
    - Subsequently, they must make minimum dispersal jumps averaging 663–8275 m to colonize each patch within their newly suitable ranges (i.e. these are the mean shortest edge-to-edge distances to each patch in the newly suitable range; Fig. 3).
    - Several lines of evidence suggest that plant dispersal on the order of kilometres across unsuitable intervening habitat is unlikely over relatively short timescales.
    - A recent review of dispersal studies found that plants disperse on average between 10–100 m and that average dispersal distances >1 km are uncommon (Kinlan & Gaines 2003).
    - Other studies have found that plants in spatially isolated habitats have evolved limited dispersal abilities (Cheptou et al. 2008; Riba et al. 2009).
- **Finding**: Our analyses also suggested that three species (Linanthus ambiguus, Polystichum lemmoni and Salix delnortensis) will have no climatically suitable serpentine outcrops in the future under one or both climate projection models, although we note the above caveat about the reliability of any such absolute predictions using current species distribution modelling methods.
- **Finding**: Three of the four studies indicate that serpentine communities may be less sensitive to climate change than communities on ‘normal’ soils.

- **Finding**: Of the four studies we found that evaluate the relative sensitivity of serpentine plant communities to those on non-serpentine soils, three studies (Harrison 1997; Briles et al. 2011; Fernandez-Going, Anacker & Harrison, in press) suggest that serpentine plant communities are less variable under climate change while one study (Damschen, Harrison & Grace 2010) indicates that they are at least as vulnerable as those on 'normal' soils.
- **Finding**: Our review of other (non-spatial) factors suggests that serpentine plant communities may be more resistant to climate change, but conflicting evidence demonstrates the importance of understanding the roles of species turnover, overstorey composition and species endemism.

De Frenne et al. 2013

- **Study**: Here we compiled plant occurrence data (1,032 species in total) from 1,409 resurveyed vegetation plots in temperate deciduous forests. The plots were distributed across 29 regions of temperate Europe and North America (Fig. 1 A and B) with an average interval of 34.5 y (range: 12–67 y) between the original and repeated vegetation surveys (Table S1). From these plots, we tested for plant community responses to recent macroclimate warming and assessed the potential role of changes in forest canopy cover in modulating such responses.
- **Climate Change Impacts**: The thermophilization of vegetation is consistent with the warming climate observed across the regions: the mean rise in April-to-September temperatures between the old and recent survey was 0.28 °C per decade (Table S1).
- **Background**: Recent global warming is acting across marine, freshwater, and terrestrial ecosystems to favor species adapted to warmer conditions and/or reduce the abundance of cold-adapted organisms (i.e., "thermophilization" of communities).
- **Background**: the temperature experienced by organisms at ground level (microclimate) can substantially differ from the atmospheric temperature due to local land cover and terrain variation in terms of vegetation structure, shading, topography, or slope orientation (8–15).
- **Background**: The daytime or nighttime surface temperature in rough mountain terrain, for instance, can deviate by up to 9 °C from the air temperature (10).
- **Background**: Likewise, forest structure creates substantial temperature heterogeneity, with the interior daytime temperature in dense forests being commonly several degrees cooler than in more open habitats during the growing season (12–15).
- **Background**: forest understories, which play a key role in vital ecosystem services of forests such as tree regeneration, nutrient cycling, and pollination(17, 18).
- **Background**: Temperate forests comprise 16% (5.3 million km2) of the world's forests (19), and understory plants represent on average more than 80% of temperate forest plant diversity (17).
- **Background**: Changing forest management regimes due to altered socioeconomic conditions, but also eutrophication, climate warming, and fire suppression, have resulted in increased tree growth, standing stocks, and densities in many temperate forests of the northern hemisphere (20–25).
- **Background**: Dense tree canopies not only lower ground-layer temperatures but also increase relative air humidity and shade in the understory (12–15). Higher relative humidity in dense forests can also protect forest herbs and tree seedlings from summer drought, decreasing mortality and thus buffering the impacts of large-scale climate change (15, 29). Furthermore, many forest herbs are known to be slow-colonizing species (30). Given the high degree of habitat fragmentation in contemporary landscapes, microclimatic buffering in dense forests may be a critical mechanism to ensure the future conservation of temperate forest plant diversity.

- **Finding**: Here we show that microclimatic effects brought about by forest canopy closure can buffer biotic responses to macroclimate warming, thus explaining an apparent climatic lag.
- **Finding**: Using data from 1,409 vegetation plots in European and North American temperate forests, each surveyed at least twice over an interval of 12–67 y, we document significant thermophilization of ground-layer plant communities. These changes reflect concurrent declines in species adapted to cooler conditions and increases in species adapted to warmer conditions.
- **Finding**: However, thermophilization, particularly the increase of warm-adapted species, is attenuated in forests whose canopies have become denser, probably reflecting cooler growing-season ground temperatures via increased shading. As standing stocks of trees have increased in many temperate forests in recent decades, local microclimatic effects may commonly be moderating the impacts of macroclimate warming on forest understories.
- **Finding**: Significant community turnover took place over time in the temperate forests we sampled: on average, one-third of the species present in the old surveys has been replaced by other species today
- **Finding**: We found that local changes in forest canopy cover modulate the thermophilization of vegetation; thermophilization was lowest in forests that became denser, and highest in forests that became more open over time (Fig. 3A).
- Management: Conversely, increases in harvesting woody biomass—e.g., for bioenergy—may open forest canopies and accelerate thermophilization of temperate forest biodiversity.
- Management: The importance of increased canopy cover in influencing understory biodiversity (i.e., the ability of canopy cover to lessen temperature increases and humidity decreases) is particularly relevant in an era when forest management worldwide is confronted with increasing demands for woody biomass, not least as an alternative source of renewable energy (31, 32).
- Management: Large-scale reopening of the canopy for woody biomass harvesting may thus hasten thermophilization of understory plant communities of temperate forests.

DellaSala et al. 1999.

- **Study**: We reviewed the conservation importance and status of the Klamath-Siskiyou Ecoregion relative to that of 30 temperate coniferous forest ecoregions in the United States and Canada and also compared the results to a related global comparison of diverse forest ecoregions.
- **Finding**: Based on comparisons of species richness, endemism, unique evolutionary and ecological phenomenona (e.g., species migrations, adaptive radiations), and global rarity of habitat types, we ranked the biodiversity of the Klamath-Siskiyou Ecoregion among the world's most outstanding temperate coniferous forests.
- **Finding**: We identified a total of 2,377 species for six terrestrial taxa that we analyzed: native plants (78%, n=1,859), birds (9%, n=222), butterflies (6%, n=141), mammals (3%, n=69), land snails (2%, n=54), and reptiles and amphibians (1%, n=32). Of this total, 168 species (7%) occur nowhere else in the world.
- **Finding**: The ecoregion supports a continental maximum of conifers (30 species); up to 17 species have been recorded in an area of 2.6 km(2). The combined freshwater habitats of the region support exceptionally high levels of endemism: 14 of 33 (42%) fish and 142 of 235 (60%) mollusk taxa are endemic to the region.
- **Finding**: We ranked the status of the region's terrestrial biodiversity as endangered. Approximately 25% of forests are intact and 10.5% are legally protected (e.g., as congressionally designated wilderness) from logging.
- **Finding**: We identified 24 stand types and plant series considered distinctive by the California Native Plant Society, 2 forest ecosystem types told-growth and mature, riparian forest) considered threatened or endangered by the National Biological Survey, and 10 plant communities listed as critically globally imperiled (G1) or globally imperiled (G2) by The Nature Conservancy.
- **Finding**: We documented 138 terrestrial and 16 freshwater taxa with state or federal listing status, 5 terrestrial species extirpated from the region.
- **Finding**: More than half of the listed terrestrial taxa were restricted geographically to the region (i.e., endemics) or were limited to elevations less than or equal to 1,524 m where few protected areas occurred.
- **Finding**: Most mollusk populations have declined dramatically (>90% historic range contractions) throughout the region, and 11 fish taxa (especially anadromous salmonids) have a special status designation due to extensive habitat degradation and changes in hydrology and water quality.

DellaSala et al. 2010 Presentation.

GEOS Institute Powerpoint Presentation

- **Background**: Klamath-Siskiyou acted as refugia in the past
    - Proximity to California Current, which lessens cold and heat extremes and produces abundance fog and precipitation
    - Located at a crossroads for species mixing
    - Extremely complex terrain provides microclimates
    - Past refugia locations are centered mostly on or near the coast, and coincide with areas of higher precipitation
- Climate Change Impacts by 2075
    - Winters increase 4-6 degrees F
    - Summers increase 6-10 degrees F
    - Declining snowpack
    - Altered peak stream flows
    - Reduced summer stream flows
    - Precipitation shifting to mid-winter and away from spring-fall
    - Decrease in coastal fog
    - Increase in evapotranspiration
- Ecological Considerations
    - Greater than 10% of all mesic species (lichens, bryophytes, salamanders, mollusks, insects) may disappear from region
    - Hundreds to thousands of species at risk
    - Coastal areas at highest risk
    - Bird communities may shift with conditions
        - More grassland species
        - Fewer shrub species
        - Fewer forest species
- Management: Reserve design
    - Robust reserve design = microfeguia + connectivity – land use stressors
    - Current protection (in 2010) of 13% of KS Region would need to increase to 50%
- Management: Goals for reserves in a changing climate
    - Represent plant communities in well-distributed reserves
    - Maintain focal species and special elements
    - Maintain key processes (fire, hydrology, evolutionary hot spots)
    - Provide for resilient ecosystem properties
    - Identify and protect microrefugia
        - Coastal influence
        - Higher precipitation
        - Middle elevations
        - Vegetation stability
        - North-facing slopes

    - Identify critical links, connectivity among microrefugia, and among elevational gradients
- Management: For microrefugia and connectivity
    - Intact old forest blocks spanning elevation zones are needed to connect refugia
- Management: Reduce non-climate stressors
    - Livestock
    - Invasives
    - Logging of old forests
    - Habitat fragmentation
    - Floodplain/coastal development
    - Flooding
    - Over allocation of water
    - Species declines
    - Energy development
    - Human footprint
    - Disease
    - Overfishing
    - Inappropriate fire management
- Management: old forest protection = carbon storage

DellaSala et al. 2015.

- **Study**: This paper (1) showcases the fundamental conservation biology and ecosystem management principles underpinning the Northwest Forest Plan as a case study for managers interested in large-landscape conservation; and (2) recommends improvements to the plan's strategy in response to unprecedented climate change and land-use threats.
- **Background**: The 1994 Northwest Forest Plan (NWFP) shifted federal lands management from a focus on timber production to ecosystem management and biodiversity conservation. The plan established a network of conservation reserves and an ecosystem management strategy on ~10 million hectares from northern California to Washington State, USA, within the range of the federally threatened northern spotted owl (Strix occidentalis caurina).
    - Twenty years into plan implementation, however, the U.S. Forest Service and Bureau of Land Management, under pressure for increased timber harvest, are retreating from conservation measures. We believe that federal agencies should instead build on the NWFP to ensure continuing success in the Pacific Northwest.
- **Background**: The NWFP amended resource management plans for 19 national forests and seven BLM planning districts with 80% of those lands dedicated to some form of conservation (Figure 1). This increased level of protection and improved management standards were necessary because for many decades federal lands were managed without proper regard for water quality, fish and wildlife viability, and ecosystem integrity. Overcutting of older forests and rapid road expansion were the main factors responsible for the 1990 threatened species listing of the northern spotted owl, 1992 threatened listing of the marbled murrelet (Brachyramphus marmoratus), multiple listings of Evolutionary Significant Units (ESUs) of salmonids (Oncorhynchus spp.), and pervasive and mounting water quality problems.
- **Background**: Older forests in the Pacific Northwest are a conservation priority because they harbor exceptional levels of forest biodiversity (e.g., >1000 species have been recognized) and numerous at-risk species [2]. Historically, such forests widely dominated much of the Pacific Northwest landscape, especially in wet areas (coastal) where the intervals between successive fires were centuries long [5].
- **Background**: Most forest types in this region generally begin acquiring older forest characteristics at 80 years, depending on site productivity and disturbance history, with full expression of structural diversity at 400+ years [7]. Upper elevation subalpine fir (Abies lasiocarpa) and Pacific silver fir are not considered old growth until they are 260–360 years old [8]. Notably, researchers have recently developed an old-growth structure index (OGSI) to represent a successional continuum from young to older forests. The OGSI is a continuous value of 0–100 used to delineate older forests based on four features: (1) large live tree density; (2) large snag density; (3) down wood cover; and (4) tree size diversity at the stand level [9].
- **Background**: Young forests <80 years old that originate from natural disturbance in older forests, known as complex early seral forest, also have high levels of structural

complexity (e.g., snags and downed logs) and species richness (especially forbs, shrubs; [10,11]). These younger forests have only recently been recognized as a conservation priority and like old growth have been replaced by structurally simplistic tree plantations [10].

- **Background**: Conservation scientists have long-recognized that effective conservation planning involves two complementary approaches: a coarse filter consisting of representative reserve networks, and fine filter that includes local protections for species outside reserves [18,19]. FEMAT [2] emphasized the need for a large, interconnected reserve network as fundamental to biodiversity conservation [1,20,21]
- **Background**: conservation biology principles guided the design of the NWFP [2]:
    - Species that are widely distributed are less prone to extinction than those with more restricted ranges because local population dynamics are more independent [31]. Large patches of habitat supporting many individuals are more likely to sustain those populations than small patches because larger populations are less subject to demographic and environmental stochasticity [32,33].
    - Populations residing in habitat patches in close proximity are less extinction prone than those in widely separated patches because the processes of dispersal and recolonization are facilitated [34].
    - The extent to which the landscape matrix among habitat patches (supporting local populations of the focal species) resembles suitable habitat, the greater the connectivity among local populations leading to lower extinction risks [35].
    - Sustaining a species over the long-term requires that demographic processes be evaluated at three key spatial scales: territory, local population, and metapopulation [36].
- **Background**: The Marbled Murrelet nests in older-aged forests usually within 80-km of the coast from northern California to Alaska. The murrelet was listed as threatened in the Pacific Northwest due to habitat fragmentation from roads and clearcuts that expose murrelets to increased levels of nest predation [57–59]. Murrelet distribution and population trends are determined by the amount of suitable nesting habitat within five coastal "conservation zones" from Washington to California [60]. In general, as nesting habitat decreases murrelet abundance goes down, although abundance is also related to near-shore marine conditions (e.g., fish-prey abundance). Over the NWFP area, the trend estimate for the 2001–2013 period was slightly negative (~1.2%) (confidence intervals overlapped with zero [60]).
- **Background**: About 1 million ha of potential suitable nesting habitat for murrelets remained on all lands within the range of the murrelet at the start of the NWFP (estimate based on satellite imagery [60]). Of this, only ~186,000 ha was estimated as high quality nesting habitat based on murrelet nest site locations. Over the NWFP baseline (1993–2012), net loss of potential nesting habitat was 2% and 27% on federal and nonfederal lands, respectively [60]. Losses on federal lands were mostly due to fire (66%) and logging (16%); on nonfederal lands logging (98%) was the primary cause of habitat loss [60].
- **Background**: Older forests and intact watersheds generally provide a myriad of ecosystem services associated with high levels of biodiversity [77,78]. Some examples of

ecosystem services that have benefited from the NWFP include net primary productivity, water quality, recreation such as camping and hunting, salmon productivity, and carbon storage and sequestration. Older forests with high biomass (>200 mg carbon/ha, live above ground biomass of trees) most abundantly provide these services in aggregate primarily on federal lands [79].

- **Background**: The storage of carbon on federal lands is especially noteworthy because the region's high-biomass forests are among the world's most carbon dense forest ecosystems [80,81]. When cut down, these forests quickly release about half their carbon stores as CO2 [82]. Reduced logging levels and increased regrowth under the NWFP has resulted in the regional forests shifting from a net source of CO2 prior to the NWFP to a net sink for carbon during the NWFP time period [83]. While most of the carbon losses on federal lands are the result of forest fires, logging (mostly on nonfederal lands) remains the leading cause of land-use related CO2 emissions [84]. Forests regenerating from natural disturbances including fire also rapidly sequester carbon and can then store it for long periods via succession if undisturbed. By comparison, logging places forests on short-rotation harvests, thereby precluding long-periods of carbon accumulation [82,83].
- **Background**: Improvements to the NWFP's ecosystem and conservation focus are especially relevant today given: (1) the spotted owls' precarious status, including increased competition with barred owls; (2) continuing declines in murrelet populations; (3) other at-risk species recently proposed for listing (e.g., Pacific fisher Martes pennanti, North Oregon Coast Range distinct population segment of the red tree vole Arborimus longicaudus); (4) numerous forest associated invertebrates and lesser known species with restricted ranges that are vulnerable to extinction as a result of climate change [24]; and (5) additional ESU's of Pacific salmon that have been listed with none recovered to the point of delisting. Recent and ongoing land-use stressors acting alone or in concert, especially on nonfederal lands, also need to be reduced along with improved forest management practices and stepped up conservation efforts (Table 4).
- **Background**: Unfortunately, attempts to revise the Northwest Forest Plan have been bogged down by ongoing controversy over timber vs. biodiversity values that has led to a perpetual tug-of-war between decision makers that either support or seek to dismantle the NWFP. If this trend continues, federal land management may regress and recreate many of the problems the NWFP was implemented to correct, including re-inflamed social conflict, a cascade of endangered species listings, permanently increased conservation burdens on private landowners due to additional endangered species listings, and loss of ecological integrity that underpins the region's ecosystem services and their adaptive capacity to climate change.
- **Finding**: Table 4 provides specific suggestions for improving conservation impact of Northwest Forest Plan: page 3340.
- **Management**: We urge federal land managers to:
  - (1) protect all remaining late-successional/old-growth forests;
  - (2) identify climate refugia for at-risk species;
  - (3) maintain or increase stream buffers and landscape connectivity;
  - (4) decommission and repair failing roads to improve water quality;

  - (5) reduce fire risk in fire-prone tree plantations;
  - (6) prevent logging after fires in areas of high conservation value.
- **Management**: As forest plan revisions go forward in the region, the reserve network needs to be expanded in response to increasing land-use stressors to ecosystems and at-risk species, and to provide for a more robust conservation framework in response to climate change.
- **Management**: Livestock grazing in combination with climate change is also now the biggest impact to biodiversity on federal lands that needs to be offset by new protections such as large blocks of ungrazed areas [88].
- **Management**: Regional carbon storage capacity can be increased if managers both protect carbon stores in older high biomass forests and allow young forests to re-grow for longer periods [83,84]. Managing for high-biomass forests is also associated with the multifunctionality of ecosystems because carbon dense forests are associated with high levels of biodiversity and numerous other ecosystem services [79].

DellaSala. 2016. White Paper.

- **Study**: This paper summarizes results from dozens of recent field studies from multiple regions (Pacific Northwest, Pacific Southwest, Rockies) and forest types (mixed conifer, mixed evergreen, subalpine, lodgepole pine, spruce-fir) on effects of mountain pine beetle tree kill on fire severity.
- **Finding**: There is now substantial field-based evidence showing that beetle outbreaks do not contribute to severe fires nor do outbreak areas burn more severely when a fire does occur.
- **Finding**: In terms of the effects of thinning and logging on mountain pine beetle outbreaks, the studies show mixed effects on reducing tree mortality before outbreaks at the stand level, no effect during outbreaks of landscape scales, and substantial impacts of post-fire logging on resilience of forests to natural disturbances, including the potential for logging and road building to increase future fire risk and severity.
    - Many studies recommend treating the home-ignition zone, 100-200-ft from a home structure outward, and building with fire-resistant materials as proven fire-risk reduction methods.
    - Focusing on defensible space requires treating a narrow zone nearest homes totaling ~12,282 square miles in 13 states.
    - Treating forests in the backcountry, or outside of this zone, is costly and does nothing to stop insect outbreaks, diverting limited resources away from incentivizing and creating defensible space.
- **Finding**: As mountain pine beetle outbreaks increased across the western United States, fires did not track outbreaks and where fires did occur they were by and large were not in the areas affected by mountain pine beetle (fig2).
- **Finding**: In mixed-evergreen forests below 5,000 feet in the San Bernardino Mountains of California, pre-fire tree mortality from drought and western pine beetles did not influence subsequent fire severity in stands where most pre-fire dead trees had retained needles6.
- **Finding**: Empirical studies of forest fuel levels immediately following outbreaks and retrospective studies of fires that burned in lodgepole pine and spruce-fir forests throughout the U.S. Rockies that were recently affected by outbreaks suggest that outbreaks may actually decrease risk of high-severity fires. This is the case even during and immediately following outbreaks. There is general agreement that the risk of active high-severity crown fires actually decreases in years to decades following outbreaks due to reduced forest canopy density (i.e., more dead trees means forest canopies are less dense).
- **Finding**: In upper Douglas-fir forests of Wyoming, pre-fire outbreak severity did not increase fire severity when fires occurred4. In another study, also in Douglas-fir forests of Greater Yellowstone, beetle outbreaks killed 38-83% of the basal area within forest stands resulting in a reduction in canopy fuel loads and bulk crown density during the red stage that continued into the silver stage5. These studies demonstrate that

following beetle outbreaks there is actually a reduction in the likelihood of subsequent crown fires for decades given reduced forest crown densities and fuels.

- **Finding**: Research conducted on beetle outbreaks has consistently shown that fire-weather and climate are more important factors than effects of outbreaks in determining fire behavior in western forests1-5.
- **Finding**: Studies that have looked directly at thinning effects on tree vigor in Douglas-fir and ponderosa pine forests show mixed results7. While some researchers have found thinning reduces beetle susceptibility in forest stands when there is not an outbreak, others have found that bark beetles do not preferentially infest trees with declining growth. Under some circumstances, thinning may alleviate tree stress at the stand level but does not mitigate susceptibility against extensive or severe outbreaks7.
    - Specifically, while thinning can maintain adequate growing space and resources, there is accumulating evidence that suggests tree injury, soil compaction, and temporary stress caused by thinning may increase susceptibility of remaining trees to bark beetles and forest pathogens that invade weakened trees7.
- **Finding**: There is general scientific agreement that forest thinning cannot effectively stop outbreaks once a large-scale (landscape) insect infestation has started. Most “control efforts” involving thinning have had little effect on the final size of outbreaks and can do more harm than good7. This is because once an extensive outbreak has started, active management is unlikely to stop it as beetles overwhelm host resistance to outbreaks. Thinning large areas also can have major consequences (impacts) to soils, water quality (e.g. from soil runoff), wildlife, recreation, and other forest values8.
- **Finding**: Post-disturbance logging is common practice in forests that removes trees or other biomass to produce timber. By reducing habitat for species that specialize by feeding on insects, post-disturbance logging can actually inadvertently lead to greater insect activity.
- **Background**: Mountain pine beetle outbreaks are primarily the result of a warming climate that has allowed more beetles to survive and to have multiple broods within a breeding season.
- **Background**: Since the mid 1990s, mountain pine beetles have killed pine trees across some 27,413 square miles1, an area larger than the state of West Virginia. Such outbreaks have led to widespread concerns that the dead trees left behind by these outbreaks increase the risk of high-severity fire. Recent field studies in western forests have consistently shown that outbreaks actually do little to increase fire severity[2,3].
- **Background**: In sum, the observed effect of beetle outbreaks on severe fires appears to be negligible. This is true for “red-stage stands” (needles fade to red within a year of tree death) to “gray-stage stands” (needles have fallen off and are no longer present within 2-3 years of tree death) during peak years of wildfire activity based on multiple studies1-7.
- **Background**: Thus, the effect of fires on susceptibility to outbreaks may be contingent on current and future climate influences on beetle populations and tree resistances. Occurrence of large severe bark beetle outbreaks also may deplete tree host populations that then reduce the probability of subsequent outbreaks for 70 years or

more4. For example, under a weather scenario of future dry climate, reduction of host tree populations may lower the probability of subsequent bark beetle outbreaks in some forest types

- **Background**: In general, the major results of roads on the terrestrial environment include increases in forest fragmentation and disruption of the natural movement of species across the landscape. Aquatic systems are impacted through disruption of natural infiltration of water into the soil and increased runoff to streams. While proper road engineering can help mitigate some negative effects, it does not mitigate the overall impact of roads on hydrologic processes, water flow, and fragmentation of wildlife habitat by roads that act as chronic stressors to ecosystems. Roads also increase human-caused fire ignitions due to greater access during fire season.
- **Background**: Bark beetle outbreaks do not destroy the forest as forests are quite resilient to them, rebounding soon after the outbreak with vigorous plant growth. Bark beetle-caused tree mortality also increases the diversity of plant species by creating gaps in the forest canopy that provide increased sunlight and nutrients for plant growth. Dead trees (snags) caused by outbreaks are the most ecologically valuable structures of a forest, used by numerous woodpeckers, owls, hawks, songbirds, bats, squirrels, and martens. The ensuing “complex early seral forest” (snag forest) is one of the most biologically diverse and rarest forest types in western North America because salvage logging nearly always destroys these forests8,9.
- **Background**: Beetle-killed trees also contribute to recruitment of large coarse woody debris into riparian areas and streams, which exerts important beneficial influences on storage of sediment and organic matter and river and floodplain habitat for wildlife, including trout. In comparison to logging that can remove all riparian wood and severely deplete instream wood recruitment, beetle outbreaks provide a source of instream wood for decades.
- **Management**: We recommend that priority be given to limited removal of hazardous trees within the immediate road prism and campgrounds to prevent potential loss of life from falling dead trees overtime. Moreover, in order to reduce existing and future risks of fire, it is prudent to concentrate fuel reduction activities within a defensible space of 100-200 foot zone around homes as this method has been shown to be most effective in reducing a home’s ignitability (Fig. 3)10.
- **Management**: Since beetle outbreaks and fires are both linked to global warming, prudent policies first and foremost would focus rapidly reducing greenhouse gas emissions rather than having a preoccupation with the effect of warming – outbreaks and fires. Logging to contain outbreaks or fire events simply does not work, is an expensive and ineffective use of taxpayer resources, and comes with significant costs to ecosystems that are otherwise quite resilient to natural disturbance events13.

Dobrowski. 2011

- **Study**: Here I examine the climatic basis for microrefugia and assert that the interaction between regional advective influences and local terrain influences will define the distribution and nature of microrefugia. I review the climatic processes that can support their subsistence and from this climatic basis: (1) infer traits of the spatial distribution of microrefugia and how this may change through time; (2) review assertions about their landscape position and what it can tell us about regional climates; and (3) demonstrate an approach to forecasting where microrefugia may occur in the future.
- **Background**: Microrefugia (Definition)— Microrefugia are sites that support locally favorable climates amidst unfavorable regional climates, which allow populations of species to persist outside of their main distributions.
- **Background**: The response of biota to climate change of the past is pertinent to understanding present day biotic response to anthropogenic warming (Noss, 2001; Pearson, 2006; Provan & Bennet, 2008).
- **Background**: Climatic refugia are typically thought of as large regions in which organisms took refuge during glacial advances and retreats during the Pleistocene (2.5 million years ago to 11 500 years ago), which then acted as sources for colonization during more favorable climatic periods (Hewitt, 2000; Davis & Shaw, 2001).
- **Background**: there is compelling evidence that climatic refugia occurred at local scales during the LGM and were also utilized during interglacial warm periods, including the current interglacial (Willis & Van Andel, 2004; Birks & Willis, 2008). These 'microrefugia' or 'cryptic refugia' were sites that supported isolated low-density populations of species beyond their reconstructed range boundaries. It is hypothesized that these refugial habitats occurred in favorable microclimates during periods of unfavorable regional climate and allowed for postglacial colonization via local dispersal (McLachlan et al., 2005; Pearson, 2006; Birks & Willis, 2008; Provan & Bennet, 2008).
- **Background**: During interglacial stages, microrefugia were presumably found in areas with cooler microclimates that allowed for the persistence of cold-adapted species. During the longer glacial stages, microrefugia presumably supported warm microclimates that allowed for the persistence of thermophilous species (Table 1) (Birks & Willis, 2008; Rull, 2009).
- **Background**: Coughlan & Running (1997) demonstrated that after canopy cover, net solar radiation is the most important factor affecting snowpack duration.
- **Background**: For example, the author (Dobrowski et al., 2009) decomposed in situ temperature measurements into components associated with regional free-air temperature and local physiographic effects and found that roughly 20–30% of the temperature variance of a mountainous region over an 11 year period could be attributed to spatial variance in physiographic features. This influence is likely to be even greater at sites with pronounced topoclimatic effects.
- **Background**: Valleys promote the persistence of cold air pools which result in lower minimum temperatures on average than upland locations.

- **Background**: Topographic depressions could also have protected thermophilous taxa from the desiccating influence of wind. This description is more consistent with the physiographic characteristics of valley bottoms and is an important distinction in that it suggests a different limiting climatic factor, namely water availability as opposed to minimum temperature.
- **Finding**: In the current interglacial period, microrefugia are likely to have lower temperatures and support more mesic environments than their surroundings. These represent climatic environments that will become increasingly scarce in the next century due to anthropogenic warming (IPCC, 2007; Williams et al., 2007).
- **Finding**: Additionally, warming over the past century has been asymmetric with minimum temperature increasing nearly twice as rapidly as maximum temperature (IPCC, 2007). Because minimum temperature is rising at a greater rate than maximum temperature under anthropogenic warming, current, and future microrefugia are likely to support minimum temperature regimes of extant climates.
- **Finding**: Here I draw attention to three terrain influences that affect the level of coupling between the boundary layer and the free atmosphere, and drive local variation in air temperature and water balance: (1) cold air drainage, (2) elevation, and (3) slope and aspect effects.
- **Finding**: Terrain positions that consistently promote cold-air pooling and the maintenance of temperature inversions are primary candidates for microrefugia. This is because they represent landscape positions whose climatic environments are consistently decoupled from regional circulation patterns (Lundquist et al., 2008; Daly et al., 2009). Convergent environments (e.g. valley bottoms, local depressions, coves, sinks, basins, etc.) also accumulate water and soil (which helps retain water). Thus, they conceivably could act as microrefugia for mesophilous taxa in arid regions (Table 1).
- **Finding**: Cold air pooling is a widespread phenomenon in areas of complex terrain. In the absence of strong winds, temperatures drop rapidly after sunset resulting in strong nocturnal cooling near the ground surface. Cold dense air drains into convergent environments, resulting in stable cold air pools that can be hundreds of meters thick (Lindkvist et al., 2000; Whiteman et al., 2004). This results in an increase in temperature with increasing elevation (inversion). Inversions are promoted by stable atmospheric conditions. In many cases, sites in topographic depressions (e.g. heavily incised valleys) are sheltered from regional advective influences. The lack of vertical mixing within these cold air pools decouples air within the inversion from the free atmosphere above (Whiteman, 1982; Whiteman et al., 2004; Daly et al., 2009).
- **Finding**: Cold air pooling occurs frequently in basins, valleys, and sinks of mountainous regions. It has been documented to occur as often as 30–60% of the daily observations made in mountainous regions around the globe (Bolstad et al., 1998; Iijima & Shinoda, 2000; Dobrowski et al., 2007; Blandford et al., 2008). Cold air pools are not solely nocturnal phenomena, but also influence diurnal temperature patterns. Researchers have demonstrated that inversions can last from 3 to 6 h past sunrise (Whiteman, 1982; Muller & Whitemen, 1988; Colette et al., 2003).

- **Finding**: Slope and aspect influence near-surface temperature and water availability due to varying exposure to solar radiation and wind (Mccutchan & Fox, 1986; Barry, 1992; Bolstad et al., 1998). Solar radiation has been used as a predictor variable in modeling temperature in complex terrain (Geiger, 1965; Lookingbill & Urban, 2003; Chung & Yun, 2004; Dobrowski et al., 2009; Fridley, 2009).
    - However, many of these authors note that the effect of direct beam solar radiation is most pronounced on daily maximum temperatures and has little influence on minimum temperature.
    - Further, this effect is strongly modified by cloud cover which diminishes radiation differences between exposures, as well as by high soil moisture or canopy cover which can shift the conversion of shortwave radiation to latent as opposed to sensible heat flux.
- **Finding**: In the Great Smoky Mountains of the Eastern US, Fridley (2009) showed that topoclimatic effects resulted in 2–4 degree C of in situ temperature variance, depending on the temperature variable (minimum or maximum), and time of year.
- **Finding**: In the Sierra Nevada, USA the author demonstrated that physiographic effects on climate can result in average temperature differences up to 5 C during the winter months, minimum temperature differentials of 5–8 C, and over a 20% difference in reference evapotranspiration between proximal sites at the same elevation (Dobrowski et al., 2009).
- **Finding**: In a particularly relevant example, Daly et al., (2009) demonstrates that topoclimatic modeling of coldair pooling coupled with projected climate warming, can result in widely divergent temperature changes of up to 6 C for proximal locations (o2 km) in mountainous terrain. These topoclimatic effects exceeded values of the imposed regional temperature change.
- **Finding**: sites with weak coupling to the free atmosphere (e.g. valley bottom sites), have the largest variance in trend magnitude, exhibiting both warming and cooling trends [fig. 4c and d; (Pepin & Lundquist, 2008)]. Consequently, these sites have a greater potential to support temperature trends that deviate from regional averages and are more likely to be able to support relict climates through time.
- **Finding**: The physiographic settings and climatic processes that can potentially support microrefugia are widespread in areas of complex terrain. Consequently, the utilization of microrefugia is likely to be an adaptive strategy that is widespread.
- **Finding**: As time passes and regional climate becomes less suitable for a given species, the number of microrefugia that can support a locally favorable climate for that species will decrease with those remaining becoming increasingly isolated.
- **Finding**: The first assumption to look at is that terrain position can result in sites with consistent climate deviations from regional averages. This contention has received much attention in this review and is well supported by research in climate science, meteorology, and landscape ecology.
- **Finding**: we can posit that climate change impacts will be most prevalent and readily observed at sites that are strongly coupled to the free atmosphere (e.g. Alpine sites, nival summits, etc.).

- **Finding**: In contrast to glacial stages, convergent environments may act as thermal refugia for cold-tolerant or mesophilous species during interglacial warm periods (Table 1). A potential mechanism for this is that the lower minimum temperatures in these locations may actually exclude more competitively dominant thermophilous taxa, thus reducing competitive pressure on cold-adapted species (e.g. Alpines; Birks & Willis, 2008).
    - **Finding**: An extreme example of this is known as a 'vegetation inversion' (Geiger, 1965; Whiteman et al., 2004) and occurs where high elevation species find habitat in low elevation depressions or sinks.
- **Finding**: Further, temperature effects due to slope must be balanced against water loss at these sites.
- **Finding**: north-facing slopes can support microrefugia for mesophilous taxa in that they have lower evaporative demand than south-facing slopes.
- **Finding**: However, slope and aspect are topographic proxies of moisture, light, and temperature. Species may respond to each of these in an idiosyncratic fashion which may undermine the utility of slope and aspect in identifying microrefugia (Warren, 2010).
- **Finding**: This review has noted that the proximal climatic mechanisms that shape microrefugia are likely to occur at local scales. As such, our ability to identify microrefugia will be strongly dependent on the use of appropriately scaled and physiographically informed climate data.
- **Finding**: Approaches that couple physiographically informed climate data with SDM are likely to provide the foundation for efforts aimed at identifying and mapping microrefugia under historic and future climates.
- **Finding**: Microrefugia are likely to be found in terrain positions that promote the consistent decoupling of the boundary layer from the free-atmosphere. These terrain positions are likely to have climate states and trends that are decoupled from regional averages, a requisite for microrefugia to persist through time. Convergent environments (local depressions, valley bottoms, sinks, and basins) are primary candidates for microrefugia based on these criteria.

Dugger et al. 2016.

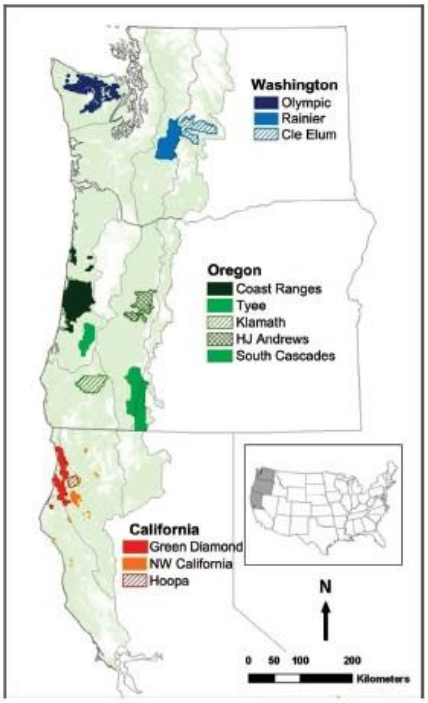


FIGURE 1. Locations of 11 study areas used in the analysis of vital rates and population trends of Northern Spotted Owls, 1985–2013.

- **Study**: We used mark–recapture, reproductive output, and territory occupancy data collected during 1985–2013 to evaluate population processes of Northern Spotted Owls (Strix occidentalis caurina) in 11 study areas in Washington, Oregon, and northern California, USA. We estimated apparent survival, fecundity, recruitment, rate of population change, and local extinction and colonization rates, and investigated relationships between these parameters and the amount of suitable habitat, local and regional variation in meteorological conditions, and competition with Barred Owls (Strix varia).
- **Background**: The harvesting of old-growth forest habitat suitable for Spotted Owls and other dependent species (e.g., Marbled Murrelet [Brachyramphus marmoratus], red tree vole [Arborimus longicaudus]) on federal lands has declined since the adoption of the NWFP. However, low rates of loss continue on all lands within the NWFP area (~3% since 1993), although on federal lands this loss has been primarily attributed to large wildfires (Davis et al. 2011, 2015).
- **Ecological Consideration**: The Barred Owl is a medium-sized, congeneric owl species that was historically restricted to the forests of eastern North America, but has now invaded the entire range of the Northern Spotted Owl (Bent 1938, Livezy 2009). The cause of this range expansion is unclear, but there is mounting evidence that the species is having a negative effect on the Spotted Owl (e.g., Dugger et al. 2011, Forsman et al. 2011, Yackulic et al. 2014), most likely through competition for resources. Recent studies have confirmed high overlap in resource use between the 2 species (Hamer et al. 2001, 2007, Livezy 2007, Singleton et al. 2010,Wiens et al. 2014)
- **Climate Change Impacts**: Climate change is expected to increase the risk of large, high-intensity wildfire in the Pacific Northwest and throughout the western U.S. in general (Westerling et al. 2006, Davis et al. 2011, Stavros et al. 2014).
- **Climate Change Impacts**: In addition, climate change may cause changes in forest tree species composition (Peterson et al. 2014) and even potentially the growth rates of tree species in the Pacific Northwest (Littell et al. 2010, Albright and Peterson 2013).
- **Finding**: Estimated mean annual rates of population change (lambda) suggested that Spotted Owl populations declined from 1.2% to 8.4% per year depending on the study area.
    - Klamath study area: -2.8% annual population change
    - Southern Cascades study area: -3.7% annual population change
    - NW California study area: -3.0% annual population change

    - Hoopa study area: -2.3% annual population change
- **Finding**: an estimated range-wide decline of 3.8% per year from 1985 to 2013.
- **Finding**: Barred Owl presence was associated with increased local extinction rates of Spotted Owl pairs for all 11 study areas
    - Our results indicate that competition with Barred Owls may be the primary cause of Northern Spotted Owl population declines across their range.
- **Finding**: recruitment rates were highest when both total precipitation (29 cm) and minimum winter temperature (9.58C) were lowest, with the lowest levels of recruitment occurring when conditions during the previous winter were cold and wet, and the highest levels of recruitment occurring when the previous winter was cold and dry.
    - There was no support for a lag effect of these covariates, so the relationships likely reflected direct effects on survival of non-territorial birds (potential recruits), particularly first-year birds, in the previous winter. The survival rate of nonterritorial or nonbreeding birds is usually difficult to measure, and, when estimated, is usually lower than the survival of territorial birds (Lenda et al. 2012).
- **Finding**: a greater amount of suitable owl habitat was generally associated with decreased extinction rates of northern spotted owl.
    - We observed strong positive associations between habitat characteristics, especially increased amounts of nesting and roosting habitat
    - Results were counterintuitive for the Green Diamond-R study area in northern California, where we observed higher estimates of habitat disturbance (HD) and edge habitat associated with higher colonization rates, and more core habitat associated with increased extinction rates. Northern Spotted Owls occupied younger-aged stands in the GDR study area compared with most other study areas, and it is possible that they responded differently to habitat disturbance and the amount of edge and core habitat in these study areas because of their local dependence on dusky-footed woodrats (Neotoma fuscipes) as prey (Sakai and Noon 1993, Hamm and Diller 2009).
- **Finding**: Mean fecundity of spotted owl females was highest for adults (0.309 +/- 0.027 SE), intermediate for 2-yr-olds (0.179 +/- 0.040 SE), and lowest for 1-yr-olds (0.065 +/- 0.022 SE).
- **Finding**: We found strong support for a negative effect of Barred Owl presence on apparent survival of Spotted Owls in 10 of 11 study areas, but found few strong effects of habitat on survival at the study area scale.
- **Finding**: meta-analysis results suggested that Spotted Owl survival was higher across all study areas when the Pacific Decadal Oscillation (PDO) was in a warming phase and the Southern Oscillation Index (SOI) was negative, with a strongly negative SOI indicative of El Ni ˜no events.
    - We observed higher survival rates when winters were warm (positive association with PDO) and dry (negative association with SOI), rather than higher survival when conditions were warm (positive association with PDO) and wet (positive

association with SOI) as observed in a meta-analysis of 6 Northern Spotted Owl study areas by Glenn et al. (2011a).

- **Finding**: In the study areas where habitat was an important source of variation for Spotted Owl demographics, vital rates were generally positively associated with a greater amount of suitable owl habitat.
- **Finding**: However, Barred Owl densities may now be high enough across the range of the Northern Spotted Owl that, despite the continued management and conservation of suitable owl habitat on federal lands, the long-term prognosis for the persistence of Northern Spotted Owls may be in question without additional management intervention.
- **Management**: Based on our study, the removal of Barred Owls from the Green Diamond Resources (GDR) study area had rapid, positive effects on Northern Spotted Owl survival and the rate of population change, supporting the hypothesis that, along with habitat conservation and management, Barred Owl removal may be able to slow or reverse Northern Spotted Owl population declines on at least a localized scale.

Dunk et al. 2006.

Everything you want to know about land mollusc and salamander distributions in the northern California portion of the K-S Region.

- **Study**: we used field data from a random sampling design to map the distribution of local and regional richness of terrestrial molluscs and salamanders within northern California's portion of the Klamath-Siskiyou region
- **Study**: We also evaluated the protection afforded by reserves to hotspots of species richness and species representation of these taxa.
- **Study**: Roberge & Angelstam (2004) noted that the greatest challenge to evaluating the umbrella species concept was data from actual, not hypothetical, reserves designed around umbrella species. Herein, we provide such an evaluation for a conservation plan designed largely around the northern spotted owl (Strix occidentalis caurina ; Merriam, 1898).
- **Study**: We evaluated the distribution of terrestrial mollusc and salamander species richness and the protection afforded by two reserve types and non-reserved lands to hotspots of species richness and to species representation. We also evaluated the concordance of richness patterns of terrestrial molluscs and salamanders.
- **Study**: We had three goals.
    - Our first goal was to identify hotspots of local and regional richness for each taxon (molluscs and salamanders). Local richness is ultimately limited by the regional richness surrounding a local site. However, due to the varying histories of impacts (e.g. timber harvest, fire) across our study area, we could conceive of several factors that could 'uncouple' a strong correlation between local and regional richness, such that hotspots of local richness could be found outside of hotspots of regional richness.
    - Our second goal was to evaluate the concordance of local and regional distributional patterns between these disparate taxa to determine whether either taxon would be a good surrogate for the diversity of the other (e.g. Moritz et al ., 2001).
        - Although not closely related taxonomically, terrestrial molluscs and terrestrial salamanders share two key features: (1) both have low vagility and (2) both appear to need microclimates that provide abundant moisture during, at least, a part of the year, and thus one might expect them to show similar geographical patterns of diversity.
    - Our third goal was to compare how the pre- and Northwest Forest Plan reserves protect hotspots of species richness, and represent species composition, within

these taxa, even though these were not explicitly considered when either reserve type was established.

    - Conservation of hotspots alone may neglect other important and valued attributes of an area's biota (Kareiva & Marvier, 2003), including protection of rare (Lennon et al ., 2004) or endemic (Orme et al ., 2005; Stohlgren et al ., 2005) species; as well as species representation and persistence (Margules & Pressey, 2000).
    - Hence, we also evaluated the degree to which regional hotspots for each taxon sheltered the rarest species within each taxon.
    - Our analyses can be considered an evaluation of the protections the spotted owl provides as an umbrella for hotspots of mollusc and salamander richness and species representation within each taxon.

- **Background**: No existing reserves in the KS region were created specifically for molluscs and salamanders, yet it was assumed that reserves established largely around considerations for the northern spotted owl (Strix occidentalis caurina) would afford adequate protection for many lesser-known species.
- **Background**: Species of terrestrial molluscs and salamanders share two general features: (1) they have extremely low vagility, and (2) they are often associated with moist, cool microclimates.
- **Background**: In the Pacific Northwest of the USA, the Northwest Forest Plan (hereafter NFP; USDA/USDI, 1994) was developed as a large-scale (c . 10 million ha) ecosystem management plan; striving to provide a predictable and sustainable timber supply and to adequately protect species.
- **Background**: More recently, through the Northwest Forest Plan, the US government created a network of 'late successional reserves' and 'riparian reserves' (USDA/USDI, 1994). The late successional reserve network was designed, largely, based on quantitative information and conservation considerations of the northern spotted owl as well as, generally, qualitative, expert-based considerations of > 1000 other species; including some terrestrial molluscs and salamanders.
- **Background**: Land management activities within NFP reserves must generally be consistent with the goal of facilitating late-successional forest conditions more rapidly than would otherwise occur.
- **Background**: The Klamath-Siskiyou region is considered extremely ecologically diverse (DellaSala et al., 1999; Ricketts et al., 1999), primarily because of its geological and climatic history. For example, regarding the Klamath-Siskiyou region's flora, Coleman & Kruckeberg (1999) stated 'following the increased aridity of the Miocene, the KS [Klamath-Siskiyou] region, with its benign climate, became the refuge for elements of a shrinking warmtemperate flora in the Far West. Second, the spatial isolation, coupled with a long-persisting high level of habitat diversity, created a multiplicity of settings for both the genesis of new species and the persistence of relictual species.'
- **Ecological Considerations**: Due to the limited dispersal ability of land molluscs and salamanders, areas containing the highest local species richness are of conservation importance.

- **Finding**: Existing reserves disproportionately included areas of hotspots of species richness for both taxa, when hotspots included the richest c . 25% of the area, whereas non-reserved lands contained greater than expected areas with lower species richness.
    - However, when a more strict definition of hotspot was used (i.e. the richest c .10% of areas), local hotspots for both taxa were not disproportionately found in reserves.
- **Finding**: Reserves set aside largely for human aesthetics and recreation and those set aside for biodiversity both contributed to the protection of areas with high (greatest 25%) species richness.
- **Finding**: Existing biodiversity reserves represented 68% of mollusc species and 73% of salamander species, corresponding to the 99th and 93rd percentiles, respectively, of species representation achieved by simulating a random distribution of the same total area of reservation.
    - Cumulatively, however, reserves set aside for inspiration and biodiversity represented 83% of mollusc species and 91% of salamander species.
    - The existing reserves provide conservation value for terrestrial molluscs and salamanders.
    - This reserve network, however, should not be considered optimal for either taxa.
- **Finding**: A total of 47 mollusc species and 11 salamander species were detected. Mean local richness for molluscs per survey plot was 1.15 (SD = 1.19) and ranged from 0 to 6 (Fig. 1). Mean local richness for salamanders was 0.48 (SD = 0.74) and ranged from 0 to 3 species (Fig. 1).
- **Finding**: The local richness hotspots 90 and hotspots 75 for molluscs were those 14 plots (4.5% of all plots), where ≥ 4 species were detected, and 103 plots (33.6% of all plots), where ≥ 2 species were detected, respectively (Fig. 2a).
- **Finding**: The local richness hotspots 90 and hotspots 75 for salamanders were those 22 plots (9.4% of all plots) where ≥ 2 species were detected and those 85 plots (36.3% of all plots) where ≥ 1 species was detected, respectively (Fig. 2b).
- **Finding**: Mollusc hotspots had more reserved land than expected and less non-reserved land. Salamander hotspots had much more reserved land than expected and much less non-reserved.
- **Finding**: Local richness of salamanders and molluscs was significantly, though extremely weakly, correlated (F = 7.135, P = 0.008, r 2 = 0.029).
- **Finding**: The 100 simulations of reserve locations resulted in 17–35 mollusc species and two to nine salamander species being represented within the reserves. The actual NFP reserves contained 32 mollusc species and eight salamander species; with only one and seven simulated reserves ranking higher than the actual reserve system's representation of mollusc species and salamander species, respectively.
    - Although both taxa had species represented much greater than would be expected by chance, only 68% and 73% of all mollusc and salamander species were detected in reserves, respectively. However, when including pre-NFP reserves, reserved lands contained 39 mollusc species (83% of all mollusc species) and 10 salamander species (91% of all salamander species).

- **Finding**: For terrestrial molluscs and salamanders, the most species-rich areas were discovered in the western/northwestern portion of our study area (Figs 2 and 3), an area that overlaps the area Stebbins & Major (1965; see their Fig. 2) identified as having a high frequency of relictual plant species.
- **Finding**: Our finding that the regional mollusc hotspots75 encompassed 61% of the regional salamander hotspots75, but only 45% overlap vice versa provides equivocal support to our contention that both taxa may have responded similarly to historical, and perhaps contemporary, factors.
- **Finding**: Our analyses, however, showed that the reserves they delineated, together with pre-existing reserves, disproportionately protected hotspots of local and regional richness for both taxa. Hotspots of both taxa at the local and regional scale, and hotspots of both taxa at the regional scale were represented by reserves more than non-reserved lands. Although regional richness hotspots of both taxa were disproportionately associated with reserved lands, those locations where local richness was greatest (local hotspots) were not disproportionately associated with reserved lands.
    - Therefore, our sample suggests that the current reserve network does not provide disproportionate protection to those local areas richest in species of terrestrial molluscs and salamanders
- **Finding**: Both mollusc and salamander species representation was much greater in Northwest Forest Plan reserves than would be expected by chance.
- **Finding**: Rare molluscs were disproportionately (nearly twice the number expected) found in regional hotspots and local hotspots. Even so, 12 of the 26 rare mollusc species were not found within the mollusc regional hotspots. Similarly, only two of the four rare salamanders were found in regional salamander hotspots75, and none in the regional salamander hotspots90.
    - Thus, a large proportion of the rare species within each taxon would go unprotected with conservation plans developed only around such hotspots (see Lennon et al., 2004).
- **Finding**: If the Northwest Forest Plan reserves represent a large-scale plan largely for the northern spotted owl, as well as other organisms having smaller spatial requirements than the owl, our findings suggest that owl conservation provides some umbrella protection for areas with high species richness of Richness, representation, and reserves terrestrial molluscs and salamanders in national forests in northern California. In terms of species representation, NFP reserves (and thus the northern spotted owl as a focal species for conservation) do fairly well; but taken together with pre-NFP reserves represent a large percentage (> 80%) of terrestrial mollusc and salamander species.

Fontaine et al. 2009.

- **Study**: We studied bird communities using point counting in the Klamath-Siskiyou ecoregion of Oregon, USA at various points in time after one or two high-severity fires. Time points included 2 and 3 years after a single fire, 17 and 18 years after a single fire, 2 and 3 years after a repeat fire (15 year interval between fires), and >100 years since stand-replacement fire (mature/oldgrowth forest).
- **Study**: We conducted our study in the Klamath-Siskiyou region in northwestern North America that is characterized by a wet Mediterranean climate and a mixed severity fire regime in which fires burn every 5–75 years (Agee, 1993; Taylor and Skinner, 1998).
- **Study**: Our objectives were to compare bird communities at different times since stand-replacement fire and use the unique opportunity afforded by the 200,000 ha Biscuit Fire – which reburned a preexisting 15-year old fire – to assess the effect of short-interval repeated high-severity fire on bird communities.
- **Study**: We used community-level (species richness, total density, ordination) and species-level (indicator species) metrics to identify bird communities and species associated with fire-based disturbance as well as the predominant environmental gradients associated with those communities.
- **Study**: In July 2002, at least two separate lightning strikes ignited fires in southwestern Oregon which became the 200,000 ha Biscuit Fire. The Biscuit Fire completely reburned the 38,000 ha 1987 Silver Fire while the nearby 8000 ha 1987 Galice Fire remained outside the Biscuit Fire perimeter (Fig. 1). All three fires burned for extended periods (weeks to months), generating a complex mosaic pattern of fire severities.
- **Study**: Forest types in the study area are typical of the upper mixed-evergreen zone, trending into the white fir zone (Franklin and Dyrness, 1973), dominated by conifer species such as Douglas-fir (Pseudotsuga menziesii), sugar pine (Pinus lambertiana), and white fir (Abies concolor). Typical evergreen hardwoods include Pacific madrone (Arbutus menziesii), tanoak (Lithocarpus densiflorus), and canyon live-oak (Quercus chrysolepis) and shrubs such as manzanita (Arctostaphylos sp.) and ceanothus (Ceanothus sp.). Elevations spanned 400–1400 m on a full range of aspects, primarily on slopes >20%.
- **Study**: Avian point counts were conducted during days with no precipitation and light to no wind from mid-May to early July.
- **Study**: The results presented in this paper are from patches that experienced stand-replacement fire and postfire salvage logging 1–3 years after the initial fire event. High-severity fire in this study constituted >95% overstory mortality while postfire salvage logging represented partial removal of fire-killed trees. Salvage logging intensities were somewhat higher in the two 1987 fires than the 2002 Biscuit Fire due to changes in management practices.
    - In 1987 fires, snag retention ranged from 7 to 18 snags ha————————————1 while Biscuit Fire snag retention levels were 3–29 large (>41 cm) snags per hectare, and variable retention of smaller (<41 cm) snags depending on merchantability (USDA, 2004, see Section 3).

- **Study**: Despite the confounding of fire and post-fire salvage in our study, we believe that the amplitude of short-term ecological change resulting from high-severity fire is much greater than that of post-fire salvage logging and that the results presented are correctly attributed to gross changes in seral stage due to fire.
- **Finding**: Avian species richness did not differ significantly among habitats. Bird density was highest 17 and 18 years after fire, lowest 2 years after fire, and intermediate in repeat burns and unburned forest. Bird community composition varied significantly with habitat type ($A = 0.24$, $P < 0.0001$) with two distinct gradients in species composition relating to tree structure (live to dead) and shrub stature. Using indicator species analysis, repeat burns were characterized by shrub-nesting and ground-foraging bird species while unburned mature forests were characterized by conifer-nesting and foliage-gleaning species.
- **Finding**: Contrary to expectations, repeated high-severity fire did not reduce species richness, and bird densities were greater in repeat burns than in once-burned habitats. Broad-leaved hardwoods and shrubs appear to play a major role in structuring avian communities in the Klamath-Siskiyou region.
- **Finding**: Vegetation: The short-term effect of high-severity fire was to transition mature forest from high basal area of live conifers to a high basal area in sound snags (Fig. 2a). The older burn was characterized by low amounts of tree basal area, most of which was composed of regenerating conifers and hardwoods (Fig. 2a). The repeat burn also had low tree basal area but was composed largely of snags (Fig. 2a). Post fire shrub growth (canopy volume accumulation) was significantly greater in repeat burn stands at 7200m3 ha————————————1 by 3 years post fire, than in recent once burned stands (3027m3 ha————————————1) (Fig. 2b). Additional effects of the Biscuit Fire included a reduction in litter cover and an increase in bare ground (Table B1); repeat burn stands had higher forb cover than any other treatment type (Table B1). Dominant hardwoods and shrubs such as tanoak, madrone, snowbrush, and chinquapin (see Table B1 for scientific names) were present in all treatments while repeat burn stands had reduced amounts of Sadler oak and old burn stands had the highest cover of madrone (Table B1).
- **Finding**: Estimates of avian species richness per point count had overlapping confidence intervals for all treatments and years, showing no statistical difference (Fig. 3a).
- **Finding**: In contrast to species richness, avian density was significantly different among treatments based on lack of confidence interval overlap (Fig. 3b); recent burn stands had the lowest densities of birds in both years while mature forest and old burn stands had higher bird density. Avian density in repeat burn stands was intermediate between recent burn and old burn, and showed a significant increase in density from 2004 to 2005 (2 and 3 years after fire), paralleling the increase in shrub volume over the same period (Fig. 2b).
- **Finding**: Mature forest and repeat burn treatments had the largest numbers of species with indicator values >40, reflecting their more unique species composition. Single burn treatments (recent and old) had smaller numbers of indicator species (Table 2). Several rare species with significant associations but low indicator values were identified (e.g.

green-tailed towhee, golden-crowned kinglet, winter wren; see Appendix C for scientific names and relative frequency of each species within treatments) while species with high indicator values reflected both abundance and restricted occurrence in one treatment (e.g. lazuli bunting, hermit warbler, hairy woodpecker, Table 2).

- **Finding**: In both years, the basal area of snags was a poor predictor of avian density with correlation coefficients of —0.26 and —0.25 in 2004 and 2005, respectively, and slope estimates not different from zero (2005 values: slope = —0.01, SE = 0.01, t = —1.3, P = 0.22). In contrast, shrub height was positively correlated with avian density with correlation coefficients of 0.67 and 0.75 in 2004 and 2005, respectively, and positive slope estimates significantly different from zero (2005 values: slope = 2.76, SE = 0.50, t = 5.5, P < 0.0001).
- **Finding**: Bird community composition shortly after high-severity fire in our study was similar to those reported from other forest types (Bock and Lynch, 1970; Morissette et al., 2002; Smucker et al., 2005; Kotliar et al., 2007). Species associated with dead wood (hairy woodpecker), bare ground (dark-eyed junco) and aerial foraging (Townsend's solitaire) were prevalent whereas fire obligate species typical of stand-replacement fire regime forests such as black-backed (Picoides arcticus) and American three-toed woodpeckers (P. dorsalis) did not occur in our study area (Hutto, 1995; Koivula and Schmiegelow, 2007). The observation of decreased avian densities is consistent with the decrease in vegetation complexity following high-severity fire.
- **Finding**: Longer-term (17 and 18 years) response of birds was consistent with Raphael et al. (1987) who characterized bird communities following high-severity fire in the Sierra Nevada of California. Important structural elements in older post-fire stands are dense broad-leaved shrubs and scattered snags in advanced stages of decay. Shrub-associated species such as wrentit and weak excavators such as acorn woodpecker were prevalent in old burn stands we studied.
    - Old burn stands also possessed the highest estimate of species richness and bird densities similar to unburned forest despite possessing much simpler vegetation complexity. This likely results from the intermediate nature of these stands possessing some bird species characteristic of both recent burns (dark-eyed junco, hairy woodpecker) and mature forest (Swainson's thrush, hermit warbler).
- **Finding**: Similar to the review of boreal bird and fire studies by Schieck and Song (2006), our ordination results placed old fire patches between mature forest and recent burns. This suggests that, as expected, avian community succession is following a trajectory of recovery from recent burn to old burn to mature forest. In particular, our results suggest that bird densities are strongly related to the rate of vegetation recovery following fire.
- **Finding**: The effect of a repeat burn on bird communities was not to simply 'reset' the successional clock; rather, it resulted in a species assemblage (defined in terms of composition and abundance) unique from both recent and old burns. This result likely stemmed from legacy effects of the initial fire disturbance, which created an early seral plant community characterized by snags and regenerating shrubs and hardwoods. Propagule banks for both seeding and sprouting early seral vegetation were likely larger

prior to the second fire, leading in part to the rapid recovery of shrubs and hardwoods following the repeat burn (Donato et al., 2009).

- **Finding**: Ordination results were consistent with the expectation that, over time, twice burned and once-burned avian communities may converge. Convergence of bird community composition could occur after once-burned stands possess a more developed shrub component, small snags fall resulting in more open stands, and large snags advance in decay stage, losing their bark and fine branches.
- **Finding**: In our study, shrub stature was an important predictor of both avian abundance and composition while snag abundance was associated with compositional differences but not abundance.
- **Finding**: See table 2 for indicator species value of different bird species for each habitat type: mature forest, recent burn, old burn, and repeat burn (i.e., see which bird species associate with each of these habitats).
- **Background**: Over time, the frequency and intensity of repeated fires may act to retain or exclude particular species and regulate forest structure and seral stage (Agee, 1993; Pyne et al., 1996).
- **Background**: Recent increases in the frequency and extent of large wildfires in western North America (Westerling et al., 2006) raises the probability of recurrent (short-interval) high-severity fires via greater probability of fire overlap.
- **Background**: Many species of birds are adapted to, or dependent upon, disturbances such as fire or insect outbreaks in all or portions of their distribution (MacArthur, 1958; Brennan et al., 1998; Saab and Powell, 2005).
- **Background**: Fire heavily influences vertical and horizontal heterogeneity of vegetation; characteristics well known to structure avian communities in terms of abundance and species richness (MacArthur and MacArthur, 1961; Holmes et al., 1979).
- **Background**: Research has largely been focused on short-term (<5 years) responses of birds to single high-severity fire events in boreal (Morissette et al., 2002) and mixed conifer forests (Smucker et al., 2005) and single prescribed fires in pine-dominated forests (Bock and Block, 2005; Engstrom et al., 2005; Hurteau et al., 2008). Studies of repeated fire and fire interval on birds are limited to repeated prescribed surface fire in longleaf pine forests (Provencher et al., 2002; Whiting et al., 2007) and grasslands (Reinking, 2005).
    - Thus avian response to short-interval high-severity fires in forested ecosystems remains poorly studied. This is key information for forest managers tasked with conserving disturbance-dependent bird species as well as landscape-scale avian biodiversity.
- **Background**: The mixed severity fire regime—found in the Klamath-Siskiyou region—is among the most complex and least understood of ecological disturbance regimes; the combination of surface and stand-replacement fire over varying spatial and temporal scales results in a complex mosaic of plant communities and successional stages on the landscape (Agee, 1993). In stand-replacement patches, rapid vegetation recovery and resulting fuel continuity create the potential for recurrent high-severity fires over short (decadal, <50 years) time scales (Thompson et al., 2007).

- **Background**: A related study (Donato et al., 2009) found that nearly all plant species found in mature/old-growth stands were present at similar relative abundance in both long-interval and short-interval burns, indicating high community persistence through multiple high-severity fires. The short interval burn had the highest species richness and total plant cover with additions of disturbance-associated forbs and low shrubs, likely due to a propagule bank of early seral species that developed between fires.
- **Background**: In a separate study of avian response to salvage logging of the Biscuit Fire, Fontaine (2007) found non-significant responses of most species to salvage logging and, most importantly, very little change in overall community composition (see also Section 2). The few published studies examining the effects of postfire salvage logging from the western United States, where logging prescriptions are similar, have shown some negative responses of cavity-nesting species (e.g. Saab et al., 2007) but no extirpations of the species detected in this study or broad changes in community composition (Hutto and Gallo, 2006; Cahall and Hayes, 2009).
- **Background**: Schieck and Song (2006) reviewed bird community succession in boreal forests, noting that logged and burned communities within the same forest type converged once snags fell and communities became dominated by shrub-associated birds after ~25 years.
- **Management**: In our study of high-severity wildfire, many species were significantly associated with mature forests but a greater number were associated with early seral post-fire habitats. The high number of indicator species, and similar species richness suggest that early seral conditions created by wildfire are integral to maintaining
- **Management**: In our study, the repeat burn (15 year interval) possessed a unique bird community characterized by both shrub-associated and openhabitat associated bird species with species richness and density comparable to unburned forest. Given the historic regime of frequent mixed severity fire, this habitat type has likely occurred on the landscape in the past. Recognition of the importance of a variety of early seral habitats as well as late-seral forests will likely bolster the maintenance of regional avian biodiversity.
- **Management**: Taken together – the lack of a negative impact of repeated highseverity fire on bird species richness, the unique composition of early seral bird communities, and the association of broad-leaved vegetation with bird abundance and traits – our study suggests that land managers faced with competing goals and limited resources could consider allowing naturally generated early seral conditions to persist for a period in some places, rather than focusing on rapid establishment of conifers and/or closed forest. Extended periods of early successional conditions in the Klamath- Siskiyou ecoregion likely would benefit a broad suite of species and complement regional biodiversity within a landscape mosaic.

Frey et al. 2016.

- Study: Here, we examine whether the structural characteristics present in old-growth forests (for example, heterogeneous canopies, high biomass, and complex vertical structure) increase site-scale thermal buffering capacity over more structurally simple, yet mature plantation forest stands.
- Study Site: H J Andrews Experimental Forest, in southern Cascades east of Eugene
- Finding: Complex forests do good job of regulating temperatures on the ground… the more structurally complex the forest (more big trees, more vertical layers), the cooler it was, as much as 4.5 degrees F on warm days.
  - Old growth forests also held in heat during cold weather--these forests have a moderating effect on temp extremes.
- Finding: Old-growth vegetation appeared to have insulating effect on temperature; max springtime monthly temps decreased by 2.5 degrees C across the old growth gradient (from structurally simple plantations to complex old-growth forests). Overall, these influences of old-growth forests on thermal conditions were consistent between years.
  - These cooling effects across a gradient in forest structure are of similar magnitude to 50-year forecasts of the Intergovernmental Panel on Climate Change and therefore have the potential to mitigate climate warming at local scales.
- Finding: Maximum monthly temperatures (C) decreased by 2.5°C (95% confidence interval, 1.7° to 3.2°C) and observed minimum temperatures (D) increased by 0.7°C (0.3° to 1.1°C) across the observed structure gradient from plantation to old-growth forest.
- Finding: Sites with old-growth forest traits (for example, taller canopies, higher biomass, and more complex vertical structure) had reduced temperatures and greater temperature stability (fig. S2).
- Finding: To our knowledge, this is the first evidence that subtler structural differences within mature forest types (that is, mature plantations versus old-growth forests) mediate under-canopy temperature regimes.
- Ecological Considerations: Observed inter-annual consistency in site-level conditions in Old Growth Forests, which occurred despite substantial differences in annual climatic conditions, lends support to the notion that thermally buffered sites may provide temporally consistent refugia for biodiversity (7).
- Ecological Considerations: However, although elevation predicted most temperature metrics well, it was less effective in predicting temperature variability and degree-day accumulation from January to March—both of which are microclimatic factors that are likely to influence species behavior and demography (29).
- Management: Management strategies to conserve old-growth characteristics and to curb current rates of primary forest loss could maintain microrefugia, enhancing biodiversity persistence in mountainous systems under climate warming.
- Management: Our findings indicate that management practices that result in single-species, even-aged plantations are likely to reduce the thermal buffering capacity of

forest sites, potentially limiting the availability of favorable microclimates for some species.

- Management: In jurisdictions where biodiversity maintenance is the goal, conservation and restoration of structures associated with old-growth forests are more likely to sustain favorable microclimates (35) and to reduce climate change impacts on temperature-sensitive species.
- Management: Recent work shows that the understory microclimate differences documented here could be highly relevant to biodiversity conservation in temperate forests; cooler forest types have attenuated the widespread loss of cool-adapted understory plant species (13) and have promoted tree recruitment (36). Amphibians, lizards, insects, and even large mammals are shown to take advantage of microclimate conditions when regional climate moves beyond the range of thermal preferences (5, 37, 38).
    - **Caveat**: Our findings apply to species inhabiting forest understory, and cannot speak to canopy-occurring species.
- Management: because older seral stages provide the highest levels of buffering, management options may be limited for species inhabiting early successional forests (42), unless they are able to take advantage of the microclimatic buffering of older forests or cooler microclimates that are near old-forest edges (34).
    - Currently, early seral species are of high conservation concern in the Pacific Northwest, largely as a result of habitat loss (42); given that early seral forests may not have equivalent thermal refuges, we predict synergistic negative effects on these species when combined with climate.
- Management: By conserving or creating forest conditions that buffer organisms from the impacts of regional warming and/or slow the rate at which organisms must adapt to a changing climate, it may be possible to ameliorate some of the severe negative effects of regional warming.
- **Background**: In forested montane regions, microclimate is thought to be influenced by elevation, microtopography, and vegetation.
- **Background**: in heterogeneous mountain landscapes with complex thermal regimes, climate-sensitive species have the potential to disperse to, and persist in, favorable microclimatic conditions
- **Background**: the impacts of climate change on biodiversity are expected to be particularly substantial in mountainous regions
    - **Source**: Mountain Research Initiative EDW Working Group, Elevation-dependent warming in mountain regions of the world. Nat. Clim. Change 5, 424–430 (2015).
- **Background**: Given that old-growth forests continue to decline globally (23) and that plantations continue to proliferate (24), understanding microclimatic impacts is of great conservation importance.

Grant et al. 2016.

https://www.sciencedaily.com/releases/2016/05/160523125907.htm

- **Background**: Amphibian declines are a global phenomenon and declines in the USA have continued unabated since at least the late 1960s, occurring even in protected areas and national parks.
- **Study**: "We combined nearly half a million actual observations of 84 species across 61 study areas to answer questions about the causes of wide-scale amphibian declines."
- **Finding**: the average decline in overall amphibian populations is 3.79% per year, although the rate of decline is more severe in some regions, such as West Coast and Rocky Mountains.
    - If this rate remains unchanged, these species would disappear from half of the habitats they occupy in about 20 years.
- **Climate Change Impacts**: Evidence shows that climate changes are the cause of amphibian declines across the southern USA and the West Coast
- **Management**: "Implementing conservation plans at a local level will be key in stopping amphibian population losses, since global efforts to reduce or lessen threats have been elusive," said Evan Grant, a USGS research wildlife biologist who led the study published in Scientific Reports today.
    - "This research changes the way we need to think about amphibian conservation by showing that local action needs to be part of the global response to amphibian declines, despite remaining questions in what is causing local extinctions."

Gunderson. 2000.

- **Study:** This review is divided into three parts.
    - The first section reviews concepts and multiple meanings of resilience as they have appeared in the literature. That section reviews examples of modeling and field experiments that enrich our understanding of ecological change.
    - The second section includes an assessment of how resilience is related to other key ecosystem properties.
    - The review concludes with a section on how ecological resilience is key to management of complex systems of people and nature.
- **Background**: Ecological resilience was defined, in 1973 by C.S. Holling, as the amount of disturbance that an ecosystem could withstand without changing self-organized processes and structures (defined as alternative stable states)
- **Background**: Example of ecosystem changing from one stable state to another
    - Zimbabwe and Australia: rom grassland to woody semi-arid rangeland
        - Alternative stable states are defined by dominant plant form
        - Disturbance is grazing pressure
    - From clear lake to turbid lake
        - Alternative stable states are defined by primary produces in water (micro-producers in water column versus rooted macrophytes)
        - Disturbance is amount of fertilizer in water
    - The Everglades: from sawgrass or wet prairie communities to cattail
        - Increased phosphorus concentration in the soils allow cattails to dominate
- **Background**: Walker (58) developed a driver and passengers analogy. Walker proposed that functional groups of species can be divided into 'drivers' and 'passengers.' Drivers are keystone species that control the future of an ecosystem, while the passengers live in but do not alter significantly this ecosystem. However, as conditions change, endogenously or exogenously, species shift roles. In this model, removing passengers has little effect, but removing drivers can have a large impact. Ecological resilience resides both in the diversity of the drivers, and in the number of passengers who are potential drivers.
- **Background**: Walker has more recently shown how the diversity of functional groups also maintains the resilience of ecosystem structure and function (56). Such diversity provides robustness to ecosystem functions and resilience to the system behavior. Moreover, this seems the way many biological processes are regulated-overlapping influences by multiple processes, each one of which is inefficient in its individual effect but together operating in a robust manner.
- **Background**: Species combine to form an overlapping set of reinforcing influences that help spread risks and benefits widely to retain overall consistency in performance independent of wide fluctuations in the individual species. Because of the robustness of this redundancy within functional groups, and the non-linear way behavior suddenly flips from one pattern to another and one set of controls to another, gradual loss of species

involved in controlling structure initially would have little perceived effect over a wide range of loss of species. As loss of those species con- tinued, different behavior would emerge more and more frequently in more and more places. To the observer, it would appear as if only the few remaining species were critical when in fact all add to the resilience.

- **Background**: Adaptive Management
    - Integrative and holistic, searching for simple structures and relationships that explain much of nature's complexity
    - Assumes surprises are inevitable, that knowledge will always be incomplete, and that human interaction with ecosystems will always be evolving
    - Natural resources being managed will always change, so humans must respond by adjusting and conforming as situations change
    - Views management policies as hypotheses
    - Develop and evaluate hypotheses around a set of desired system outcomes
- **Management**: In practice, maintaining a capacity for renewal in a dynamic environment provides an ecological buffer that protects the system from the failure of management actions that are taken based upon incomplete understanding, and it allows managers to affordably learn and change.
- **Management**: When faced with shifting stability domains and resulting crises, management options fall into one of three general classes of response.
    - The first is to do nothing and wait to see if the system will return to some acceptable state. One consequence of this option is that the social benefits of the desired state are foregone while waiting to see if the system will return to the desired state.
    - The second option is to actively manage the system and try to return the system to a desirable stability domain.
    - The third option is to admit that the system is irreversibly changed, and hence the only strategy is to adapt to the new, altered system.
- **Management**: In order to add resilience to managed systems, at least three strategies are employed:
    - increasing the buffering capacity of the system
    - managing for processes at multiple scales
    - nurturing sources of renewal (18).
- **Governance**: Institutions (defined broadly as the set of rules and structures that allow people to organize for collective action) can add resilience to a system
    - Learning, trust and engagement are key components of social resilience.
    - Social learning is facilitated by recognition of uncertainties, monitoring and evaluation by stakeholders.
    - The most difficult issues to deal with are those whose consequences will be realized 10 to 50 years in the future over broad scales.

Halofsky et al. 2011.

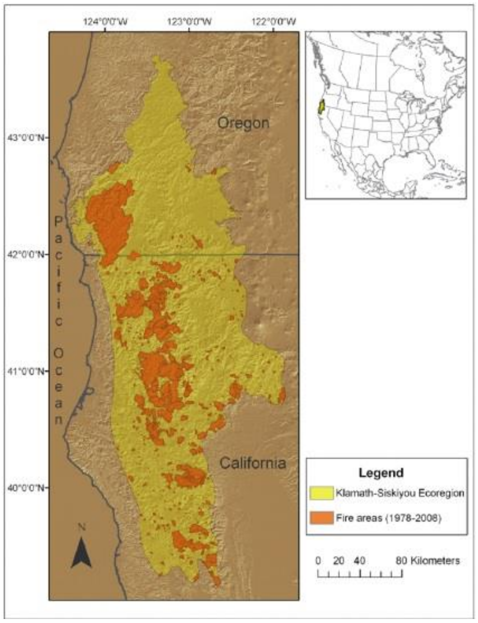
A wealth of information drawn from the 2002 Biscuit Fire (southern Oregon) about how mixed-severity fire promotes biodiversity. Includes lots of info on the fire dynamics of the Biscuit Fire, as well as on wildlife and soil response to the fire.

- **Study**: Since 2002, we have engaged in studies of early ecosystem response to 15 of these fires, ranging from determinants of fire effects to responses of vegetation, wildlife, and biogeochemistry. We present here some of our important early findings regarding mixed-severity fire, thereby updating the state of the science on mixed-severity fire regimes and highlighting questions and hypotheses to be tested in future studies on mixed-severity fire regimes.
- **Study**: Since 2002, we have engaged in studies of early ecosystem response to the fires, ranging from determinants of fire effects to responses of vegetation, wildlife, and biogeochemical dynamics. Here we synthesize results of our various studies, which focus on 15 fires that have occurred over the last twenty years in the Klamath-Siskiyou region. Our purpose is to highlight some important early discoveries from a model M-S fire region, and use these findings as a platform to develop hypotheses and research directions that may be explored in other systems influenced by M-S fires.
- **Background**: Although mixed-severity fires are among the most widespread disturbances influencing western North American forests, they remain the least understood.
- **Background**: The Klamath-Siskiyou Mountains of southwestern Oregon and northwestern California provide an excellent laboratory for studies of mixed-severity fire effects, as structurally diverse vegetation types in the region foster, and partly arise from, fires of variable severity. In addition, many mixed-severity fires have occurred in the region in the last several decades, including the nationally significant 200,000-ha Biscuit Fire.
- **Background**: Typically defined as mortality of dominant vegetation (e.g., overstory trees), severity ranges from low, or non-lethal surface fires, to high, or stand-replacing crown fires (Agee 1993, Keeley 2009).
- **Background**: Mixed-severity (M-S) fire regimes have been described for portions of several major forest types, including coastal Douglas-fir (Pseudotsuga menziesii) (Morrison and Swanson 1990), interior mixed-conifer (Arno et al. 2000, Fule´ et al. 2003, Schoennagel et al. 2004, Hessburg et al. 2007), and ponderosa pine (Pinus ponderosa) (Shinneman and Baker 2003). M-S fire regimes are generally recognized as the most complex and least understood fire regimes in North America because of the varied importance of climate and fuels as drivers and the complex burn patterns that result (e.g., Schoennagel et al. 2004, Agee 2005, Lentile et al. 2005).
- **Background**: The concept of M-S fire is scale-dependent and is typically defined at meso-scales (e.g., forest stand or loworder watershed), because at the finest scales (e.g., individual tree), fire effects such as mortality are binary, while at a coarser scale

(e.g., large or multiple watersheds), nearly all fires exhibit some degree of mixed fire effects (Turner and Romme 1994, Baker et al. 2007).

- **Background**: The Klamath-Siskiyou Mountains of southwestern Oregon and northwestern California (Fig. 1) provide an excellent laboratory for studies of M-S fire effects. Fires in the area are variable in frequency and severity, both spatially and temporally (Agee 1993, Taylor and Skinner 1998). Situated at the convergence of major North American floristic zones (Whittaker 1960), the region is characterized by an exceptionally diverse flora, with strong components of broadleaf hardwood, coniferous, and herbaceous vegetation. Mosaics of these structurally diverse vegetation types foster and may, in part, arise from repeated exposure to variable fire frequency and severity (Agee 1991, 1993).
- **Background**: Fire behavior and resulting severity is a product of interactions between weather, fuels, and topography (Agee 1993). Interactions between, and varying strength of, these three drivers of fire severity in the Klamath-Siskiyou region result in system behavior that is difficult to predict;
- **Background**: For the Klamath-Siskiyou region, the Biscuit Fire appears to have been unusually severe, as estimates of crown damage greatly exceed estimates from historical fires within the region (e.g., Weatherspoon and Skinner 1995, Odion et al. 2004, Alexander et al. 2006). The high severity of the Biscuit Fire was likely due in part to the dominance of weather as a driver; an earlier fire in the same area, the Silver Fire, burned under cooler conditions and resulted in generally lower fire severity (Thompson et al. 2007, Thompson and Spies 2010; Fig. 2). This importance of weather as a dominant driver of M-S fire is consistent with studies in other M-S fire regions (Bradstock et al. 2010; Schoennagel et al. in press).
- **Background**: Smucker et al. (2005) and Kotliar et al. (2007) both found intriguing wildlife dynamics such as hump-shaped patterns of response to varying fire severity following M-S fires in forests of western Montana and New Mexico, respectively. This higher abundance in moderate/mixed severity conditions suggests a suite of species responds most positively to increased edge and heterogeneity in fire effects. Examples reported such as dark-eyed junco (Junco hyemalis) and western tanager (Piranga rubra) also showed high abundances in the Biscuit Fire (Fontaine et al. 2009). Similarity in species responses to fire across regions, some of which have very different vegetation composition and understory structure (Kennedy and Fontaine 2009), further suggests that burn mosaic structure may be a dominant driver of wildlife response across M-S fire regions.
- **Background**: Examining the effects of longer fire intervals, Odion et al. (2004) concluded that severity of the 1987 fires in the Klamath-Siskiyou region was lower in closed forests where fire had been absent since 1920 compared to areas burned more recently. Odion et al. (2004) suggest that as combustible understory fuels (i.e., shrubs and evergreen hardwoods) decrease with succession due to shading and as height to live crown increases in the absence of fire in this region, the likelihood of a fire transitioning to the canopy decreases. Thus, following a stand-replacing fire, there may be a temporal threshold in the likelihood of additional stand-replacing fires, with positive feedbacks (i.e., high-severity fire followed by high-severity fire) over short timescales (,30 years)

owing to the rapid growth and dominance of evergreen hardwoods and shrubs, and negative feedbacks (i.e., high-severity fire followed by low-severity fire) over longer timescales (.75 years) owing to the development of higher crown base heights and less continuous understory fuels. The nature and timing of such a threshold would have important implications for long-term landscape structure (see Odion et al. 2010) and is an important direction for further research on M-S regimes.



- **Finding**: Our studies in the Klamath-Siskiyou Ecoregion suggest that forests with mixed-severity fire regimes are characterized primarily by their intimately mixed patches of vegetation of varied age, resulting from complex variations in both fire frequency and severity and species responses to this variation.
- **Finding**: Based on our findings, we hypothesize that the proximity of living and dead forest after mixed-severity fire, and the close mingling of early- and late-seral communities, results in unique vegetation and wildlife responses compared to predominantly low- or high-severity fires.
    - These factors also appear to contribute to high resilience of plant and wildlife species to mixed-severity fire in the Klamath-Siskiyou Ecoregion. More informed management of ecosystems with mixed-severity regimes requires understanding of their wide variability in space and time, and the particular ecological responses that this variability elicits.
- **Finding**: high moisture conditions and associated vegetation/fuel conditions in riparian areas influenced fire behavior and effects; canopy and soil damage (but not tree mortality) were lower in riparian areas compared to uplands in the Biscuit Fire, particularly along larger streams (Halofsky and Hibbs 2008; T. Spies, unpublished manuscript).
- **Finding**: Evergreen hardwoods, an important structural and compositional component in forests in the region, experienced relatively high levels of burn damage in the subcanopies below conifers. However, there was no evidence that hardwood presence increased fire severity
- **Finding**: Somewhat surprisingly, low-productivity, sparsely treed sites on ultramafic soils experienced the highest rates of conifer crown damage (Thompson and Spies 2009). However, these sites were found to have high shrub cover, and there was a positive relationship between shrub cover and crown damage in the Biscuit Fire (Thompson and Spies 2009).
- **Finding**: Few places within the Biscuit Fire perimeter were entirely unburned; 98% of the area was affected by surface fire (Campbell et al. 2007, Thompson and Spies 2009).

- **Finding**: Across the entire fire, approximately half the conifer crowns remained intact, and there were few areas greater than several hectares that did not contain a mixture of both live and dead trees (Thompson and Spies 2009). This pattern was also found in other fires in the Klamath-Siskiyou region over the last 20 years (Shatford et al. 2007).
- **Finding**: Topography in the Klamath-Siskiyou region generally results in drier and more flammable fuels on southwesterly aspects and in upper topographic positions, which generally leads to higher fire severity (Weatherspoon and Skinner 1995, Taylor and Skinner 1998, Alexander et al. 2006).
- **Finding**: Surprisingly, however, severity patterns in the Biscuit Fire were not strongly associated with topography (slope, aspect, elevation), with weather and vegetation instead being the main drivers (Thompson and Spies 2009)—a finding similar to conclusions from the 1988 Yellowstone Fires.
    - It is possible that dry winds out of the northeast and a maritime climate influence on west facing slopes confounded any positive relationship between southwest aspects and fire severity in the Biscuit Fire (Thompson and Spies 2009).
    - Relationships between burn patterns and topography could thus vary by region and should be explored in future fires in the Klamath-Siskiyou and other regions with M-S fire regimes.
- **Finding**: Supporting evidence included profound changes in soil properties in some stands subject to high-severity fire, where combustion temperatures over 6608C and convective erosion in the fire’s plume apparently contributed to losses of about 2.5 cm of fine mineral soil and one-third of soil nitrogen (N) and half of soil carbon (C) (Bormann et al. 2008). Stands with partial or no fire mortality had lower C and N losses from mineral soil.
- **Finding**: The resulting contrast in soil productivity between low- and high-severity patches suggests the potential for long-term legacies of burn severity patterns. Such legacies of M-S fire could be one factor underlying the well-known variation in vegetation productivity, structure, and composition of the Klamath-Siskiyou region (e.g., conifer forest and broadleaf vegetation such as sclerophyllous shrubs).
    - At our current state of knowledge, however, the long-term consequences of these soil changes remain unclear, and it is possible that N-fixing shrubs (e.g., Ceanothus)— which are often abundant in this region following severe fire (Shatford et al. 2007, Fontaine et al. 2009)—could help offset losses in some areas.
- **Finding**: Other geochemical dynamics varied surprisingly little across the mixed-severity mosaic of the Biscuit Fire, such as overall C emissions. Compared to the patchy nature of canopy combustion, the combustion of surface fuels (e.g., litter, duff, and fine woody debris) was relatively uniform and near complete across the entirety of the Biscuit (Campbell et al. 2007). This, combined with the fact that dead surface fuels have higher combustion efficiencies than do standing live components, meant that nearly 60% of the estimated 3.8 Tg C released to the atmosphere during the Biscuit arose from surface fuels (Campbell et al. 2007). This analysis of fuel consumption across a large MS fire

reveals that the majority of pyrogenic emissions are not strongly related to canopy mortality.

- **Finding**: Vegetation responses to M-S fire regimes are as complex as the burn patterns themselves. Spatial variation in fire severity has a vegetation legacy effect and perhaps a soil fertility effect.
    - These fire effects coupled with variation in regeneration strategies by different plant groups—conifers by seed dispersal, broad-leaved trees primarily by sprouting, shrubs by both sprouting and seed banking—results in a diverse post-fire vegetation mosaic.
- **Finding**: As a result of these edge effects, small-to-medium burn patches and edges of large patches contained conifer seedlings and sprouting hardwoods, while interiors of large patches (.400 m from edge) were characterized by hardwood regeneration with delayed or no conifer establishment four years post-fire (Donato et al. 2009a). Burn patch size thus had a threshold effect on regeneration composition, resulting in potentially different successional pathways in the interior versus perimeter of larger patches.
- **Finding**: Conifer- and hardwood-dominated riparian plant communities, each found in specific topographic settings, were self-replacing. In both riparian and upland sites, abundant regeneration and the self-replacement of pre-fire vegetation communities after the Biscuit Fire suggest high species and community resilience after M-S fire.
- **Finding**: Working in several post-fire landscapes (n = 11 fires) throughout the Klamath-Siskiyou region, Shatford et al. (2007) found that conifer regeneration continued over a two-decade period across highly variable ecological settings. Shrub and sprouting hardwood communities were also abundant and diverse, forming a dominant to co-dominant canopy with conifers during early successional stages across a range of sites. Aspect, precipitation and elevation were found to be important predictors of all vegetation recovery processes (Lopez Ortiz 2007, Shatford et al. 2007). Only on very dry sites was conifer regeneration scarce or lacking, suggesting that early-colonizing shrubs and hardwoods are more likely to maintain long-term dominance in these locations.
- **Finding**: The interaction between patch-size and seed source dynamics was remarkably similar between small M-S fires and the exceptionally large Biscuit Fire; most high-severity burn area was ,400 m from edge, and conifer regeneration was generally abundant within this distance (Shatford et al. 2007, Donato et al. 2009a).
- **Finding**: M-S fire regimes appear to play a role in maintaining a significant hardwood presence in the Klamath-Siskiyou region. All of the hardwoods basal-sprout vigorously after fire; all except tanoak (Lithocarpus densiflorus) are at least moderately shade intolerant; and all have a mature height much shorter than the associated conifers. In coniferous forest, hardwoods form a shrub and mid-layer canopy (Franklin and Dyrness 1973, Agee 1993) that provides structural diversity and habitat for a large suite of wildlife species (Hagar 2007). Short intervals (less than 30 years) between fires maintain an open canopy in places, providing the ecological space for these species to persist (Agee 1993, Odion et al. 2010).

- **Finding**: We found that early post-fire hardwood cover is moderate to high (Shatford et al. 2007, Donato et al. 2009a, Fontaine et al. 2009), providing important habitat for open-cup nesting birds (Betts et al. 2010; M. Donaghy Cannon, unpublished manuscript) and contributing to soil function and mycorrhizal networks (Borchers and Perry 1990).
- **Finding**: In mesic forest types such as the Klamath-Siskiyou and western Cascade Mountains, conifer regeneration densities are often high in areas burned with low- to moderate severity and several hundred meters into high-severity patches (Shatford et al. 2007, Chappell and Agee 1996, Donato et al. 2009a), while in drier forest types such as ponderosa pine, regeneration can be mostly absent from high-severity patches except near edges (Bonnet et al. 2005, Lentile et al. 2005, but see Haire and McGarigal 2010).
- **Finding**: Thus, the longterm importance of burn patch structure may vary along a spectrum of forest types, from dry interior pine forests in which burn mosaics may persist strongly (with purported state changes in patch interiors), to moist forest types in which burn mosaics may have an important but more ephemeral effect on gross vegetation composition.
  - The Klamath-Siskiyou region would appear to lie near the middle of the moisture-regeneration continuum among forests affected by M-S fire.
- **Finding**: Data from the Klamath-Siskiyou region suggest that the vegetation mosaic and broadleaf abundance associated with the M-S regime are important drivers of wildlife response to fire (Fontaine et al. 2009, Meehan and George 2003, Betts et al. 2010; Clark et al. in press). Avian community composition and abundance within high-severity portions of the Biscuit Fire were remarkably resilient relative to unburned, late-successional reference forests outside the fire (Fontaine et al. 2009). While avian communities in unburned and burned patches were distinct in composition, species richness was not reduced by high-severity fire and density was reduced by ;50%, likely a consequence of the fine-grained burn mosaic and regenerating broad-leaved vegetation (Betts et al. 2010, Fontaine et al. 2009). Following disturbance, many broadleaved species resprout and may rapidly grow (.2 m in height 4 yrs post-fire, J. Fontaine, unpublished data), providing foraging and nesting substrates for a range of species. This effect may persist for two decades or longer following fire (Fontaine et al. 2009).
  - Species such as lazuli bunting (Passerina amoena), Nashville warbler (Vermivora ruficapilla), and black-headed grosbeak (Pheucticus melanocephalus) heavily utilize this regenerating vegetation (Betts et al. 2010, Fontaine et al. 2009).
- **Finding**: Certain species thought of as late-successional forest specialists may also use recently burned areas, a response likely associated with the presence of a complex burn mosaic. For example, interspersion of low- and high-severity patches allowed for the persistence of birds that nest and forage in canopy foliage (e.g., hermit warbler (Dendroica occidentalis) M. Donaghy Cannon, unpublished data). Amount of edge habitat was positively associated with olive-sided flycatcher (Contopus cooperi) prevalence post-fire (Meehan and George 2003).
- **Finding**: Over long time scales it is evident that fire maintains the broad-leaved vegetation and landscape heterogeneity on which many bird species depend (Betts et

al. 2010, Franklin et al. 2000, Schlossberg and King 2008). However, in the short-term further research is required to test questions addressing the relative importance of the post-fire mosaic (coarse-scale) and vegetation regeneration patterns (fine-scale) for determining post-fire wildlife abundance across a range of fire severities (see Kotliar et al. 2007, 2008).

- **Finding**: Recent evidence from the Klamath-Siskiyou region suggests that the interval between fires, and thus successional stage when burned, is a key determinant of how strongly sequential fires interact. Where the Biscuit Fire burned over the 15-year-old M-S Silver Fire, fire severity was strongly influenced by the severity mosaic of the earlier fire, after accounting for other biotic and abiotic factors. Low-severity patches were more likely to reburn with low severity, and highseverity patches reburned with high severity (Thompson et al. 2007, Thompson and Spies 2010; Fig. 2). Thus, sequential disturbances separated by 15 years exhibited a positive feedback, reinforcing the spatial pattern on the landscape.
- **Finding**: The shrub and hardwood dominated vegetation that establishes after fire in this region is highly combustible and can maintain dominance for up to approximately 30 years without fire (Odion et al. 2010).
- **Finding**: Surprisingly, two sequential fires led not to a depleted forest community, but rather to an increase in plant species richness, with little evidence of species extirpation (Donato et al. 2009b). Increases in species richness were largely due to increases in fire-ephemeral species (e.g., Epilobium spp.).
- **Finding**: Wildlife showed similar responses to recurrent M-S fires. Compared to once-burned areas, bird species richness and density in twice-burned areas were higher and dominated by shruband hardwood-nesting species (Fontaine et al. 2009). Shrub- and hardwood-nesting and disturbance- adapted bird species (e.g., lazuli bunting (Passerina amoena)) were strong indicators of twice-burned habitats. Small mammal species richness and community structure in twiceburned areas were similar to once-burned areas but with significantly higher densities (Fontaine 2007).
- **Finding**: Observations in the Klamath-Siskiyou region suggest that variation in dominant drivers of fire behavior (fuels, topography, and weather) leads to varied burn patterns both within and among M-S fires. The range in fire effects—fire severity, patch size, and legacy generation—appears to be a major driver of ecosystem dynamics in these systems, as we have described here.
- **Finding**: The edge-to-interior ratio of burn patches is typically much higher in M-S fires than in low- and high-severity fires (Agee 2005); i.e., edge abundance is non-linearly related to severity regime. The M-S fire is therefore characterized by the mixing at relatively fine scales (tens to a few hundreds of meters) of patches of vegetation burned to varied levels of severity. Similarly, the irregularity of the fire return interval leads to highly variable patch age.
- **Finding**: our studies in the Klamath-Siskiyou region suggest that, taken together, the suite of M-S fire characteristics may give rise to unique ecological dynamics in M-S regimes (Table 1). We observed that varied fire effects result in (and result from) fine-

scale variation in patch age and composition, which provides habitat for a variety of species in relatively close proximity.

- **Finding**: A consistent finding among the diverse ecosystem responses summarized here is the high resilience of plant and wildlife species composition in Klamath-Siskiyou forests to M-S fire. Although the 2002 Biscuit Fire made national headlines and was considered to be outside characteristic ranges in terms of size and severity, several studies of this and nearby fires showed rapid and sustained response of both flora and fauna, even in areas that had burned twice with high-severity within a 15-year period.
- **Management**: Of high management relevance, northern spotted owls and California spotted owls (S. o. occidentalis) may also utilize the M-S mosaic. In the Klamath-Siskiyou region, Northern Spotted Owl fitness is higher in landscapes containing a mixture of old forest and younger brushy vegetation (Franklin et al. 2000), suggesting that in this part of its range, the spotted owl is well suited to a M-S fire regime.
    - However, in the short term, a large extent of high-severity fire within owl territories may provoke negative short-term responses (e.g., displacement, lower survival). While partially confounded by salvage logging, Clark et al. (in press) found that survival of northern spotted owls within fires was lower than in adjacent unburned habitat in the initial years (1–4 yrs post-fire) following high-severity fire.
- **Management**: studies in the Klamath-Siskiyou region suggest that some common postfire management actions—such as tree planting, snag removal, and vegetation control—may not always be needed to meet the management objectives of providing wildlife habitat, promoting forest regeneration, and reducing fire hazard (Donato et al. 2006, Lopez Ortiz 2007, Shatford et al. 2007, Thompson et al. 2007, Kayes 2008).

Halofsky et al. 2016. Developing and Implementing Climate Change Adaptation Options in Forest Ecosystems: A Case Study in Southwestern Oregon, USA. Forests 7: 268.

- **Study**: We developed an approach to facilitate development and implementation of climate change adaptation options in forest management
- **Study**: This approach, applied in a southwestern Oregon study region, involved establishment of a science–manager partnership, a science-based assessment of forest and woodland vulnerabilities to climate change, climate change education in multiple formats, hands-on development of adaptation options, and application of tools to incorporate climate change in planned projects.
- **Background**: Climate Change-related changes to SW Oregon will likely be driven mainly by wildfire and drought
- **Background**: Currently, most federal agencies have broad-scale strategic plans that describe approaches and priorities for climate change in general, and for adaptation in particular, and several departments and agencies have built on initial strategic documents to increase capacity and develop more detailed plans for assessing vulnerabilities and adapting management to climate change [14].
    - For example, the U.S. Forest Service has a national climate change office, a roadmap that guides response to climate change, a scorecard that tracks accomplishments in ten areas, and climate change coordinators at the regional and national forest levels.
- **Background**: Much of the progress in climate change adaptation in natural resource management to date has been accomplished through collaboration between scientists and resource managers [14,15,18–21].
- **The Klamath-Siskiyou**: Diverse floras from several western U.S. floristic provinces intermingle in the complex environmental and geomorphological gradients that characterize the landscape. These complex gradients have allowed for persistence of localized climatic conditions, or climate refugia, amid broader climatic changes in the past.
- **Climate Impacts**: Trends of increasing temperatures, changing precipitation patterns, and increasing extreme events such as drought and fire are expected to continue in this century, driving changes in forest ecosystems [10,11].
- **Finding**: Engaging managers throughout the project increased ownership of the process and outcomes, as well as the applicability of the adaptation options to on-the-ground actions.
- **Finding**: Science–management partnerships can effectively incorporate evolving science, regardless of the socio-political environment, and facilitate timely progress in adaptation to climate change.
- **Findings**: Through this approach, we improved local manager understanding of the potential effects of climate change in southwestern Oregon, and enabled evaluation of proposed management activities in the context of climatic stressors.

Harrison et al. 2010.

- **Study**: We analyzed change in understory herb communities over a 60-y period (1949/1951–2007/2009) in a complex montane landscape (the Siskiyou Mountains, Oregon) where mean temperatures have increased 2 °C since 1948.
- **Study**: Our 185 sites included primary and secondary-growth lower montane forests (500–1.200 m above sea level) and primary upper montane to subalpine forests (1,500–2,100 m above sea level).
  - Our study sites were not grazed by livestock and have not burned since Whittaker's time, and exotic species were too sparse to be detectable in our sampling. In the sites that were not clear-cut in the 1960s through the 1980s, there have been no other large-scale human disturbances.
- **Study**: Our analyses are based on the 181 herb species, all perennial, for which either we in 2007–2009 or Whittaker in 1949–1951 found >0% cover in at least one of the 185 plots. All these 181 species were native to the region, because neither we nor Whittaker found any exotic species common enough to register a cover value of >0%.
- **Findings**: Our results provide community level validation of predicted nonlinearities in climate change effects.
- **Findings**: In lower montane forests, regardless of land-use history, we found multiple herb community changes consistent with an effectively drier climate, including lower mean specific leaf area, lower relative cover by species of northern biogeographic affinity, and greater compositional resemblance to communities in southerly topographic positions.
  - These compositional changes were driven by small declines in the abundances of large numbers of species, with no species showing substantial increases in abundance (Fig. S1).
- **Findings**: At higher elevations we found qualitatively different and more modest changes, including increases in herbs of northern biogeographic affinity and in forest canopy cover.
  - This may be the result of the longer snow-free growing season (e.g., 5, 11, 12, 52). In turn, increased shading from a more vigorous overstory at these elevations may have suppressed herb cover and richness (11, 12) as well as contributing to the observed shift toward shade-tolerant herbs of northern biogeographic affinity.
- **Findings**: Species richness declined more in primary and secondary low-elevation forests (which did not differ significantly from each other) than in high-elevation forests (F=5.44,P=0.02), whereas declines in total cover did not differ between low and high elevations (F=0.45, P= 0.51).
- **Findings**: We found no change in the relative cover by herbs considered to be indicators of late-seral forest conditions in either primary lower montane forest (t = 0.65, P = 0.52) (Fig. S3) or upper montane to subalpine forest (t = 0.19, P = 0.85) (Fig. S3), suggesting these forests already were in late-successional condition in 1949–1951 (consistent with Whittaker's description of his site selection; ref. 25).

    - However, the secondary lower montane forests that were logged in the 1960s through the1980s showed the expected lower percent of cover by late-seral indicator herbs in 2007–2009 compared with 1949–1951 (t = 4.93, P < 0.001) (Fig. S3).
- **Findings**: In analyses using aerial photographs from 1940 and 2005 (41), mean canopy cover showed no change in primary lower montane forest (t = 0.95; df = 1, 3; P = 0.39) (Fig. S3), a slight and marginally significant decrease in secondary lower montane forest (t = 1.01; df=1, 23; P=0.06) (Fig. S3), and a significant increase in the primary upper montane to subalpine forest (t = 8.41; df = 1, 43; P < 0.001) (Fig. S3). These patterns are inconsistent with forest succession as a cause of the observed herb-community changes at low elevations, although they suggest a possible role for warming-induced canopy expansion at high elevations.
- **Findings**: Our study adds to growing ecological evidence for drier forest understory conditions in many parts of the world (e.g., 45, 46–49).
- **Background**: Upward and poleward shifts of species and vegetation zones are expected under climatic warming, and considerable evidence has been found in support of these broad predictions (1–5).
- **Background:** However, large differences among communities in the magnitude, rate, and direction of responses to climatic warming are also expected, based on factors such as topography and substrate, land use history, and community-level variation in species functional traits (e.g., 6, 7–10).
- **Background**: Clear-cut logging was widespread [in the Klamath-Siskiyou] in the 1960s through the 1980s at low to moderate elevations, leaving a mosaic of secondary forests composed largely of the same species but in altered relative abundances and age classes (31).
- **Climate Change Impacts**: One of the earliest and best-known expectations about contingency is that climate change effects should be most pronounced at high elevations where plant growth is most strongly limited by temperature (14), specifically by the length of the snow-free growing season.
    - This expectation is based on studies in the alpine and nival zones of the European Alps and elsewhere, where warming temperatures have been observed to lead to increases in plant productivity and species richness, although with losses of high-elevation specialist species, presumably as the result of competition (e.g., 9, 14–16).
- **Climate Change Impacts:** However, growing evidence also shows severe effects of climatic warming in warm and water-limited biomes, such as the western United States at low to moderate elevations, where enhanced drought stress has led to widespread vegetation die-off (e.g., 2, 17, 18).
    - In fact, physiologically based models predict that a given amount of growing-season warming should reduce plant growth at water-limited low elevations while enhancing it at temperature-limited higher elevations (e.g., 12, 19), a straightforward prediction that accords with data on tree growth rates (11), remotely sensed productivity indices (20), and shifts in flowering phenology (21).

- **Climate Change Impacts**: Mean annual temperatures and mean summer temperatures have increased [in the Klamath-Siskiyous] ≈2 °C since 1948, and snow-water equivalent (the product of snow depth and snow relative density) has declined, although mean and seasonal precipitation have not changed significantly (28–30).
- **Climate Change Impacts**: The primary effect of climatic warming in water-limited environments, in the absence of changes in precipitation, is to exacerbate drought stress (5, 17, 18). Accordingly, we found that Siskiyou low-elevation forest herb communities have shifted toward a greater prevalence of species with small, thick leaves (lower SLA) that are better adapted to dry conditions than species with large, thin leaves (32–34).
- **Climate Change Impacts**: Had our study extended into still higher Siskiyou elevations where there is no forest cover, we would expect to find increases in herb cover and richness similar to those observed in Alpine studies (e.g., 15, 16, 50).
- **Climate Change Impacts**: Water limitation may potentially become more important at progressively higher elevations as the snowpack diminishes or disappears completely.
- **Management**: Anticipating ecological contingency in responses to climate change is especially critical for managers of natural resources, who are well aware of the potential for major nonlinearities ("surprises") in community change and of the particular difficulty of making predictions for physically and biotically complex landscapes (e.g., 11–13).
- **Management**: the main effect of logging on herbs may be to reduce the abundances of species with modes of persistence, dispersal, and regeneration that are ill-adapted to recovery from heavy disturbance (e.g., 31, 53, 54), and this effect acts largely independently of climatic limiting factors.

Harrison et al. 2015.

- **Study**: Much evidence suggests that plant communities on infertile soils are relatively insensitive to increased water deficit caused by increasing temperature and/or decreasing precipitation. However, a multidecadal study of community change in the western USA does not support this conclusion. This paper tests explanations related to macroclimatic differences, overstorey effects on microclimate, variation in soil texture and plant functional traits.
- **Study**: A re-analysis was undertaken of the changes in the multi-decadal study, which concerned forest understorey communities on infertile (serpentine) and fertile soils in an aridifying climate (southern Oregan) from 1949–1951 to 2007–2008.
    - Macroclimatic variables, overstorey cover and soil texture were used as new covariates. As an alternative measure of climate-related change, the community mean value of specific leaf area was used, a functional trait measuring drought tolerance.
    - We investigated whether these revised analyses supported the prediction of lesser sensitivity to climate change in understorey communities on infertile serpentine soils.
- **Background**: Grime et al. (2000, 2008) showed that a native grassland on infertile limestone soils changed very little in response to a prolonged application of warming, drought and watering treatments that had caused dramatic compositional changes in other plant communities. These authors largely attributed the relative climate resistance of infertile limestone grasslands to a suite of plant functional traits associated with low relative growth rate and high tolerance for resource scarcity. [See also Damschen et al. (2012) for related evidence.]
- **Background**: Our research in recent years has focused on testing 'Grime's hypothesis' in native-dominated plant communities on infertile soils in the California Floristic Province. In this semi-arid region, climatic warming is expected to drive increased seasonal water deficits that will dominate the future impacts of climate change on natural vegetation (Cornwell et al., 2012; Hannah et al., 2012; Thorne et al., 2012), making water availability a natural focus.
- **Background**: Serpentine soils are high in Mg and low in Ca and primary nutrients; they are found throughout the world, and are particularly floristically rich in tropical and mediterranean climates (Brooks, 1987).
- **Background**: Prior to our recent work, several lines of evidence hinted at unusually low sensitivity to climatic variation in Californian serpentine plants. Vegetation on serpentine barrens looked scarcely different in photos taken several decades apart (Kruckeberg, 1984). Plant community turnover on a coastal-to-interior climatic gradient was much lower on serpentine than on non-serpentine soils (Harrison, 1999).
- **Background**: Since 2010, our work in serpentine plant communities has added considerably more evidence supporting both lower climate sensitivity on infertile soils and the causal role of plant functional traits.

    - In two multi-year experiments, the effects of watering on grassland biomass and/or composition were lower on serpentine soils (Eskelinen and Harrison, 2013; Fernandez- Going and Harrison, 2013).
    - In a 10-year observational study, grasslands on serpentine soils fluctuated less in response to annual variability in rainfall than those on non-serpentine soils, and functional traits were important predictors of this difference (Fernandez-Going et al., 2012).
    - In a geographical study across a 1200-km, 10-fold precipitation gradient, serpentine plant communities had consistently 'stress-tolerant' functional trait composition, while communities on more fertile soils varied strongly from 'stress tolerant' at the dry southern end to 'stress intolerant' at the wet northern end (Fernandez-Going et al., 2013).
    - Finally, in a 15-year observational analysis, grassland species diversity has declined and composition has changed to more 'stress tolerant' as the climate has become more arid, but less so on serpentine than on non-serpentine soils (S. Harrison, E. Gornish and S. Copeland, unpubl. data).
- **Background**: Overstorey shading is known to buffer forest understorey herbs against climate change by modulating temperature extremes (De Frenne et al., 2013)
- **Background**: A growing number of climate change studies are using SLA and other functional traits as both predictors and indicators of change (e.g. Harrison et al., 2010; Sandel et al., 2010; Soudzilovskaia et al., 2013). Traits show great promise as a currency of plant community change, because they are easily measured by highly repeatable means (e.g. Garnier et al., 2001; Cornelissen et al., 2003) and make it possible to compare responses among communities with few or no species in common (e.g. Wright et al., 2004; Westoby et al., 2006).
- **Finding**: We conclude that the balance of evidence supports what we have called Grime's hypothesis, linking soil infertility to a stress-tolerant functional trait syndrome that tends to confer unusually high resistance of plant species and communities to climate change.
    - We qualify this by saying that our evidence only applies to communities that are becoming effectively drier because of declining precipitation and/or increasing temperatures leading to greater water deficits.
    - Such aridification is both observed and projected in California, much of the western US, and other arid and semi-arid climates (Seager et al., 2007; Thorne et al., 2012).
    - We also caution that less sensitive does not mean insensitive, and that the future survival of endemic-rich communities on infertile soils could be undermined by nutrient deposition, stress-tolerant invasive species and habitat loss (Damschen et al., 2012).
- **Finding**: Overstorey cover, but not macroclimate or soil texture, was a significant covariate of community change over time. It strongly buffered understorey temperatures, was correlated with less change and averaged >50 % lower on serpentine soils, thereby counteracting the lower climate sensitivity of understorey herbs on these

soils. Community mean specific leaf area showed the predicted pattern of less change over time in serpentine than non-serpentine communities.

- **Finding**: Based on the current balance of evidence, plant communities on infertile serpentine soils are less sensitive to changes in the climatic water balance than communities on more fertile soils. However, this advantage may in some cases be lessened by their sparser overstorey cover.
- **Finding**: In support of our overstorey hypothesis, higher tree and shrub cover was associated with significantly lower mean
  (P<0
  00
  1) and maximum
  (P<0
  00
  1) understorey temperatures as measured in July 2014.
- **Finding**: Overstorey cover was negatively related to the biogeographical measure of community change, and interacted with soil to affect the topographic measure of community change (Table 2, Fig. 1). Overstorey cover was negatively related to the topographic measure of change on serpentine soils, but had no effect on non-serpentine soils.
- **Finding**: Using the regression relationship observed on serpentine soils, a serpentine community would change much less if it had the same overstorey cover as the average non-serpentine community (Fig. 1).
- **Finding**: As expected, community mean SLA was considerably lower on serpentine than on non-serpentine soils in both time periods (1949–1951 and 2007–2008), suggesting that serpentine species are more stress-tolerant on average. Also as expected, community mean SLA declined between these time periods on nonserpentine soils only (Fig. 2), indicating that on these soils, there was a differential loss of drought-intolerant (high SLA) species.
- **Finding**: Using as our measure of change the mean value of Specific Leaf Area (SLA), a key climate-related functional trait, we found a result that supported 'Grime's hypothesis' and helped to reconcile our historical study with other evidence: initially higher prevalence, followed by greater decline, of drought-intolerant species on fertile soils.
- **Finding**: we found that well-shaded understorey communities changed less over the six decades of climatic warming than did more open understories. This result agrees well with recent work suggesting that forest canopies buffer understorey herbs against climatic 'thermophilization' (De Frenne et al., 2013). Our results suggest that for herb communities on serpentine soils, the benefit of more stress-tolerant functional traits is counterbalanced by the disadvantage of less shading. Clearly, any generalizations about the relative vulnerability of plant communities on infertile soils to climate change (e.g. Grime et al., 2000, 2008; Damschen et al., 2012) need to take into account whether soil infertility is associated with lower overstorey cover.

Heller and Zavaleta. 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. Biological Conservation 142: 14-32.

- **Study**: Scholarly articles recommending measures to adapt conservation to climate change have proliferated over the last 22 years. We systematically reviewed this literature to explore what potential solutions it has identified and what consensus and direction it provides to cope with climate change.
- **Study**: We recorded 524 recommendations from 113 papers, published in 57 different source journals and three books
- **Background**: Landscapes outside of protected areas are hostile to the survival of many species due to human infrastructure and associated stressors, such as invasive species, hunting, cars, and environmental toxins. Such fragmentation directly limits species migration and gene flow.
- **Background**: Further, despite widespread favor for ecological networks, assessment of their effectiveness remains in its infancy. Similarly, the field of corridor ecology, while recognized as integral to conservation practice in fragmented landscapes for years, is still young (see Hilty et al., 2006). Some authors warn of a significant need for more empirical data to support the effectiveness of corridors, optimize their spatial arrangement, and minimize risks of increased transmission of disease or invasive species before the conservation community embraces corridors uniformly as the tool to combat biodiversity loss in the face of global climate change (Graham, 1988; Halpin, 1997; Scott and Lemieux, 2005; Williams et al., 2005).
- **Background**: A second popular recommendation for improving landscape connectivity is to change how we manage the matrix (Da Fonseca et al., 2005; Eeley et al., 1999; Lovejoy, 2005). Many authors advocate creating buffer zones around reserves (Rank 8) or flexible landuse zoning at reserve boundaries to allow for land swaps in the future as species distributions shift (Rank 14). Others recommend urban planning and zoning to avoid climate-related risks (Rank 14). In general, enlisting people and human communities to ‘soften’ landuse through sustainable or less damaging practices (e.g. low intensity forestry or alternatives to building sea walls) (Rank 9) and to restore habitat (Rank 9) will facilitate species movement and persistence in the future.
- **Background**: Despite wide acknowledgement, these connectivity strategies were among the most poorly developed recommendations, limited mainly to very general actions (e.g. ‘‘build flexibility’’, ‘‘manage the matrix’’, ‘‘modify land use practices’’) without identification of kinds of actors that might need to be involved (e.g. reserve managers, policymakers, individuals) or information gaps. Land use reform likely needs to bring together local governments, urban planners, community groups and conservation organizations and to involve high degrees of coordination across multiple jurisdictions to provide landscape cohesion (Press et al., 1995). Substantial work to flesh out this process, as well as to guide information acquisition, is needed before new forms of management across land use types can be implemented.
- **Finding**: Most common climate change adaptation recommendation from review of 112 scholarly articles: (1) increase connectivity (recommended in 24/112 articles); (2) integrate climate change into planning exercises (19/112 articles); (3) mitigate other threats (e.g., invasive species, fragmentation, pollution, etc.); etc. etc.
- **Finding**: To improve landscape connectivity, so that species can move, is the most frequent recommendation for climate change adaptation in the literature reviewed here (Rank 1).
    - There was little guidance in this literature set for corridor implementation beyond common-sense reasoning, however.
- **Findings**: Several consistent recommendations emerge for action at diverse spatial scales, requiring leadership by diverse actors.

- **Findings**: Broadly, adaptation requires improved regional institutional coordination, expanded spatial and temporal perspective, incorporation of climate change scenarios into all planning and action, and greater effort to address multiple threats and global change drivers simultaneously in ways that are responsive to and inclusive of human communities.
- **Finding**: However, in the case of many recommendations the how, by whom, and under what conditions they can be implemented is not specified. We synthesize recommendations with respect to three likely conservation pathways: regional planning; site-scale management; and modification of existing conservation plans.
- **Finding**: We identify major gaps, including the need for (1) more specific, operational examples of adaptation principles that are consistent with unavoidable uncertainty about the future; (2) a practical adaptation planning process to guide selection and integration of recommendations into existing policies and programs; and (3) greater integration of social science into an endeavor that, although dominated by ecology, increasingly recommends extension beyond reserves and into human-occupied landscapes.
- **Finding**: About 70% of recommendations were classified as general principles under our classification scheme rather than specific, actionable strategies or tactics (Fig. 1).
- **Finding**: Widespread calls exist for immediate action to adapt conservation practice to ongoing climate change in order to ensure the persistence of many species and related ecosystem services. However, the majority of recommendations in the published journal literature lack sufficient specificity to direct this action.
- **Finding**: Recommendations to date also largely neglect social science and are overwhelmingly focused on ecological data (Fig. 4c). This bias is alarming given the obvious importance of human behavior and preferences in determining conservation outcomes (Watson, 2005) and the increasingly important role of multi-use public and private lands in conservation practice.

Hodgson et al. 2009. Climate change, connectivity and conservation decision making: back to basics. Journal of Applied Ecology 46: 964-969.

- **Study**: In this study, we revisit the principles of spatial ecology and conservation planning. We summarize how connectivity emerges as a complicated function of habitat area, habitat quality, the spatial arrangement of habitat and species-specific dispersal. We argue that uncertainty associated with connectivity is generally higher than uncertainty about habitat area and quality, and threatening processes such habitat destruction.
- **Background**: Increasing 'connectivity' has emerged as the most favored option for conservation in the face of climate change.
- **Finding**: We argue that the importance of connectivity is being overemphasized: quantifying the benefits of connectivity per se is plagued with uncertainty, and connectivity can be co-incidentally improved by targeting more concrete metrics: habitat area and habitat quality.
- **Finding**: As uncertainties about connectivity tend to be high, and increases in habitat quantity and quality coincidentally improve connectivity, we conclude one should generally provide higher weight in decision-making to actions that increase area and quality. Theoretically, we know that populations will sometimes benefit more from a small, well-connected piece of habitat than a larger, more isolated one, but the relative uncertainties and the probability of worse-than-expected outcomes should also affect our decision making.
- **Finding**: renewed effort and additional funding to conserve extra land is warranted. Locations that have low human impacts should remain good for many species, even if the identities of those species change.
- **Finding**: Thirdly, the majority of small-range terrestrial species are clustered into a small percentage of the land surface (centres of endemism ⁄ areas of high irreplaceability, cf. Wilson, Carwardine & Possingham 2009), many of which are mountain ranges.Ahigh percentage of the species threatened with extinction from climate change are found in such locations: they are expected to show range retractions within the regions where they currently occur, and are unlikely to achieve long distance colonization of other parts of the world (Midgley et al. 2002; Williams, Bolitho, & Fox 2003; Thomas et al. 2004; Malcolm et al. 2006;Ohlemu¨ ller et al. 2008). So, our thirdmessage is that concentration of conservation effort in centres of endemism remains a valid strategy.
- **Finding**: Fourthly, almost all threatened species are negatively impacted by multiple factors. In some instances, mitigating known threats other than climate change may be sufficient to permit a population to persist, even if the local climate has deteriorated. When this strategy cannot ensure persistence in its own right, mitigating known threats should be regarded as an essential first step in making populations robust to climate change. We recommend dealing with known (stoppable) threats for which there are known solutions before addressing uncertain and ⁄ or unstoppable threats with less certain or less feasible solutions (Pressey et al. 2007; Wilson et al. 2007).
- **Finding**: These four principles, increasing protected area, maintaining and in some cases increasing environmental heterogeneity, concentrating efforts in centers of endemism, and reducing other pressures are likely to be beneficial and robust, with or without climate change.
- **Finding**: Land conversion and land-use change leading to habitat loss is still the most cited threat to currently endangered species, and the most straightforward way to tackle this is to maintain and restore larger areas of natural habitat. Species will not be able to survive where they are or shift their distributions to new climatically suitable areas unless there are sufficient habitats for

them, and it should be remembered that increasing habitat area is an effective way of increasing ‘connectivity’.

- **Finding**: Furthermore, conserving habitats will be beneficial even if the particular species found in an area are gradually replaced by others as the climate changes. The conservation of high quality existing habitats should therefore remain the primary focus of conservation efforts to maintain biodiversity.

Honnay et al. 2002. Possible effects of habitat fragmentation and climate change on the range of forest plant species. Ecology Letters 5: 525-530.

- **Study**: We report the results of two forest plant colonization studies in two fragmented landscapes in central Belgium.
- **Background**: The associated changes in the ratio of extinctions and colonizations at the boundaries of species ranges are expected to result in northward range shifts for a lot of species. However, net species colonization at northern boundary ranges, necessary for a northward shift and for range conservation, may be hampered because of habitat fragmentation.
- **Climate Impacts**: Global circulation models predict an increase in mean annual temperature between 2.1 and 4.6 C by 2080 in the northern temperate zone.
- **Finding**: Almost all forest plant species (85%) had an extremely low success of colonizing spatially segregated new suitable forest habitats after c. 40 years. In a landscape with higher forest connectivity, colonization success was higher but still insufficient to ensure large-scale colonization. Under the hypothesis of net extinction at southern range boundaries, forest plant species dispersal limitation will prevent net colonization at northern range boundaries required for range conservation.

Lienard et al. 2016.

- **Study**: Here, we develop and apply an intermediate approach wherein we use stand-level tolerances of environmental stressors to understand forest distributions and vulnerabilities to anticipated climate change throughout the USA.
  - In contrast to other existing models, this approach can be applied at a continental scale while maintaining a direct link to ecologically relevant, climate-related stressors.
  - We first demonstrate that shade, drought, and waterlogging tolerances of forest stands are strongly correlated with climate and edaphic conditions in the conterminous United States. This discovery allows the development of a tolerance distribution model (TDM), a novel quantitative tool to assess landscape level impacts of climate change. We then focus on evaluating the implications of the drought TDM.
- **Study**: In our Tolerance Distribution Model (TDM), we determine relationships between tolerance traits and climate variables and use the resulting best model to identify regions that are vulnerable to anticipated climate change.
  - We first employ species-level rankings of shade, drought, and waterlogging tolerance developed by foresters (Niinemets & Valladares, 2006; Valladares & Niinemets, 2008; Lienard et al., 2015) to examine whether and how major climate and edaphic factors in the conterminous United States affect tree species distributions.
- **Finding**: We estimate that 18% of US ecosystems are vulnerable to drought-related stress over the coming century. Vulnerable areas include mostly the Midwest United States and Northeast United States, as well as high-elevation areas of the Rocky Mountains.
- **Finding**: Some of the climate conditions (and hence drought tolerance characteristics) anticipated to occur over the next several decades do not currently exist in the conterminous United States (Williams et al., 2007; Ackerly et al., 2010). The Pacific Northwest's Cascades are anticipated to have a climate similar to China's Fujian Province or Southern Brazil's Parana and Santa Catarina. As all analogs for the projected US Pacific Northwest climate area are far away, it is uncertain what species will migrate to fill the ecological niches created by a changing climate.

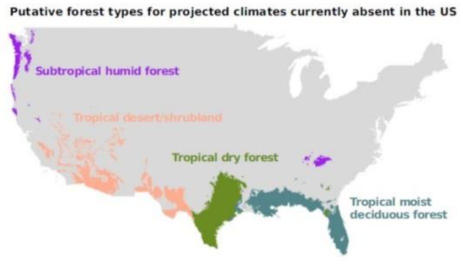


Fig. 4 Putative forest types for which projected future climatic conditions are outside the TDM range in the United States (areas in purple in d and f) using RCP 8.5 as a forcing scenario.

- **Background**: Understanding and predicting how forest distributions will respond to ongoing and anticipated climate change is a challenge with great ecological, economic, and cultural implications (Levin, 1999).

- **Background**: Current efforts to predict future distribution of forested ecosystems as a function of climate include species distribution models (for fine-scale predictions) and potential vegetation climate envelope models (for coarse-grained, large-scale predictions).

Morelli et al. 2016

- **Study**: Our goals are to: (1) build on recent literature to elaborate the value of climate change refugia as a short- to medium-term management strategy; (2) aid identification of climate change refugia by describing the processes that create them; and (3) introduce a framework for operationalizing the concept of refugia for climate adaptation.
- **Study**: We briefly review the theoretical framework for refugia, based in the Quaternary literature but with application to conservation (also see [7, 8, 9]).
- **Study**: We delineate seven steps for managing refugia (Fig 3, Table 1).
- **Study**: We have outlined the opportunities and challenges for effective implementation of the climate change refugia concept.
- **Background**: Climate Change Refugia (definition): areas relatively buffered from contemporary climate change over time that enable persistence of valued physical, ecological, and socio-cultural resources.
- **Background**: Climate change refugia are at least large enough to sustain a manageable unit of the focal resource, such as a small population or metapopulation [7], rather than smaller, transient micro-environmental “refuges” from exposure and disturbance [9, 18].
- **Background**: A focus on areas resistant to ongoing climate change is increasingly suggested as a potential conservation strategy [4], yet lack of clarity on how to identify and manage these “climate change refugia” hampers practitioners [5].
- **Background**: Populations persisted and survived during the last glacial maximum in habitats where climate change was buffered or compensated, and in regions where suitable climates were displaced toward the equator or to lower elevations relative to their postglacial distribution.
- **Background**: Not only did refugia provide a safe haven during periods of unfavorable climate, but they served as sources for colonization following climate warming [10].
- **Background**: Physically-based definitions of climate refugia emphasize the mechanisms that enable an area to remain buffered from regional influences and usually do not attempt to link refugia to particular ecological components, such as species or habitats [7].
- **Background**: Climate change refugia are characterized by the occurrence of relatively stable local climatic conditions that persist over time, despite change at regional and global scales [22].
- **Background**: strong microclimatic gradients allow for short distance dispersal and movements to compensate for climate changes and thus can act as climate change refugia.
- **Background**: Managing climate change refugia for local persistence of valued resources gains time for systems to adapt and for managers and society to develop longer-term solutions [2].
- **Finding**: Physical characteristics that tend to result in climate refugia:
    - Topographically complex terrain creates varied microclimates and increases the likelihood that current climates will continue to exist nearby
    - Deep snow drifts provide insulation to the surface below and provide water later in the season
    - Valleys that harbor cold air pools and inversions can decouple local climatic conditions from regional circulation patterns
    - Canopy cover can buffer local temperatures maximums and minimums throughout the year
    - Areas near or in large deep lakes or oceans will warm more slowly due to the high heat capacity of water

    - Cold groundwater inputs produce local cold-water refuges in which stream temperature is decoupled from air temperature
    - Poleward-facing slopes and aspects result in shaded areas that buffer solar heating, particularly during the low solar angles of winter and early spring
- **Finding**: Characteristic examples are cold-air pools (CAPs [28]), where temperature inversions are created by concentrated air in valleys and other topographic depressions that is cooler and moister than surrounding uplands. Although most common under clear night skies, still air, and low temperatures, CAPs can become a semi-permanent feature in topographically sheltered areas.
- **Finding**: Persistent seasonal features, such as inland penetration of coastal fog and low stratus clouds caused by offshore upwelling, can also produce large climatic response gradients over short distances [29].
- **Finding**: Wet areas, including wetlands, riparian zones, rock glaciers, and talus slopes (see American pika case study in Fig 2), can act as climate change refugia [30]. In semi-arid and desert regions, groundwater-fed seeps and springs support persistent populations of highly diverse taxa [31].
- **Finding**: Pole-facing slopes generally experience slower hydrologic change [32]. Similarly, deep snow drifts, which can be found in downwind topographic depressions, in granite fissures, or at the base of steep slopes, can serve as important hydrologic reserves. Furthermore, large bodies of water and their surroundings, like coastal areas or deep lakes, are buffered from regional warming because more of the sun’s energy is expended in evaporation than in surface heating [7, 33].
- **Finding**: Streams and rivers that are buffered from regional air temperatures via cold groundwater inputs from deep aquifers provide cold, sustained streamflows in regions where water temperatures would otherwise become too warm or streamflows too low during the summer months [37]. Such large, cold, connected river networks are recognized as regional strongholds for imperiled fish populations facing increasing pressures from climate warming and other stressors [38].
- **Finding**: forest canopies and riparian corridors buffer against climate extremes and variability [44] with consequences for both temperature and water balance.
- **Finding**: Habitat variability (e.g., variable stand densities, forest gaps, evergreen/deciduous mosaics, riparian corridors) can also increase spatial variability in climate, creating shade and allowing for short-distance dispersal and movements to compensate for climate changes.
- **Finding**: Areas that are protected from climate-related disturbance, such as increasingly severe fires and extreme floods, also can be considered climate change refugia [45, 46].
- **Finding**: Ecosystem engineers such as beaver and termites that alter water movement and storage and influence the structure and function of heat exchange processes [47] could also contribute to processes creating and maintaining climate change refugia for other species. For example, deep persistent pools created by beavers buffer aquatic species like trout from extreme drought and effects of wildfire [48].
- **Finding**: Climate change refugia might only be relevant for a certain degree of climatic change, after which conditions in refugia might become climatically stressful for the populations they were designed to protect [29]. Thus, climate change refugia are not necessarily long-term solutions [76]. They function best when coupled with contingency plans, such as tracking geographic shifts in refugial habitats to keep pace with climate change or maintaining genetic material in seed banks, captive propagation, or zoos for future re-introduction.

- **Finding**: Challenges also include questions about the scale at which climate change refugia should be identified and managed, uncertainty about the duration of their effectiveness, and confusion over how to incorporate multiple species or other resources that will respond to climate change in different ways.
- **Finding**: we suggest that climate change refugia will not be appropriate for conserving all resources. Species already limited to extreme environments, such as alpine species restricted to mountain summits, might not be candidates for management with refugia. On the other hand, some species with extensive home ranges could benefit from climate change refugia; the wide-ranging wolverine (Gulo gulo), for example, requires minimum levels of snowpack for den sites that could potentially be managed [65].
- **Management**: Recommendations for managing climate change refugia:
    - Step 1: the first step of managing climate change refugia is to determine the purpose and scope (Table 1, step 1) by defining the management or conservation target ("valued resource"). The relevant spatial scale can be global, regional, or local
    - Step 2: Assessing vulnerability of the resource to climate change is the next step (Table 1, step 2). Vulnerability assessment considers the sensitivity of a resource and measures its exposure to particular aspects of, as well its adaptive capacity to adjust to, climate change [1, 52].
    - Step 3: Following the vulnerability assessment, management or conservation goals should be reevaluated to ensure they remain attainable [3], including whether refugia management is an effective strategy (Table 1, Step 3). Climate change refugia will be most relevant to resources that are moderately to highly vulnerable to climate change on a regional scale, but for which spatial variability in vulnerability factors suggest local buffering of climate change impacts.
    - Step 4: Where extensive climate and resource data are lacking, first approximations of refugia can be identified based upon the physical and biotic processes that buffer climate change (Fig 1). For example, Ashcroft and colleagues [22] used climatically stable regions within a topographically diverse landscape to predict regions associated with refugial communities.
        - Other methods recognize climate change refugia based on biological data. Past persistence through climate change might be a clue to locations buffered in the future, either for native species or those that will shift into the area [33]. For example, disjunct populations of cool-temperate plant species (e.g., Tsuga canadensis) are scattered across Ohio, Indiana, Illinois, and Kentucky, apparent relicts of northward postglacial migrations in the late-glacial or early Holocene. The populations are concentrated in unique microhabitats, usually north-facing slopes and shaded ravines.
        - Similarly, relict populations at the rear or trailing edge of a species' range might indicate climate change refugia [59].
        - One can also identify areas of high genetic diversity or persistence for climate vulnerable species or other resources, which might indicate places where populations have persisted owing to climatic stability or high topographic variability.
        - Multiple lines of evidence from combining different approaches can be used to increase confidence in the identification of climate change refugia [63, 64, 69].
        - An essential though rarely accomplished step to use independent data to validate potential climate change refugia by testing predictions for specific taxa

    or ecological characteristics. The key is to evaluate, as fully as possible, whether a refugial location really meets the needs of the valued resource.

- Step 5: The next step is to prioritize climate change refugia for management. In addition to connectivity, capacity, and size [4, 8, 23, 51, 70], other criteria will be important for prioritization, including representation of valued resources, potential for protecting multiple resources within refugia now and into the future, existing and expected land use change [71], and practical considerations such as the feasibility of management actions and public perspectives.
- Step 6: Once locations are prioritized, management options can be identified (Table 1, step 6). Current suites of management tools and actions will need to be analyzed on a case-by-case basis with the best information of future climate and ecological settings to evaluate long-term benefit.
    - protecting, maintaining, and fostering the features and processes of climate buffering identified in the previous steps could include reducing direct and indirect stressors. For example, removing recreation trails through wet meadows to redirect visitor use improves hydrologic function, increases resilience, and could ultimately protect federally listed wetland species.
    - Active fire and fuel management could be prioritized to protect climate change refugia from, or enhance resilience to, extreme fires that otherwise might damage the ecosystem irreversibly.
    - Similarly, managing groundwater by limiting withdrawals and setting minimum ecological flows is relevant for common conservation practice, but storage, pumping, and other active manipulations may become more important options, despite their associated risks.
    - Unprotected lands identified as climate change refugia could be the focus of acquisitions or easements. If publicly owned, a new area selected for protection specifically for its resistance to climate change could be designated as a climate change refugium via enabling legislation or by another legal or regulatory instrument, or as a “climate change refugia emphasis area” in management plans.
- Step 7: Given the inherent uncertainty in ways that climate change will affect physical resources, habitats, species interactions, and ecosystem functions, adaptively monitoring the effectiveness of identified refugia and realigning locations and management practices accordingly are critical to the climate change refugia conservation cycle (Table 1, step 7). Millar and colleagues [72] recommended flexible approaches that promote reversible and incremental steps and encouraged ongoing learning and modification.
    - Depending on the situation, management actions could focus on improving resistance of refugia (e.g., habitat restoration; [30]) or strategies for assisted migration of prioritized species. Monitoring could also ensure that actions taken, such as prescribed burns and increased connectivity, are not increasing the presence of invasive species.

Mote et al. 2003.

- **Study**: This paper examines the influence of past climatic variability and likely future climatic change (20-50 year time scenarios) on three key climate-sensitive resources in the Pacific Northwest (PNW), namely, water, salmon, and forests. Undergirding the work is a retrospective analysis of connections between climatic variations and each resource.
- **Climate Change Impacts:** Warmer, drier years, often associated with El Niño events and/or the warm phase of the Pacific Decadal Oscillation, tend to be associated with below-average snowpack, streamflow, and flood risk, below-average salmon survival, below-average forest growth, and above-average risk of forest fire.
- **Climate Change Impacts**: During the 20th century, the PNW experienced a warming of 0.8 ◦C.
  - Using output from eight climate models, we project a further warming of 0.5–2.5 ◦C (central estimate 1.5 ◦C) by the 2020s, 1.5–3.2 ◦C (2.3◦C) by the 2040s, and an increase in precipitation except in summer. The foremost impact of a warming climate will be the reduction of regional snowpack, which presently supplies water for ecosystems and human uses during the dry summers.
- **Governance**: a warming at the rate projected would pose significant challenges to the management of natural resources.
- **Climate Change Impacts:** For water resources, all climate scenarios lead (with high confidence) to the large-scale loss of snowpack at moderate elevations by mid-century, bringing large reductions in summer flow in all streams and rivers that depend on snowmelt.
- **Climate Change Impacts**: For forests, the first-order effects of reduced snowpack will enhance establishment and growth at high elevations and increase drought stress at lower elevations, but the effects will depend strongly on the site and moisture conditions of specific stands, and are subject to two important uncertainties: the magnitude and consequences of CO2-induced increases in water-use efficiency, and the capacity for increased seasonal soil-moisture storage, which could allow increased winter rains to offset the increased drought stress from warmer summers.

Myer. 2013.

- **Study**: It is our hope that the science and recommendations put together by the Climate Action Planning team and partners will lead to an all lands approach to forest management to increase resilience to climate change in the Rogue River Basin.
- **Study**: This planning process included an assessment of the risks and opportunities related to the economy, forest, and water of the Rogue Basin. A variety of stakeholders and experts provided their input. After gathering data and information to assess the past, current, and projected future conditions of the Rogue Basin, a list of risks and stressors was created. From that list, relative risk values were assigned to the emergent risks (high, medium, low), as well as priority values and the capacity to respond. From that exercise, goals, objectives, and specific, on-the-ground strategies were developed. This plan calls for identifying restoration need, management that plans for projected changes in the climate, and economic opportunity. It gives equal weighting on economic, ecological and social goals for forest management consistent with the Productive Harmony Guidelines of the Southern Oregon Forest Restoration Collaborative. The plan explicitly integrates climate change projections, habitat protection, riparian and forest restoration, fire safety, ecosystem services, and economic activity.

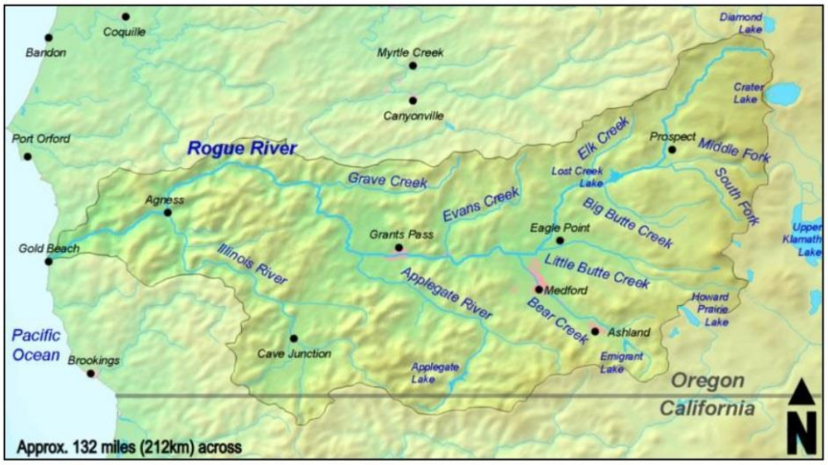


Figure 3. Map of the Rogue Basin. *Source: Map taken from the Demis Map Server [http://www2.demis.nl/mapserver/mapper.asp] and modified by Little Mountain 5, Wikipedia commons, 2013.*

- **Findings**: The key risks identified include
    - uncharacteristic impacts of severe wildfire to forest ecosystems;
    - declines in water quantity and quality;
    - risks to the various values (ecosystem services) people receive from the forests.
- **Findings**: Key solutions and opportunities identified are:
    - an opportunity to utilize SOFRC's integrated forest restoration approach and incorporate ecosystem services in multi-party collaborative processes to move projects forward while meeting objectives of federal agencies;
    - the opportunity to restore natural forest structure, function, and fire regimes;
    - an opportunity to provide alternative management recommendations, supported by a variety of partners, that could increase resiliency and resistance to the impacts of climate change while providing economic benefits and a potential solution to the current land management issues present in the Rogue Basin.
- **Findings**: Broad goals include:

  - Manage risk and reduce uncharacteristic impacts of wildfire
  - Ensure the highest possible water quantity and quality
  - Use an ecosystem services approach to incorporate values into planning outcomes and provide economic rationale for restoration/resilience focused management
- **Finding**: The Southern Oregon Forest Restoration Collaborative and partners have been working to develop a common sense strategy and analytical framework to identify forest restoration need and opportunity in the Rogue Basin. Broad goals for the strategy include:
  - restore a diverse mosaic of healthy, resilient forests;
  - conserve habitat with special attention to species and risk;
  - support regional forest products and associated workforce capacity (SOFRC, 2013).
- **Climate Change Impacts**: Key climate impacts in the Rogue Basin include
  - increase in severity and frequency of wildfires;
  - decreased snowpack and earlier snowmelt affecting water quality and quantity for humans and wildlife;
  - increase severity in droughts and flooding;
  - higher elevation transition from snow to rain;
  - increasing stream temperatures which are already a large issue in the Basin;
  - biogeographic shifts in species' ranges.
  - Average temperatures are expected to rise in the Rogue Basin between 2.3 and 4.5^{o}C (4.3 and 8.2^{o}F) by 2075-2085 (USFS MAPSS data), even if efforts are taken to mitigate climate change.
- **Climate Change Impacts**
  - Snowfall
    - Rising temperatures will likely cause precipitation to fall as rain at lower elevations rather than as snow on peaks so average January snowpack will decrease; by 2035 – 2045 snowpack may be reduced 60 – 65% and by 2075 – 2085 as much as 90%. This will likely reduce run-off during late summer / fall and substantially reduce available irrigation and drinking water.
  - Severe weather
    - Weather variability is likely to increase as both wet and dry cycles are likely to increase in length and severity. Many more days are likely to exceed 900F and 1000F while more heavy rainfall days are likely. More precipitation falling as rain at low elevations rather than snow at high elevations is likely to increased flash flood frequency in Winter and Spring.
  - Wildfires
    - Longer droughts and higher temperatures with more intense heat waves will likely increase substantially the amount of (vegetation) forest lost to wildfire.
  - Vegetation

        - With warming and drying, climatic conditions will likely become more appropriate for deciduous forest communities such as oaks and other hardwoods while conditions for higher elevation spruce/fir/hemlock communities will be severely compromised and those for Douglas-fir will likely be reduced in area. Grassland and scrubland conditions are likely to expand as forest conditions diminish.
    - Native aquatic systems
        - With increases in storms and fires, enhanced soil erosion will likely cause greater stream sediment and mineral build-up. Increased summer air temperatures will elevate water temperatures reducing critical dissolved oxygen concentrations and potentially enhancing bacterial and disease conditions. Reduced snowpack and earlier snowmelt will likely modify current stream flow patterns. With warmer water temperatures earlier aquatic insect emergence is probable, compromising historic food availability pulses for migratory fish. Reduction in conditions for many native fish species may be accompanied by range expansion of non-native species.
    - Native terrestrial systems
        - Probable increase in wildfires and lengthened fire seasons may induce dramatic shifts in vegetation communities towards more fire-adapted associations. Both invasive and non-native species abundances may be enhanced as natives are reduced. Particularly at risk are mature forests and the wildlife species they support as well as amphibians which will have limited dispersal capacity conditions become dryer. Disruption of synchronicity is likely between insect development and nesting / hatching particularly of migrant bird species. Bark beetle conditions will be enhanced, increasing the threat to native forests.
- **Climate Change Impacts**: Additionally, several studies indicate that climate change is likely to exacerbate forest damages resulting from disease and pests such as the mountain pine beetle.
    - Mountain pine beetle populations are typically held in check by cold winters (EcoNorthwest, 2009). As the frequency of cold winters decreases, the mountain pine beetle's population will no longer be constrained. This could lead to rapid and widespread tree mortality. Furthermore, the mountain pine beetle is now beginning to show a potential to jump to non-pine species if pine is no longer available (EcoNorthwest, 2009). Mountain pine beetles potentially could impact the majority of remaining forest in Oregon. Adding to the problem, stressed trees increase the concentration of amino acids in their tissues, making them more nutritious for herbivorous insects (that are generally nitrogen limited) (Hsiao, 1973). Stress from insects and pathogens coupled with other local stressors such as increased temperatures and decreased soil moisture, will hasten tree mortality.

- **Climate Change Impacts**: Potential ecological implications of these hydrological changes, especially in conjunction with increases in air temperature, earlier snowmelt, and changes in precipitation, could result in shifts in native fish assemblages.
- **Climate Change Impacts**: One of the greatest current and future risks to the water system is stream temperatures. All of the sub basins of the Rogue Basin are over the recommended stream temperatures by ODEQ, and these are projected to increase further in stream temperature.
- **Climate Change Impacts**: Southwestern Oregon is one of the key regions where fire frequency is expected to increase with climate change (Westerling et al. 2006). There has been a six-fold spike in the area of forest burned since 1986 in the Pacific Northwest as compared with the 1970-1986 period (CIER 2007). One can see a notable shift to larger fires in terms of acres burned starting around 1985, with the fires of 2013 (Figure 23) bringing a record number of acres burned for the region in the past 50 years. Forests are expected to continue to have large impacts from increased incidence of fire (CIER 2007). Duration of fires has also increased from 7.5 to 37.1 days since 1986 (CIER 2007). This affects forest, water quality for human use, human health, soil quality, forest productivity, and habitat for a variety of species.
- **Climate Change Impacts**: A primary effect of climatic change in water-limited environments, such as the dry forests of Southwest Oregon, is to exacerbate drought stress.
- **Background**: Collaboration on forest restoration has been critically important in building shared understanding and community support for management to address current conditions, and promote forest health and resilience in southwest Oregon. On-the-ground projects including the Medford District Secretarial Pilot Project and Ashland Forest Resiliency Project have helped to advance stakeholder understanding and support.
- **Background**: The Rogue Basin of southwestern Oregon occupies part of the Klamath Province identified in the Northwest Forest Plan. The basin drains water from both the Klamath Mountains (Siskiyous) and the Cascade Mountains and forms a regional confluence of Western US floristic provinces as well. The variety of inland forests here follow complex environmental gradients reflecting hot dry summers and cool moist winters contributing to historically very frequent fire and fire-adapted vegetation.
- **Background**: Fire suppression, widespread even-aged stand management, land use, and other stressors have dramatically reduced and degraded critical wildlife habitat and generated dense overcrowded stands, leading to tree stress and low vigor, and placing the oldest most structurally important trees at risk of uncharacteristic wildfire. Younger stands are threatened by density driven wildfire risk, and moisture competition; without active management their development into mature stands dominated by large trees is slowed. Forest diversity, a hallmark of the region, has been reduced at both the landscape and stand scale.
- **Background**: Nearly 300,000 people live in the Rogue Basin. The area is highly valued for its scenic attractions and cultural significance. Many enjoy recreational uses, such as fishing, rafting, hiking, Off Highway Vehicle trails, wine tasting, hunting, camping, parks,

scenic byways, horseback riding, boating, and nature viewing. The Rogue Basin provides clean drinking water, critical wildlife habitat, wood products, and non-timber forest products; it's also a large pear exporter, and is one of the most biologically diverse regions in North America. The Rogue River was named one of the original eight rivers in the Wild and Scenic Rivers Act of 1968 (National Wild and Scenic Rivers System). There are more than 4,000 miles of fish-bearing tributary streams found throughout the Rogue Basin. The Klamath-Siskiyou temperate coniferous forests are among the four most diverse of its kind in the world (World Wildlife Fund, 2008). The ecosystem services provided by the Rogue Basin are integral to the survival of the local culture and economy.

- **Background**: The Rogue Basin is comprised of 5 sub basins that drain to the Pacific Ocean (Figure 3): the Lower Rogue River, Middle Rogue River, Upper Rogue River, Illinois, and Applegate.
- **Background**: This report has a good overview of the physics of climate change. See report for details, page 9.
- **Background**: Streams in the Rogue Basin provide habitat for many cold-water species including Coho salmon, spring Chinook salmon, fall Chinook salmon, summer and winter steelhead, many species of trout, amphibians, and other fish such as the Pacific lamprey, green sturgeon, white sturgeon, Klamath smallscale sucker, speckled dace, prickly sculpin, and others (ODEQ 2012).
- **Background**: the city of Medford undertook a cost-benefit analysis on different methods to cooling the Rogue River due to their non-compliance of effluent water temperatures. They discovered that restoring riparian areas along the Rogue Basin would cost nearly half the amount of other methods of cooling water temperatures, and would have the highest benefits. They are using a water quality trading program with The Freshwater Trust (and ODEQ's approval) to conduct restoration work and mitigate the temperature impacts. The goal of the trading program is to plant almost 30 miles of riparian shade in the Rogue Basin over the next 20 years to obtain 400 million kilocalories of thermal credit in late fall (DEQ Approves Medford's Thermal Trading Program, 2011).
- **Ecological Considerations**: The American Pika lives in the Western U.S., including Oregon, in cold areas near mountain tops. Due to the warming temperatures snowfall is declining in higher elevations, causing the Pika to die off below elevations of 7,000 ft. (Figure 24). More than one third of their population has already disappeared.
- **Ecological Considerations**: Interestingly, serpentine soils of the Siskiyou Mountains have hosted unusual and diverse vegetation for millennia and this vegetation has not been responsive to changing climate (Briles et al. 2011). However, the relative stability of this vegetation could be due to dispersal limitations, suggesting a possible vulnerability in the face of anthropogenically driven climate change (e.g. Olson et al. 2012). In-fact, dramatic changes in endemic serpentine herb communities since 1960 suggest this may be the case (Damschen et al. 2010).
- **Ecological Considerations**: Projections show significant declines in conditions for maritime evergreens, and two models show an increase in conditions for maritime needleleaf and temperate deciduous broadleafs (Figure 25). The dimensions of the

changes that projections suggest might occur have the potential of devastating effects on many terrestrial communities.

  - In particular by late century, it is possible that: high elevation spruce/fir/hemlock associations will be eliminated, Douglas-fir associations will be reduced, ponderosa pine associations will expand, Oak-chapparral association will expand, and shrubland/grassland will expand. As species shift, the structure and function of the ecosystems in the Rogue Basin will be impacted.
- Ecological Considerations: Analyses of the impact of climate projections on the forests of southern Oregon (e.g. Doppelt et al. 2008) indicate that the Douglas-fir association is likely to diminish but that the ponderosa pine and oak chaparral associations are likely to expand. By way of contrast, the climate envelope analyses of Rehfeldt et al. (2006) that identify where future conditions are likely to be suitable for the success of western tree species indicate that both the Douglas-fir and ponderosa pine are at risk.
- Ecological Considerations: Ecologically speaking, forest density, species conversion to shade tolerant trees, degraded aquatic habitat, and increased fuel loads are the primary stressors on forested lands. Primary solutions are landscape planning, forest density reductions, and the reintroduction of large-scale fire (both prescribed and from natural ignitions).
- Ecological Considerations: As temperatures increase, salmon populations will be at greater risk of thermal stress from warm water temperatures (Heyn 2008; Mantua 2010). High water temperatures can limit distribution, migration, health, and performance of salmonids (Mantua 2010). Projected temperatures in the Pacific Northwest suggest a decrease in habitat for cold water aquatic species.
  - In the Rogue Basin salmon runs are relatively strong, but it must be protected and resilient to climate change for these runs to be able continue.
- Ecological Considerations: Invasive species, also a large concern in the Rogue Basin with Himalayan Blackberry overrunning several riparian areas, are also likely to increase as native vegetation is stressed by changes in precipitation and temperatures.
- Ecological Considerations: Additionally, over 137 species depend on salmon directly for survival. Salmon are a keystone species and an indicator species: if salmon disappear, there will be a domino effect, threatening the ecological and economic vitality of the region. Salmon are even important to the health of forests. Their decomposing bodies provide nutrients important for tree growth. When salmon are abundant, trees grow up to three times as fast as when salmon are scarce (Helfield, 2001 and Reimchen, 2003). Salmon are also important for providing streams and lakes with carbon, nitrogen, phosphorus, and micronutrients (Helfield, 2001 and Reimchen, 2003).
- Management: A critical strategy is to restore fire's role in maintaining resilient, healthy forest ecosystems capable of adapting to environmental disturbances.
  - This will involve thinning the forest in identified priority areas, promoting shade-intolerant species and returning spatial heterogeneity through gap creation, and appropriate fire use.
- Management: A second strategy is to identify those forest communities most at-risk, buffer them from the more direct impacts of climate change (i.e., severe fire), and

ensure that corridors are open for species migration and community adaptation to future climate.

- **Management**: A third strategy is to prioritize riparian restoration efforts to enhance water quality and quantity.
- **Management**: Uncertainty underlines the need for caution in forest management and the need for an adaptive management framework for management to maintain forest health in the face of climate change (Lawler et al. 2010).
- **Management**: Primary strategies to adapt forests to future threats include reducing competition and promoting drought and fire tolerant species (Millar et al 2007; Joyce et al. 2009; Allen et al. 2010, Lawler et al. 2010, Spies et al. 2010, Peterson et al. 2011, Franklin and Johnson 2012). Specifically that means reducing numbers of shade tolerant tree species (e.g. white fir) and regenerating tree species like ponderosa pine that are shade intolerant but resistant to drought and fire (North et al. 2012).
- **Management**: Since major fire events can devastate forests and release vast amounts of carbon, managing our forests to reduce the likelihood of such events constitutes a sound policy in support of carbon sequestration, particularly when such activities are conducted conservatively, in an adaptive management framework (Millar et al. 2007, Lawler et al 2010, Spies et al. 2010, Peterson et al. 2011) and scaled to historical and likely future fire return intervals (Hurteau & Brooks 2011).
- **Management**: Our greatest challenge is our capacity to effectively create change that will minimize the negative impacts and risk of landscape-scale, stand-replacing fires.
- **Management**: Beechie at al. (2012) conducted a literature review to determine strategies most likely to ameliorate stream flow and temperature changes and increase habitat for salmon. They determined the most effective measures to be: restoring floodplain connectivity, restoring stream flow regimes, and restoring channels. The restoration of stream complexity and connectivity will improve salmon spawning habitat and allow for aquatic animal movement to new areas if needed, and the restoration of riparian corridors will provide a safe migratory route for land animals as well (Beechie et al. 2012).
    - Restoration should include identifying and protecting thermal refugia provided by ground-water and tributary inflows,
    - improving or decommissioning roads to reduce temperature impacts and soil erosion,
    - restoring vegetation in riparian zones that provide shade and complex habitat (Mantua 2010).
    - Zoning ordinances to discourage development and/or agriculture within (and immediately adjacent to) riparian areas should also be developed and incorporated into local land use planning.
- **Management**: Reducing out-of-stream withdrawals during periods of low streamflow and high temperature can help mitigate stream temperature increases (Mantua 2010).
- **Management**: Restoration and maintenance of riparian corridors, stream complexity and connectivity to floodplains can address many of the stressors both present and projected in the Rogue Basin. Planting native shade trees and restoring riparian buffers

help to protect against higher water temperatures, filter pollutants from entering the stream, increase aquifer storage capacity, reduce erosion, increase stream bank stability, mitigate storm flows and nutrient loading downstream, restore natural floodplains for both flood and drought mitigation, and can reduce risks to salmon habitat by providing refuge from high flow events.

Noss. 2001.

- **Study**: I review properties of forest ecosystems and management options for enhancing the resistance and resilience of forests to climate change.
- **Study**: In particular, I ask what inherent properties of forest ecosystems and what kinds of management are likely to enhance the resistance and resilience of forests.
- **Background**: Although forests, as a class, have proved resilient to past changes in climate, today's fragmented and degraded forests are more vulnerable.
- **Background**: Adaptation of species to climate change can occur through phenotypic plasticity, evolution, or migration to suitable sites, with the latter probably the most common response in the past.
- **Background**: Climate change is a major threat to biodiversity over the coming century (Peters & Lovejoy 1992). Therefore, efforts to lessen global warming by reducing emissions of CO2 and other greenhouse gases or by increasing uptake of carbon by vegetation are of great interest to conservationists.
- **Background**: Although the present rate of warming is higher than previous rates over the last 10,000 years, forests apparently have weathered even faster changes in the past, albeit the most rapid changes were associated with mass extinctions (Graham 1999).
- **Background**: If climate change were the only factor menacing forests today, and if the landscape were still pristine, there arguably would be little cause for worry. The fossil record shows numerous examples of species migrating and persisting through past changes. By and large, climatic change may have been as great a force for speciation as for extinction (Sepkoski 1998; Hewitt 2000). Even with the rapidity of change predicted for the next few decades, in the absence of other threats most species could be expected to adjust to these changes as they have in the past.
- **Background**: Today, however, climate change is being played out on a very different court—one in which direct destruction, fragmentation, and degradation of ecosystems by humans, accompanied by vast invasions of alien species, are proceeding at a breakneck pace worldwide. It is in combination with these threats that global warming becomes so insidious (Peters & Darling 1985; Dudley 1998; Sala et al. 2000).
- **Background**: The Intergovernmental Panel on Climate Change (IPCC 1996) concluded that forests are highly sensitive to modern climate change. Although the details of expected change in forests on a regional scale are unclear, the scenarios of general circulation models (GCMs) predict major shifts in the area occupied by forest biomes (Neilson et al. 1994; Hadley Center for Climate Prediction and Research 1998). For example, globally, the area occupied by tropical and temperate forests is projected o expand by up to 20%, whereas boreal forests may decline by 50% (Krankina & Dixon 1993), if other causes of change are ignored.
- **Background**: Over an intermediate length of time, say thousands of years, the species in a given forest represent those that have evolved under a definable range of conditions, often called a "natural" or "historic" range of variability (Landres et al. 1999; Swetnam et al. 1999). Many ecologists consider this range the appropriate set of "reference

conditions" for comparison with human-altered conditions and as a guide to management (Stephenson 1999).

- **Background**: Changes that occur at a faster rate, greater intensity, different pattern, or broader spatial scale than historically are likely to fall outside the limits of adaptability for some species.
- **Background**: The challenge for conservationists is not to prevent change. It is to keep rates, scales, and intensities of change in ecosystems within the historic range of variability for those systems—or, at least, to come close. Conservationists must also develop strategies to mitigate the effects of inevitable changes that fall outside the historic range of variability.
- **Background**: Stability has been defined in many ways, representing three general concepts: (1) the ability to maintain a relatively constant state in the face of disturbance and stress; (2) the ability to recover quickly after a disturbance; and (3) a combination of these two abilities. The first concept is often referred to as resistance. The second concept is usually referred to as resilience (Pimm 1984, 1991), although other meanings of resilience can
- **Background**: Whitford et al. (1999) found that both the resistance and resilience of vegetation to drought are reduced in intensely stressed ecosystems (in this case, desert grasslands grazed by domestic livestock) compared with lightly stressed ecosystems.be found in the literature (Table 1).
- **Background**: What properties of a forest ecosystem contribute to resistance and resilience? Some studies have demonstrated increased tolerance to environmental extremes and greater temporal stability and recovery potential as species richness increases (McNaughton 1993; Tilman & Downing 1994; Tilman 1996, 1999). The most compelling explanation for how species richness enhances stability is the redundancy provided by multispecies membership in critical functional groups (Walker 1992, 1995; Peterson et al. 1998).
- **Background**: Diversity of functional groups, in addition to diversity of species within groups, appears to encourage ecological resistance.
- **Background**: A test of the effects of functional group richness on the invasibility of grasslands showed that invasion success was negatively related to functional group richness (Symstad 2000).
    - Three lessons emerge from these findings:
    - (1) a diversity of functional groups should be maintained;
    - (2) species richness and redundancy should be maintained within functional groups;
    - (3) keystone species must be identified and kept in ecologically optimal, not just minimally viable, populations.
- **Background**: Minimizing extinction during climate change requires that species be given opportunities to adapt. Adaptation of species to climate change can take place through phenotypic plasticity (acclimatization), adaptive evolution, or migration to suitable sites (Markham 1996; Bawa & Dayanandan 1998).

- **Background**: Migration appears to have been the primary way species responded to past climate changes. Few beetles, for example, showed morphological change over the Quaternary (Pleistocene and Holocene), whereas species shifted markedly in distribution over this period (Coope 1979).
- **Background**: Migration rates of trees recolonizing regions after glaciation have been estimated from paleoecological data as ranging from 50 m/year for American beech (Fagus grandifolia) (Davis 1983) to 2000 m/year for spruce (Picea sp.) (Dennis 1993). The slower rates are thought insufficient for response to the current pace of climate change, especially given dispersal barriers such as intensive agriculture and cities (Peters & Darling 1985).
  - Recently, however, paleontological evidence of rapid, long-distance migration of many tree species has arisen (Clark 1998; Clark et al. 1998), providing hope that at least some trees may be able to track a rapidly changing climate.
  - Haphazard, long-distance establishment events may explain the evidence of rapid migration (Clark et al. 1998). Incorporating such rare dispersal events into models is difficult, which is why empirical rates of plant migration are often substantially higher than modeled rates (Higgins & Richardson 1999).
- **Background**: Rapid range shifts in response to warming trends over the last few decades have been documented for a number of species of vertebrates and invertebrates (Wuethrich 2000).
  - For example, in a sample of 35 nonmigratory European butterflies, 63% have shifted their ranges to the north by 35–240 km during this century, whereas only 3% have shifted south (Parmesan et al. 1999).
  - Nevertheless, migration to track a rapidly changing climate may be difficult for species with poor dispersal abilities, such as small forest vertebrates and flightless invertebrates, especially in relatively homogeneous landscapes with few opportunities for short-distance moves into suitable microhabitats.
  - Barriers to movement may be formidable in fragmented landscapes (Noss & Csuti 1997).
- **Background**: Some species may adapt to climate change by in situ evolution. The modern Great Basin (U.S.) flora, for example, appears to consist of a mix of species that migrated northward from Pleistocene refugia in the southern portions of the region, and species that changed little in distribution during the Pleistocene and coped with climate change by genetic adaptation (Nowak et al. 1994).
- **Background**: Adaptive evolution ultimately depends on adequate levels of genetic variation within and among populations, although this variation can be expected to decline in response to the directional selection imposed by changing climate.
- **Background**: If educated to understand the multiple benefits of sustaining diverse, healthy, resilient forests, people will place value on protecting these forests.
- **Management**: Among the land-use and management practices likely to maintain forest biodiversity and ecological functions during climate change are
  - (1) representing forest types across environmental gradients in reserves;

    - Because we do not know precisely which forest types will be most sensitive, maintaining a full spectrum of types in protected areas will help assure
    - Ideally, reserves will span uninterrupted environmental gradients and allow dispersal of organisms to favorable micrositesthat some resistant and resilient types persist.
- (2) protecting climatic refugia at multiple scales;
    - It makes abundant sense to identify past climatic refugia wherever possible and protect these areas so that they can again function as refugia during present and future climate change (Eeley et al. 1999).
    - Climatic refugia at much smaller scales also can be important for maintaining species assemblages vastly different from those adapted to the dominant regional climate.
    - If climatic refugia at all spatial scales can be identified and protected, persisting populations may be able to recolonize the surrounding landscape when conditions favorable for their survival and reproduction return.
- (3) protecting primary forests;
    - Old-growth forests are predicted to possess considerable inertia in the face of climate change (Franklin et al. 1991). Mature trees can survive long periods of unfavorable climate, remaining “several centuries after climatic deterioration makes local conditions unsuitable for seedling establishment” (Brubaker 1986). This inertia could be a significant mechanism for ecological resistance.
    - In forest types where the dominant trees live for hundreds or thousands of years, stands protected from catastrophic disturbance might persist through a few centuries of unfavorable climate, to reproduce again when favorable conditions return.
    - Because the intensity and rate of change will be buffered in forest interiors, maintaining large patches of oldgrowth forest is a sensible strategy for maintaining biodiversity during rapid climate change.
- (4) avoiding fragmentation and providing connectivity, especially parallel to climatic gradients;
    - Fragmentation may threaten biodiversity during climate change through several mechanisms, most notably edge effects and isolation of habitat patches.
    - With progressive fragmentation of a landscape, the ratio of edge to interior habitat increases, until the inertia characteristic of mature forests is broken. Fragmented forests will likely demonstrate less resistance and resilience to climate
    - Another potentially serious impact of fragmentation is its likely effect on species migration. By increasing the isolation of habitats, fragmentation is expected to interfere with the ability of species to track shifting climatic conditions over space and time.change than intact forests.

        - Connectivity is the antithesis of fragmentation. Maintaining habitat linkages parallel to climatic gradients and minimizing artificial barriers is a prudent strategy under any climate- change scenario (Hobbs & Hopkins 1991; Noss1993).
        - Elevational corridors, which span a broader climatic gradient over a shorter distance, may better promote migration in mountainous terrain (Noss 1993; Bennett 1999).
        - In designing linkages, several considerations should be kept in mind:
            - (1) A full range of geological substrates and soil types should be included in linkages because some plant species are exacting in their requirements.
            - (2) Many species have mutualistic or other dependencies on other species, such that migration of assemblages of co-adapted species will be required (Bennett 1999).
            - (3) Because movement routes probably will vary among species, protecting broad linkages rather than narrow corridors is advised.
            - (4) As suggested by Collingham and Huntley (2000), a mixed strategy of corridors and small stepping-stone habitats is desirable to address the distinct dispersal characteristics of different species.
        - Roads are major agents of fragmentation (Noss & Cooperrider 1994; Baker & Knight 2000). In the context of climate change, roads pose two problems: they restrict the dispersal of less mobile species while they encourage
            - Closing unnecessary roads and providing wildlife crossings on roads with heavy traffic might mitigate some of these effects (Noss 1993; Clevenger & Waltho 2000).the dispersal of invasive exotics.
    - (5) providing buffer zones for adjustment of reserve boundaries;
        - With changing climate, buffer zones have the potential to provide for shifting populations as conditions inside reserves become unsuitable. For this strategy to work, buffer zones must be large. If incentives can be provided to managers outside reserves to manage their lands sensitively, species will have a better chance of shifting distributions in response to climate change than if land-use adjacent to reserves is intense.
    - (6) practicing low-intensity forestry and preventing conversion of natural forests to plantations;
        - Forestry that minimizes soil disturbance (hence reducing invasion of exotic pests, loss of carbon from soil, and potential loss of mycorrhizae; Perry 1994), size of canopy openings (Whitmore 1998), and removal of biomass will do more to promote the resistance and resilience of forests to climate change than intensive loggingAmaranthus 1998).
        - Rapid recovery of host plants after logging appears essential for maintaining obligate mycorrhizal fungi and other soil microbes. Herbicide

        treatments and other intensive “vegetation management” can destroy this linkage (Perry et al. 1990; Perry 1994;
        - Simplistic carbon accounting ignores the tremendous releases of carbon that occur when forests are disturbed by logging and related activities such as site preparation and vegetation management (Perry 1994; Schulze et al. 2000). It ignores the fate of woody debris and soil organic carbon during forest conversion (Cooper 1983; German Advisory Council on Global Change 1998). Typically, respiration from the decomposition of dead biomass in logged forests exceeds net primary production of the regrowth (Schulze et al. 2000).
        - From the standpoint of maintaining biodiversity during climate change, conversion of natural forests to plantations cannot be justified. Tree plantations around the world, especially exotic monocultures, have less biodiversity than natural forests in the same regions (Hunter 1990; Noss & Cooperrider 1994; Perry 1994). Plantations are often markedly less resistant to disturbances such as fire and more subject to pest outbreaks than natural forests (Schowalter 1989; Perry 1994).
    - (7) maintaining natural fire regimes;
        - How fire should be managed in response to climate change is a complex issue and the appropriate policy response is not straightforward.
        - A mixed strategy, in which managers let many natural fires burn, protect (to the extent possible) old growth from stand-replacing fires, and manage other stands by prescribed burning and understory thinning to reduce the risk of high-intensity fire, may be the optimal approach.
    - (8) maintaining diverse gene pools;
        - Reforestation, rather than relying on local seed sources (which under relatively stable climatic conditions would be an appropriate strategy), should incorporate individuals from a wide range of localities, but should emphasize sources at lower elevations or latitudes (Bawa & Dayanandan
    - (9) identifying and protecting functional groups and keystone species.
        - For many forests, one can only guess which species (e.g., top predators) might be of unusually high ecological importance. Efforts should be made to identify such species, functional groups, and processes for all forest types and other ecosystems; then, management must be aimed at maintaining these components in natural patterns of abundance and distribution.1998; Ravindranath & Sukumar 1998).
- Management: Good forest management in a time of rapidly changing climate differs little from good forest management under more static conditions, but there is increased emphasis on protecting climatic refugia and providing connectivity.
- Management: To protect forests from the harmful effects of climate change, we must first mitigate the proximate threats of habitat destruction, fragmentation, and degradation.

Noss et al. 2006.

- **Study**: We review the ecological science relevant to developing and implementing fire and fuel management policies for forests before, during, and after wildfires.
- **Study**: For this paper we evaluated the scientific literature that is relevant to conservation, restoration, and management of forests in the western US (excluding Alaska). Our review addresses ecological science relevant to developing and implementing fire and fuel management policies, including activities conducted before, during, and after wildfires. Our focus is primarily on wildlands, rather than the wildland-urban interface, where ecological values may be secondary to fire-risk mitigation to protect people and homes (DellaSala et al. 2004). In wildlands espe? cially, sustainable forest management must be based on well-grounded ecological principles.
- **Background**: The management of fire-prone forests is one of the most controversial natural resource issues in the US today, particularly in the west of the country. Although vegetation and wildlife in these forests are adapted to fire, the historical range of fire frequency and severity was huge. When fire regimes are altered by human activity, major effects on biodiversity and ecosystem function are unavoidable.
- **Background**: Key structural elements of western forests (eg old "veteran" trees), terrestrial and aquatic biodiversity, and habitats of many threatened and endangered species are already greatly diminished and at continuing risk of loss.
- **Background**: Increased human habitation of wildlands has intensified problems of managing fire, especially at the wildland- urban interface (Dombeck et al. 2004).
- **Background**: Fire provides fundamental services, including recycling nutrients, regulating the density and composition of young trees, creating and shaping wildlife and fish habitat, structuring the spatial pattern of landscapes, and influencing water and sediment delivery across watersheds. Many plant and animal species are adapted to postfire conditions, and populations of some (eg many bird species; Figure 1) decline after fire exclusion or post-fire logging (Hutto 1995). Different species benefit from different fire severities and intervals between fires.
- **Background**: Fires recur in western forests from once a decade or less in some dry ponderosa pine (Pinus ponderosa) forests to a cycle of 250-400 years or more in coastal forests (Hemstrom and Franklin 1982; Covington et al. 1997; Agee 1998).
- **Background**: High severity fires kill most or all trees in substantial portions of the burn, although fire pattern is often a mosaic that includes areas of unburned or less severely burned forest (Figure 2).
- **Background**: Many large, high severity fires are associated with infrequent, severe droughts (Westerling et al 2003), often related to broad-scale climatic anomalies (Gedalof et al 2005). Fire exclusion has had minimal effect on most forests characterized by high severity fire - a fact that is especially relevant to fire policy.
- **Background**: Human activities in western forests following European settlement - including fire exclusion, grazing, logging, and tree planting - dramatically modified the fuel structure in these forests.

  - Grazing reduced the fine fuels that carry surface fires and facilitated dense tree reproduction by reducing or eliminating herbaceous competition (Rummell 1951; Savage and Swetnam 1990; Belsky and Blumenthal 1997).
  - Logging also promoted higher stand densities in many dry ponderosa pine forests by stimulating dense natural regeneration (Agee 1993; Kaufmann et al. 2000).
  - These forests therefore changed from relatively open stands with low fuel loadings to dense stands that can carry crown fires (Skinner 1995).
- **Background**: Topographically complex mountain landscapes may be especially prone to mixed severity fire, because drier, south-facing slopes with lower fuel loads may burn at low severity while adjacent, moister, northfacing slopes that support higher tree densities experience high severity fire (Taylor and Skinner 2003; Spies et al. 2006) or escape fire due to wetter conditions.
- **Background**: Overall species diversity, measured as number of species - at least of higher plants and vertebrates - is often highest following a natural standrenlacement disturbance and before redevelopment of closed-canopy forest (Lindenmayer and Franklin 2002).
- **Background**: Currently, early-successional forests (naturally disturbed areas with a full array of legacies, ie not subject to post-fire logging) and forests experiencing nat? ural regeneration (ie not seeded or planted), are among the most scarce habitat conditions in many regions
- **Background**: True ecological restoration requires the maintenance of ecological processes, native species composition, and forest structure at both stand and landscape scales.
- **Finding**: Fire exclusion led to major deviations from historical variability in many dry, low-elevation forests, but not in other forests, such as those characterized by high severity fires recurring at intervals longer than the period of active fire exclusion.
- **Finding**: The complexity created by variability in fire regimes defies a one-size-fits-all management prescription
- **Finding**: Restoration is warranted where fire exclusion has led to substantial alterations in ecosystem qualities
- **Finding**: Restoration and management of fire-prone forests should be precautionary, allow or mimic natural fire regimes as much as possible, and generally avoid intensive practices such as post-fire logging and planting.
- **Finding**: Post-fire logging usually has no ecological benefits and many negative impacts; the same is often true for post-fire seeding.
- **Finding**: The inherent variability of mixed-severity fire regimes precludes easy analysis of fire-exclusion effects, because high tree density or an abundance of shade-tolerant trees is not necessarily the result of fire exclusion. The complexity created by variability in fire regimes defies a simple, one-size-fits-all prescription for restoration.
- **Finding**: See Table 1: Fire regimes of major western forests and some examples of plant association groups in each type

- **Finding**: A common-sense conservation goal is to achieve forests that are low maintenance and require minimal repeated treatment. With time, in a landscape of sufficient size, the right end of the restoration continuum (Figure 4) could be reached, where natural fire maintains the system in the desired state.
- **Management**: Although many forests will require continued management, a common sense conservation goal is to achieve forests that are low maintenance and require minimal repeated treatment
- **Management**: Restoration of ponderosa pine and dry, mixed-conifer forests (ie guiding their composition, structure, and function to a condition within the historical range of variability) is often desirable (Figure 3) and can involve active techniques such as thinning of small trees and prescribed burning or passive management such as allowing natural fires to burn and removing livestock (Allen et al. 2002; Brown et al. 2004; Schoennagel et al. 2004).
    - Large wildland landscapes are especially well-suited to passive restoration (Nossetal. 2006b).
- **Management**: In forests characterized by low-severity fire regimes, restoration varies along a continuum from restoring structure (eg reducing densities of small trees and increasing the density of large trees) to restoring the processes (eg low severity fire, competition between grasses and tree seedlings) that cre? ate and maintain that structure (Figure 4).
- **Management**: The following are some of our key findings that relate to decisions about fire management.
    - (1) Fire exclusion and other human activities led to significant deviations from historical variability in some, but not all, forests. Restoration treatments are warranted, sometimes urgently, only where such activities have resulted in major alterations in ecosystem structure, function, or composition.
    - (2) Fire exclusion has had little effect on fuels or forest structure in forests characterized by high severity (stand replacement) fire. High severity fires are relatively infrequent, occurring at intervals of one to many centuries, whereas active fire exclusion, especially in remote forests, began only decades ago. Because fuel structures or tree densities are usually within the historical range of variability, active restoration is ecologically inappropriate in these forests.
    - (3) Restoration of dry ponderosa pine and dry mixed-conifer forests - where low severity fires were historically most common - is ecologically appropriate on many sites. Active (eg mechanical thinning of small stems, prescribed fire) or passive (eg wildland fire use, livestock removal) management can restore stand densities to the levels that existed prior to fire exclusion, livestock grazing, logging, and plantation establishment. Retention of old live trees, large snags, and large logs in restoration treatments is critical. Also, restoring other key components of these ecosystems, such as native understory plants, is essential for full recovery of natural conditions, including the characteristic fire regime.
    - (4) Scientific understanding of mixed severity fire regimes is limited, making it difficult to provide defensible guidelines for restoration. These are often complex landscape mosaics; it is therefore necessary to plan and conduct

    activities at large spatial scales. Where sufficient ecological and fire-history information is available, a combination of thinning and prescribed fire may be useful in restoration. Nevertheless, only portions of these landscapes may warrant treatment.
    - (5) Restoration plans should systematically incorporate fire to maintain restored forests. Forests are dynamic; therefore, any restoration program must provide for sustained fire management to maintain the desired condition. Low-maintenance forests, which can often be achieved through managed natural fire, are an appropriate restoration goal in many cases; where this is not possible, prescribed fire should mimic the characteristic fire regime as closely as possible. Because fire regimes vary tremendously on a regional scale, managers should allow for a range of fire severities.
    - (6) Species closely associated with late- or early-successional conditions in fire-prone landscapes need special management consideration. For example, managed forests are often fragmented by periodic logging and road-building, or consist only of stands of trees too small or too open to meet the needs of late-successional dependent species, such as the spotted owl (Strix occidentalis).
- Management: A generalized policy of fire suppression is inappropriate given the documented negative ecological impacts of fire suppression during the 20th century
- Management: Our findings indicate that allowing fires to serve their natural role is ecologically beneficial.
- Management: Although fire must be managed when close to human infrastructure, in many wilderness areas, national parks, and large areas of public land there is opportunity to increase the use of wildland fire. Such management benefits species that require the shifting mosaics of post-fire habitats found in natural landscapes (Smucker et al 2005).
- Management: Furthermore, fire suppression may be ecologically warranted in some cases, particularly where special values are at risk. For example, it may be appropriate
    - where habitat of critically imperiled species could be lost,
    - where uncharacteristic fuel accumulations have created the potential for a fire outside the historical range of variability,
    - where high severity fires are not now viewed as ecologically desirable (eg old-growth forests in the Pacific Northwest).
- Management: Ecologists should be included on fire management teams to ensure that decisions consider the ecological costs and benefits of management actions.
- Management: Our key findings on post-fire management are as follows.
    - First, post-burn landscapes have substantial capacity for natural recovery. Re-establishment of forest following stand-replacement fire occurs at widely varying rates; this allows ecologically critical, early-successional habitat to persist for various periods of time.
    - Second, post-fire (salvage) logging does not contribute to ecological recovery; rather, it negatively affects recovery processes, with the intensity of impacts depending upon the nature of the logging activity (Lindenmayer et al. 2004).

Post-fire logging in naturally disturbed forest landscapes generally has no direct ecological benefits and many potential negative impacts (Beschta et al. 2004; Donato et al. 2006; Lindenmayer and Noss 2006). Trees that survive fire for even a short time are critical as seed sources and as habitat that sustains biodiversity both above- and below ground. Dead wood, including large snags and logs, rivals live trees in ecological importance. Removal of structural legacies, both living and dead, is inconsistent with scientific understanding of natural disturbance regimes and short- and long-term regeneration processes.

- Third, in forests subjected to severe fire and post-fire logging, streams and other aquatic ecosystems will take longer to return to historical conditions or may switch to a different (and often less desirable) state altogether (Karr et al 2004). Following a severe fire, the biggest impacts on aquatic ecosystems are often excessive sedimentation, caused by runoff from roads, which may continue for years.
- Fourth, post-fire seeding of non-native plants is often ineffective at reducing soil erosion and generally damages natural ecological values, for example by reducing tree regeneration and the recovery of native plant cover and biodiversity (Beyers 2004). Non-native plants typically compete with native species, reducing both native plant diversity and cover (Keeley et al 2006).
- Fifth, the ecological importance of biological legacies and of uncommon, structurally complex early-successional stands argues against actions to achieve rapid and complete reforestation. Re-establishing fully stocked stands on sites characterized by low severity fire may actually increase the severity of fire because of fuel loadings outside the historical range of variability.
- Finally, species dependent on habitat conditions created by high severity fire, with abundant standing dead trees, require substantial areas to be protected from post-fire logging (Hutto 1995).

Odion et al. 2004.

- **Study**: We tested for modern human impacts on the fire regime by analyzing temporal patterns in fire extent and spatial patterns of fire severity in relation to vegetation structure, past fire occurrence, roads, and timber management in a 98,814-ha area burned in 1987.
- **Study**: Extensive fires burned in the Klamath-Siskiyou region in 1987, creating a landscape well suited to test the following hypotheses: (1) within the same vegetation types, fire severity is greater where previous fire has been long absent, and (2) exclusive of where plantations are, the proportion of high-severity (crown) fire is lower in previously roaded and managed portions of the burned land- scape.
- **Background**: The Klamath-Siskiyou region of northwestern California and southwestern Oregon supports globally outstanding temperate biodiversity. Fire has been important in the evolutionary history that shaped this diversity, but recent human influences have altered the fire environment.
- **Background**: A complex, mixed-severity fire regime has shaped the composition and structure of Klamath-Siskiyou vegetation. Because of steep climatic, edaphic gradients, and rugged topography, fire frequencies and severities have been highly variable (Agee 1993; Taylor & Skinner 1998, 2003).
    - Such spatial and temporal variation in disturbance is believed fundamental to promoting species diversity because non-equilibrium processes enhance habitat heterogeneity (Connell 1978; Huston 1979).
    - Biodiversity is likely to be threatened where changes in fire regime become incompatible with evolutionary history (Bond & van Wilgen 1996; Swetnam et al. 1999).
- **Background**: Fire regimes have been recently modified where fire has been successfully excluded, especially if biomass that is receptive to combustion accumulates in the absence of fire (Covington 2000; Dale et al. 2000). This scenario has been commonly cited as the primary factor contributing to recent large fires in forests of the western United States (Covington 2000; Arno & Allison-Bunnell 2002; Agee 2002).
    - As a result, current land-management policies in the United States are calling for widespread tree harvests and other mechanical treatments aimed at reducing fuel.
    - However, the effects of these treatments on biodiversity remain unclear.
- **Background**: In addition, the problem of fuel build-up leading to increased fire severity has mainly been documented in formerly open forests of ponderosa pine (Pinus ponderosa Dougl. ex Laws.) that have his- torically been maintained by remarkably frequent surface fire (Covington 2000). Fire plays a very different role in many other forests (Turner et al. 2003), raising concerns that the surface-fire model of fuel dynamics is uncritically accepted in forests where it may not apply (Baker & Ehle 2001; Gutsell et al. 2001; Ehle & Baker 2003; Johnson 2003).

- **Background**: Forestry practices other than fire exclusion also may influence fire regimes. Even-aged silviculture can increase fire hazard by creating more combustible fuel complexes (Perry 1994; Weatherspoon & Skinner 1995).
- **Background**: Historical fire regimes for the study area and nearby are generally described as mixed, with fire-severity proportions ranging, in order of abundance, from low to moderate to high (crown fire) (Agee 1993).
    - Fires also have had highly variable return intervals, depending on vegetation type, topography, and elevation.
    - For <u>Douglas-fir</u> hardwood forests, recent fire return intervals have ranged from 3 to 71 years (Wills & Stuart 1994; Taylor & Skinner 1998) within the study area.
    - <u>White-fir</u> forests just west of the study area burned at intervals ranging from 12 to 161 years prior to fire suppression (Stuart & Salazar 2000).
    - Fire suppression reportedly became effective in reducing the area burned on the KNF in the 1940s (Taylor & Skinner 1998).
- **Background**: During the past few thousand years, charcoal-accumulation rates in lakes in the region have been both higher and lower than rates in recent centuries, and there has been much variation (Mohr et al. 2000; Whitlock et al. 2003).
    - In sum, extensive mixed-severity fires of variable frequency were likely instrumental in creating patchy landscape patterns and variable age-class distributions in this region for millennia.
    - The importance of patchy landscape structure in maintaining species diversity has been demonstrated in studies of age mosaics created by stand-replacing fire (Baker 1992).
- **Background**: In addition, shading decreases the leaf area of understory conifers (Waring & Schlesinger 1985); they may have relatively little high-energy foliar fuel per unit volume in their canopy. This is by far the most available aerial fuel in trees such as Douglas-fir (Fahnestock & Agee 1983). Understory temperatures are also reduced by shading, which can lower fire severity (Countryman 1955). Thus, the biological and physical effects of shading may lead to a reduction in surface-heat output during fire and, likely, in the production of firebrands
- **Background**: Because of such dynamics, in many regions of the world the long absence of fire causes vegetation that is relatively receptive to combustion to develop into vegetation that is not (Bond & van Wilgen 1996). In Tasmania, relatively long fire-return intervals (100+ years) result in the replacement of combustible vegetation with tall, open forests with a subcanopy of sclerophyll hard- woods, which are considerably less prone to combustion (Jackson 1968). These dynamics lead to alternative stable states that can be maintained by fire (Bond & van Wilgen 1996). The dynamics are similar to stand development in the structurally similar, moist temperate Douglas-fir- hardwood forests of our study area, as described by Stuart et al. (1993) and Wills and Stuart (1994).
- **Background**: Weather conditions often override the sensitivity of a fire regime to internally regulated biomass processes op- erating over time. This has been demonstrated in empir- ical studies (e.g., Moritz 2003), through analysis of stan- dard

equations for predicting fire spread (Bessie & John- son 1995), and in simulation modeling (Turner & Romme 1994). Extreme fire weather was previously invoked as the primary explanation for fire-severity patterns in the 1987 fires in the Klamath-Siskiyou region (Agee 1997), although strong local effects of plantations and logging were also observed (Weatherspoon & Skinner 1995).

- **Finding**: Despite human influences and a fire-suppression policy, most large wildland fires have been dominated by low-severity fire, with variable proportions of moderate and high severity. This is consistent with historical estimates inferred from stand age structure as shown in Fig. 3 (from Taylor & Skinner 1998).
    - One factor that contributed to the heterogeneity in fire patterns in 1987, and presumably in other large fire events, is that the fires burned under a variety of weather conditions for many weeks (Reider 1988).
- **Finding**: We found:
    - (1) a trend of increasing fire size in recent decades;
    - (2) that overall fire-severity proportions were 59% low, 29% moderate, and 12% high, which is comparable to both contemporary and historic fires in the region;
    - (3) that multi-aged, closed forests, the predominant vegetation, burned with much lower severity than did open forest and shrubby non-forest vegetation;
    - (4) that considerably less high-severity fire occurred where fire had previously be absent since 1920 in closed forests compared to where the forests had burned since 1920 (7% vs. 16%);
    - (5) that non-forest vegetation burned with greater severity where there was a history of fire since 1920 and in roaded areas;
    - (6) that tree plantations experienced twice as much severe fire as multi-aged-forests
- **Finding**: We found evidence for important changes in combustibility over time because the probability of stand-replacing fire was lower in long-unburned forests. A number of factors may contribute to this pattern.
    - Whether a forest will experience surface or crown fire depends on the height of the tree canopy, the amount of available fuel it contains per unit volume, and rates of fire spread and surface heat output (Van Wagner 1977; Johnson 2003).
- **Finding**: The much greater fire severity we found in early successional, non-forest vegetation will tend to favor the persistence of this vegetation. In the long absence of stand-replacing fire, however, it is replaced by forests (Wills & Stuart 1994).
- **Finding**: Even-aged plantations are a patch type that can persist regardless of fire frequency. Plantations of any age are more receptive to combustion than co-occurring forests in our study area. Because plantations are often established following high-severity fire, a self-reinforcing relationship is possible (Perry 1995). An ecological analog may exist where exotic species invade and become abundant through positive feedback with fire (Mack & D'Antonio 1998). Plantations in our study area have grown to cover about one-third of the roaded area burned in 1987, increasing the likelihood of future positive feed- back effects. In concert with climate change (McKenzie et al. 2004), these landscape dynamics provide reason to expect the trend of increasing fire size (Fig. 1) to continue, especially in roaded areas.

- **Management**: We concluded that fuel buildup in the absence of fire did not cause increased fire severity as hypothesized. Instead, fuel that is receptive to combustion may decrease in the long absence of fire in the closed forests of our study area, which will favor the fire regime that has maintained these forests. However, plantations are now found in one-third of the roaded landscape. Together with warming climate, this may increase the size and severity of future fires, favoring further establishment of structurally and biologically simple plantations.
- **Management**: In our study area, harvest treatments to reduce fire severity based on a model of fuel build-up in the absence of fire would be misdirected because long-unburned areas exhibited the lowest fire severity. Moreover, these treatments may be ecologically detrimental because stand- replacing or stand-thinning fire plays a key role in the regeneration of Douglas-fir and most other conifers and natural vegetation in our study area (Wills & Stuart 1994, Thornburgh 1995). Other elements of biodiversity may depend on these fire effects and the habitat heterogeneity that results. There are also more immediate biological consequences of harvest treatments-for example, to understory plants, soil organisms, and aquatic resources. The potential for these treatments to spread exotic forest diseases and plants also needs to be addressed.
- **Management**: Conversely, fuel treatments that reduce fire severity in portions of the landscape where human activities have increased available fuel will address the problem of un- naturally high fire severity. Not only have we found high fire severity in plantations, but, working in the same region, Key (2000) also found that plantations and adjacent vegetation burned more severely than natural forests (see also Weatherspoon & Skinner 1995).
- **Management**: Naturally ignited wildfires in the Klamath-Siskiyou region shape vegetation patterns that underlie biodiversity and are in alignment with the current climate. These fires are difficult for society to accommodate because they may burn for long periods, including when weather is extreme. Conservation objectives are affected by the need to protect people and property from such fires. In a de- tailed analysis of potential solutions to balancing the goals of human protection and conservation, modification of the edges of the built environment to slow or stop fire has been emphasized (Bradstock & Gill 2001). Treating the home-ignition zone as described by Cohen (2000) can almost eliminate the possibility of homes burning in wildfires. This would increase fire-management options and perhaps ultimately further conservation goals in the Klamath-Siskiyou ecoregion.

Odion et al. 2010.

- **Study**: We hypothesized that alternative community states occur in a largely forested landscape in the Klamath Mountains, north-western California, USA, where shrub-dominated sclerophyllous vegetation establishes after fire that is lethal to forests. Forests redevelop if succession is not arrested by fire. Our hypothesis would require that sclerophyll and forest vegetation states each be maintained by different self-reinforcing relationships with fire.
- **Study**: In a recent study, we investigated spatial patterns of wildfire severity in relation to management in a landscape in northwestern California and hypothesized that coexisting forest and sclerophyll vegetation are naturally occurring alternative states maintained by fire (Odion et al. 2004). Our goal here is to test this hypothesis systematically taking into account spatial autocorrelation, time-since-fire (TSF) as affected by fire exclusion and the potential for vegetation to persist for multiple generations. Our hypothesis would require that co-occurring vegetation states be maintained by different, self-reinforcing relationships with fire. Therefore, sclerophyll vegetation where TSF is relatively short should be especially pyrogenic, and forests where TSF is long should be especially non-pyrogenic.
- **Background**: Plants have interacted with fire for millions of years and can influence their own fire regimes, potentially affecting their own fitness (Mutch 1970; Bond & van Wilgen 1996; Schwilk 2003). Bond & Keeley (2005) point out how plant traits that promote fire contribute to a large mismatch between climate and potential vegetation. At a global scale, Bond, Woodward & Midgley (2005) found that half the area that could be occupied by forest is instead occupied by pyrogenic vegetation like savanna or shrublands maintained by fire.
- **Background**: High-severity fire in the study area is most common on drier and more southerly aspects and wind-exposed ridges (Weatherspoon & Skinner 1995; Taylor & Skinner 1998; Alexander et al. 2006). In these environments, succession to forest is slower, especially where soil productivity is lower as a result of the cumulative effects of fire history. Thus, climate, topography, soils, vegetation and fire tend to be mutually reinforcing determinants of landscape patterns. However, climate and topography, particularly as they affect wind, can override other factors and control fire–vegetation patterns (e.g.Geldenhuys 1994).
- **Background**: In the study region, episodic weather-driven fire events kill patches of forest when severe drought and weather conditions may allow even the most fire-resistant stands to burn. Once sclerophyll vegetation replaces forests, its self-reinforcing relationship with fire can alter successional pathways to favour its retention (Fig. 4). Sclerophyll vegetation may effectively create a ‘fire trap’, preventing tree species from developing to adult sizes (Gignoux et al. 2009; Hoffmann et al. 2009).
- **Background**: The cumulative effects of severe fire in reducing soil carbon and site productivity over time (Fig. 4) can slow growth rates of forest tree species (Waring & Schlesinger 1985), increasing the time they are vulnerable to the fire trap. This is an

example of how sclerophyll vegetation can modify the underlying environment to favour its retention (Wilson & Agnew 1992).

- **Background**: Although climate change could potentially increase rates of burning, this may not apply to the study region (Krawchuk et al. 2009). Moreover, decreases in vegetation pyrogenicity can override effects of changing climate on fire (Higuera et al. 2009).
- **Finding**: Our findings are consistent with the occurrence of alternative community states established and maintained by different self-reinforcing feedbacks with fire. Sclerophyll vegetation was more pyrogenic, especially where time-since-fire (TSF) was relatively short, a favourable relationship for this fire-dependent vegetation. Forests were much less pyrogenic, especially where TSF was long, favouring their maintenance. Fire exclusion therefore has led to afforestation and rapid retreat of fire-dependent vegetation.
- **Finding**: We have documented how different self-reinforcing combustion properties of forest and sclerophyll vegetation can naturally produce alternative states coexisting side-by-side in the same environment. Such fire-mediated alternative states may be underappreciated, in part, because they are difficult to demonstrate definitively. In addition, the dynamics they exhibit contrast with common perceptions that fire hazard increases deterministically with TSF in forests and shrublands. Addressing the impacts of fire exclusion will probably require a management shift to better allow fire to perform its ecological role in shaping landscape diversity and maintaining firedependent biota.
- **Finding**: Sclerophyll vegetation was much more pyrogenic than forests (Fig. 2a) and the null hypothesis of no association between fire severity and natural vegetation was rejected (v22 = 10.1, P = 0.006). Plantations experienced more highseverity fire than natural forests (Fig. 2a)
- **Finding**: Much of the high-severity fire within the 1987 perimeter occurred in areas that had previously burned in 1966 and particularly in 1977 (Fig. 1). Roughly 60% of the area that burned at high severity in the 1977 fire and also burned in the 1987 fires burned again at high severity in 1987, and many of the patch boundaries were identical. Much of this area was forested at the time of the 1977 fires (Odion et al. 2004) and has been sclerophyll vegetation since.
- **Finding**: We found the vegetation in the Klamath Mountains to have different combustion properties and this was a function of TSF (time since fire) at the landscape scale. Consistent with the hypothesis that co-occurring vegetation states in this landscape can be maintained by different self-reinforcing relationships with fire, sclerophyll vegetation was pyrogenic, and its highest severity as well as relative abundance occurred where TSF was shortest. Conversely, the lowest fire severity and greatest abundance of forests occurred where TSF was longest (Fig. 2b,c).
- **Finding**: With sufficiently long fire intervals conifers can escape the fire trap and reach a threshold beyond which positive feedbacks between reduced fire and vegetation pyrogenicity increasingly favour forests (Fig. 2b). These feedbacks lead to less fire-related mortality. We also found that fire intervals >75 years led to a much lower

probability and maximum size of large high-severity burned patches than where TSF was shorter (Figs 2b, 3 and Table 2).

- **Finding**: Biomass that is most available to flaming combustion, canopy foliage and fine wood on the forest floor, may reach equilibrium (Jenny, Gessel & Bingham 1949; Kittredge 1955; Waring & Schlesinger 1985), but support lower fire severity because the height of the canopy above the forest floor increases (Azuma, Donnegan & Gedney 2004). Tanoak and other hardwoods have also been associated with low fire severity in long-unburned stands in the study region (Azuma, Donnegan & Gedney 2004; Odion et al. 2004). Hardwoods in the oak family often have high lignin content and have generally been found to be much less pyrogenic than conifers (Mutch 1970;Williamson&Black 1981; Rebertus,Williamson &Moser 1989; Pausas et al. 2004).
- **Finding**: We found that alternative states of pyrogenic and non-pyrogenic vegetation are maintained in the same environment by different self-reinforcing relationships with fire. In fire-prone environments, such self-organizing dynamics between vegetation and fire may lead to sharp vegetation boundaries that do not correspond to underlying environmental gradients (Wilson & Agnew 1992).
- **Ecological Considerations**: In addition, because conifers depend on dispersal to re-colonize burned patches, they can be inhibited if patch sizes exceed a dispersal distance threshold, beyondwhich conifer regeneration may diminish rapidly (Romme et al. 1998).
- **Ecological Considerations**: Paradoxically, although the sclerophyll vegetation may inhibit forests through fire-related mechanisms, conifers can also be facilitated by shrubs. Conifer seedlings survive better under shrub canopies, where drought stress is reduced (Zavitkovski &Newton 1968; Dunne & Parker 1999) and their long-term growth potential may be increased by nitrogen-fixing Ceanothus spp. (Busse, Cochran & Barrett 1996).
- **Ecological Considerations**: As forests develop, tanoak is not excluded like pyrogenic shrubs. Instead, it transforms from shrubby, xerophytic forms with dense, small, thick and waxy leaves to more arborescent, mesophytic forms with large, shade-tolerant leaves. Phenotypic plasticity, as exemplified by these changes, is a key trait among species that are important immediately after disturbance and can remain so late in succession despite a change in the environment (Platt & Connell 2003)
- **Ecological Considerations**: Because tanoak can both persist and also recruit new canopy stems in mature forests in the absence of fire (Hunter 1997), whereas conifers like Douglas-fir rely on cohort regeneration after fire (Wills & Stuart 1994), tanoak may eventually become more dominant in the study region with fire exclusion. However, fire exclusion may increase the susceptibility of tanoak, as well as California black oak, to a highly virulent nonnative pathogen causing Sudden Oak Death disease (Moritz & Odion 2005). Thus, other hardwoods that also do not require fire for reproduction may eventually increase if fire exclusion persists, which would further reduce forest pyrogenicity.
- **Management**: There are several reasons why forests in the study region become less pyrogenic with TSF and with stand age. Understorey shrubs and small conifers are increasingly excluded by the forest canopy (Azuma, Donnegan & Gedney 2004). Closed

forests also have a microclimate that is less favourable to fire (Countryman 1955). Larger trees and fallen logs act as heat sinks during fires (Azuma, Donnegan & Gedney 2004).

- **Management**: However, our results conflict with assumptions regarding fire-prone forested landscapes of the study region (Spies et al. 2006) and western United States of America that fire exclusion leads to more pyrogenic forests, increasing the probability of high-severity fire. Current management based on these prevailing views, such as thinning forest stands, constructing fuelbreaks and establishing plantations after fire, does not address the rapid decrease in fire-dependent sclerophyll vegetation and changes to forests that are caused by fire exclusion in the study region.

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- **Finding**: They identify a provisional set of 22 highest-priority and 40 high-priority microrefugia that occur mostly outside of existing protected areas and along wetter and lower elevations of the ecoregion
- **Climate Change Impacts**: Diminishment of fog in KS region (Johnstone and Dawson 2010)
- **Background**: Current anthropogenic stressors are likely compromising the effectiveness of the KS Ecoregion as a refugium for this century's project changes.
    - Over a century of land use activities (e.g., mining, logging, livestock grazing, damming of rivers, and human-caused alterations of fire) have damaged or destroyed mesic habitats that may previously functioned as refugia
    - Loss of contiguous habitat along elevational and other environmental gradients
    - Loss and degradation of most of the mature or old-growth forests, particularly mesic lowland and mid-elevation habitats
        - Only about 28% of historic old-growth forests remain
    - Increasing prevalence of invasive plants and pathogens from road-building and land use practices
- **Background**: KS region has acted as biodiversity refuge in the past due to:
    - Special location (latitude and coastal proximity)
    - Rugged terrain
    - Climate stability
    - Complexity of soils and microclimates
- **Background**: The existing protected area system (i.e., National and State Parks, Wilderness Areas, National Monuments, Botanical Areas) is inadequate for ensuring the persistence of most of the ecoregion's vulnerable biodiversity (DellaSala et al. 1999; Noss et al. 1999; Carroll et al. 2010).
    - Existing reserves largely protect higher-elevation communities, while the lower-elevation reserves are limited in their geographic extent, thereby missing many distinct lowland species assemblages and areas that may act as potential microrefugia.
- **Background**: We define microrefugia as sites with cool and moist conditions conducive to the persistence of species vulnerable to climate change.
- **Background**: We define mesorefugia as large areas that contain nested clusters of microrefugia with similar species assemblages that have functioned as a refugium over millennia.
- **Ecological Considerations**: Most of the KS region's biodiversity, endemic species, and species vulnerable to climate change are largely restricted to persistently cool and moist late-successional forest and are:
    - Invertebrates
    - Non-vascular plants
    - Fungi
    - Bryophytes

- **Ecological Considerations**: the responses of vulnerable taxa to climate change will necessarily be local due to a limited capacity of many species to move to new habitat.
- **Ecological Considerations**: possible refugia sites for the ecoregion's at-risk endemic serpentine-subtrate flora are sites that will retain wet soil conditions, such as seeps and bogs.
- **Ecological Considerations**: The region's endemic serpentine flora is highly vulnerable to projected increases in warming and drying (Damschen et al 2010) and some taxa may only persist within persistently wet pockets and seeps surrounded by late-seral forests (mature and old-growth)
- **Ecological Considerations**: the vast majority of distinctive biodiversity for the ecoregion (all taxa being considered) occur within the coastal fog and transition zones (Figure 1; Sawyer 2007). The latter zone includes more mesic forests along the Siskiyou Crest (Oregon/California), Eddy Mountains (northwest California), Scott Mountains (northwest California), and Yolla Bolly's (southern limits of the ecoregion) that are relatively far from the coast.
- **Ecological Considerations**: Restricted-range (i.e., local endemic) species or relict taxa dependent on cool and moist habitats:
    - Brewer spruce (Picea breweriana)
    - Engelmann spruce (Picea engelmanni)
    - Foxtail pine (Pinus balfouriana) (Sawyer 2007)
    - Plethodon and Dicamptodon salamander species and subgoups (Bury 1973; Meadet al. 2005; Steele and Storfer 2006)
    - other plants (Sawyer 2007)
    - harvestman (Briggs 1969, 1971ab)
    - millipedes (Gardner and Shelley 1989; Olson 1992)
    - trapdoor spiders (Cokendolopher et al. 2005)
    - land snails (Frest and Johannes 1993)
- **Ecological Considerations**: The Russian Wilderness has an extraordinary sympatric assemblage of conifer species whose presence could be due to mesorefugia conditions
- **Management**: Important actions (note: these are *core-planning elements!*) to alleviate climate change impacts on biodiversity
    - Reduce non-climate stressors
    - Secure protection for large, complex landscapes
    - Immediately protect a network of climate change microrefugia, particularly:
        - Old growth and intact forests
            - On north-facing slopes
            - In canyon bottoms
            - At lower and middle elevations
            - In wetter coastal mountains
            - Along elevational gradients
                - **Explanation**: such areas provide local opportunities for vulnerable species to persist within the ecoregion
- **Management**: Reducing non-climate stressors

    - Reducing non-climate stressors across the landscape (e.g., road-building, mining) is *the single most important action* that land managers can take to help the regional biota and ecosystems persist in the face of climate change
        - The release from stressors should be strategically targeted to critical core habitats, old-growth forest microrefugia, and adaptation corridors along environmental gradients
        - The release of strategic areas from land use stressors would need to allow mature forests to once again dominate the landscape
- Management: Undertake ecologically based restoration in degraded areas
- Management: Conservation groups in the KS Region have identified two high-priority areas for protection
    - A 243,000 ha land bridge known as the proposed Siskiyou Crest National Monument
    - A 445,000 ha proposed Siskiyou Wild Rivers National Salmon and Botanical Area
        - Protection of these areas will greatly improve the chances for persistence of a large portion of the ecoregion's terrestrial and freshwater biota even with uncertainty of coming temperature and precipitation changes
- Management: Although the long-term efficacy of microrefugia is still uncertain (Carroll et al. 2010; Dobrowski et al. 2010), especially if they remain embedded within largely degraded landscapes, it remains a prudent, bet-hedging strategy in the face of uncertainty to protect a network of microrefugia representative of the ecoregion's distinct species assemblages.
- Management: Site features for effective microrefugia in the KSE include
    - north-facing slopes, valley bottoms and steep canyons, and sinks and basins because they are shadier and exist where cool air predictably pools in the lower sites (Dobrowski et al. 2010).
    - Forests with a northeast- and north-facing aspect also have a lower frequency of wildfires that can alter the capacity of habitats to retain cool and moist conditions (Taylor and Skinner 2003; Alexander et al. 2006).
    - Habitat types that will function well as microrefugia for climate change-sensitive species include late-seral forests, although the greater litter, understory vegetation, and canopy complexity and biomass of old-growth forests (> 150 yrs) makes them superior at retaining moisture (Chen et al. 1999).
    - Late-seral forests that occur in areas with high-precipitation and fog, such as in coastal mountains (Loarie et al. 2008; Ackerly et al. 2010; Carroll et al. 2010) or other areas that experience significant orographic precipitation (e.g., > 1143 mm annual precipitation) will, on average, be better able to retain more moisture and cooler conditions than lower precipitation zones. This is due to more abundant water and greater canopy, understory vegetation, litter biomass, and complexity in these forests.
- Management: for ensuring a robust reserve design that is responsive to climate change, it is prudent to secure priority old-growth forest microrefugia as swiftly as possible while the more time-consuming and uncertain task of conserving larger landscapes continues.

- **Management**: Targeted surveys of old-growth forest invertebrates and non-vascular plants are needed to improve our understanding of the distribution of distinct assemblages in order to refine the location of mesorefugia and better design representative networks of microrefugia.
- **Management**: see paper for more detailed information about locations of proposed microrefugia and protected areas

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- **Study**: We describe existing models of the relationship between species diversity and ecological function
- **Study**: We propose a conceptual model that relates species richness, ecological resilience, and scale.
- **Study**: Our model expands theory relating biodiversity to ecological resilience by incorporating scale.
- **Finding**: We suggest that species interact with scale-dependent sets of ecological structures and processes that determine functional opportunities. We propose that ecological resilience is generated by diverse, but overlapping, function within a scale and by apparently redundant species that operate at different scales, thereby reinforcing function across scales. The distribution of functional diversity within and across scales enables regeneration and renewal to occur following ecological disruption over a wide range of scales.
- **Finding**: These studies demonstrate that the stability of many, but not all, ecological processes increases with species richness. They also suggest that the ecological stability is generated more by a diversity of functional groups than by species richness.
- **Finding**: The model that best describes an ecosystem appears to depend upon the variety of functional roles that are occupied in that system, and the evenness of the distribution of ecological function among species. An ecosystem consisting of species that each performs different ecological functions will be less redundant than an ecosystem consisting of the same number of species that each perform a wide variety of ecological functions.
- **Finding**: The experimental results just discussed suggest ecosystems possess considerable functional redundancy. Indeed, it is difficult to envision how ecosystems without redundancy could continue to persist in the face of disturbance. We assume that since no species are identical, redundancy does not reside in groups of species, but rather it emerges from the interactions of species. Therefore, it is not possible to substitute species for one another; rather, there are many possible combinations and organizations of species that can produce similar ecological functions.
- **Finding**: We propose that the resilience of ecological processes, and therefore of the ecosystems they maintain, depends upon the distribution of functional groups within and across scales.
- **Finding**: We hypothesize that if species in a functional group operate at different scales, they provide mutual reinforcement that contributes to the resilience of a function, while at the same time minimizing competition among species within the functional group (Figure 9).
  - This cross-scale resilience complements a within-scale resilience produced by overlap of ecological function among species of different functional groups that operate at the same scales.
  - Competition among members of a multitaxa functional group may be minimized if group members that use similar resources exploit different ecological scales.

    - Ecological resilience does not derive from redundancy in the traditional engineering sense; rather, it derives from overlapping function within scales and reinforcement of function across scales.
- **Finding**: Members of functional groups maintain and therefore determine the resilience of ecosystems by spreading their influence over a range of scales. When a functional group consists of species that operate at different scales, that group provides cross-scale functional reinforcement that greatly increases the resilience of its function. This interpretation of the partitioning of ecological function suggests that what is often defined as redundancy, is not. The apparent redundancy of similar function replicated at different scales adds resilience to an ecosystem: because disturbances are limited to specific scales, functions that operate at other scales are able to persist.
- **Finding**: An indirect consequence of species loss is that it limits the potential number of ways a system can reorganize. Especially troubling is the possibility that the loss of large species, such as moose (Pastor and others 1993) or elephants (Dublin and others 1990), that generate mesoscale ecological structure may also eliminate forms of ecological organization.
- **Finding**: We propose that ecological resilience is generated by diverse, but overlapping, function within a scale and by apparently redundant species that operate at different scales.
- **Background**: One of the central questions in ecology is how biological diversity relates to ecological function. Maintaining the ecological services that support humanity, and other life, during this period of extensive and rapid global change and ecological reorganization requires understanding how ecological interactions among species produce resilient ecosystems.
- **Background**: Species perform diverse ecological functions. A species may regulate biogeochemical cycles (Vitousek 1990; Zimov and others 1995), alter disturbance regimes (Dublin and others 1990; D’Antonio and Vitousek 1992), or modify the physical environment (Jones and others 1994; Naiman and others 1994). Other species regulate ecological processes indirectly, through trophic interactions such as predation or parasitism (Kitchell and Carpenter 1993; Prins and Van der Jeud 1993), or functional interactions such as pollination (Fleming and Sosa 1994) and seed dispersal (Brown and Heske 1990). The variety of functions that a species can perform is limited, and consequently ecologists frequently have proposed that an increase in species richness also increases functional diversity, producing an increase in ecological stability (Tilman and others 1996).
- **Background**: Many competing models attempt to describe how an increase in species richness increases stability. Following previous authors, we divide these models into four classes: ‘‘species richness–diversity’’ (MacArthur 1955), ‘‘idiosyncratic’’ (Lawton 1994), ‘‘rivet’’ (Ehrlich and Ehrlich 1981), and ‘‘drivers and passengers’’ (Walker 1992). These models all explicitly or implicitly assume that a species has ecological function, and that the function of a species can be represented as occupying an area of multidimensional ecological function space (Grinnell 1917; Hutchinson 1957; Sugihara 1980).

- **Background**: Ehrlich and Ehrlich's (1981) rivet hypothesis, which is similar to Frost and colleagues' (1995) model of compensating complementarity, likens the ecological function of species to the rivets that attach a wing to a plane. Several rivets can be lost before the wing falls off. This model proposes that the ecological functions of different species overlap, so that even if a species is removed, ecological function may persist because of the compensation of other species with similar functions (Figure 3). In the rivet model, an ecological function will not disappear until all the species performing that function are removed from an ecosystem. Overlap of ecological function enables an ecosystem to persist. Compensation masks ecosystem degradation, because while a degraded system may function similarly to an intact system, the loss of redundancy decreases the system's ability to withstand disturbance or further species removal.
- **Background**: Walker's ''drivers and passengers'' hypothesis accepts the notion of species complementarity and extends it by proposing that ecological function resides in ''driver'' species or in functional groups of such species (Walker 1992, 1995). It is similar to Holling's (1992) ''extended keystone hypothesis.'' Walker defines a driver as a species that has a strong ecological function. Such species significantly structure the ecosystems in which they and passenger species exist. Passenger species are those that have minor ecological impact. Driver species can take many forms. They may be ''ecological engineers'' (Jones and others 1994), such as beavers (Naiman and others 1994), or gopher tortoises (Diemer 1986), which physically structure their environments. Or drivers may be ''keystone species'' (Paine 1969), such as sea otters (Estes and Duggins 1995) or asynchronously fruiting trees (Terborgh 1986), that have strong interactions with other species (Power and others 1996).Walker (1995) proposes that since most ecol ogical function resides in the strong influence of driver species, it is their presence or absence that determines the stability of an ecosystem's ecological function (Figure 4).
- **Background**: Tilman, for example, demonstrated that more diverse plots (4 3 4m) have greater plant cover and more efficiently utilize nitrogen (Tilman 1996). Tilman and colleagues demonstrated that ecological function was more stable in diverse communities despite, or perhaps because of, large fluctuations in populations of species (Tilman and others 1996). These results echo those of Frank and McNaughton (1991), who demonstrated that more diverse natural grass communities recovered faster than less diverse communities following drought.
- **Background**: In a series of experiments, Ewel and coworkers constructed a set of tropical ecosystems with different levels of species richness and compared their functioning to adjacent rainforest. They demonstrated that relatively few species, if drawn from different functional groups, can duplicate the ecological flows of a diverse rainforest (Ewel and others 1991). Herbivory per leaf area was lower and less variable in species-rich plots (Brown and Ewel 1987). They also demonstrated that a variety of ecosystem variables, such as soil organic matter, increase rapidly as one adds different functional types to a plot (Ewel and Bigelow 1996), and that simple agroecosystems function quite similarly to much more species-rich rainforests, at least in areas of about 1⁄3 ha (80 3 40 m) for 5 years (Ewel and others 1991).
- **Background**: Naeem and coworkers (1994) assembled replicate artificial ecosystems at a number of levels of species richness. They demonstrated that carbon dioxide

consumption, vegetative cover, and productivity increased with species richness. These increases were greater between 9 and 15 species than between 15 and 31 species, providing support for the hypothesis that an increase in species richness increases ecological redundancy. Water and nutrient retention did not vary with species richness.

- **Background**: Frost and coworkers (1995) demonstrated that ecological function is preserved if population declines of zooplankton species are compensated for by population increases in other species with similar ecological functions. Their results suggest that lakes with fewer species in a functional group would exhibit decreased ability to compensate for population declines in other species.
    - Similarly, Schindler (1990) observed that the largest changes in ecological processes and food-web organization occurred when species that were the only remaining member of a functional group were eliminated.
- **Background**: When a system can reorganize (that is, shift from one stability domain to another), a more relevant measure of ecosystem dynamics is ecological resilience (Holling 1973). Ecological resilience is a measure of the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures.
- **Background**: Ecological resilience assumes that an ecosystem can exist in alternative self-organized or ‘‘stable’’ states. It measures the change required to move the ecosystem from being organized around one set of mutually reinforcing structures and processes to another.
- **Background**: Ecological and engineering resilience reflect different properties. Ecological resilience concentrates on the ability of a set of mutually reinforcing structures and processes to persist. It allows ecologists or managers to focus upon transitions between definable states, defined by sets of organizing processes and structures, and the likelihood of such occurrence. Engineering resilience, on the other hand, concentrates on conditions near a steady state where transient measurements of rate of return are made following small disturbances.
- **Background**: Ecosystems are resilient when ecological interactions reinforce one another and dampen disruptions. Such situations may arise due to compensation when a species with an ecological function similar to another species increases in abundance as the other declines (Holling 1996), or as one species reduces the impact of a disruption on other species.
- **Background**: At the largest landscape scales, climate, geomorphological, and biogeographical processes alter ecological structure and dynamics across hundreds of kilometers and over millennia (Figure 8).
- **Background**: Species can be divided into functional groups based upon their ecological roles (Clark 1954; Ko¨rner 1996). Species can be also be divided into groups based upon the specific scales that they exploit. The ecological scales at which species operate often strongly correspond with average species body mass, making this measure a useful proxy variable for determining the scales of an animal’s perception
- **Management**: Management of natural resources often produces high short-term yields and, either purposefully or unintentionally, creates ecosystems that are less variable

and diverse over space and time. Management channels ecological productivity into a reduced number of ecological functions and eliminates ecological functions at many scales. This simplification reduces cross-scale resilience, leaving systems increasingly vulnerable to biophysical, economic, or social events that otherwise could have been absorbed—disease, weather anomalies, or market fluctuations.

- **Management**: The distribution of functional diversity within and across scales allows regeneration and renewal to occur following ecological disruption over a wide range of scales. The consequences of species loss may not be immediately visible, but species loss decreases ecological resilience to disturbance or disruption. It produces ecosystems that are more vulnerable to ecological collapse and reduces the variety of possible alternative ecological organizations.

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- **Study**: In two related field studies: (1) a multiscale riparian forest inventory and (2) a comparative study of natural forest gap and nongap environments, we explored regeneration patterns of native riparian trees in relation to large- and small-scale ecological drivers in four western Oregon watersheds spanning a climatic gradient from dry to wet.
- **Study**: In this study, we explored relationships between environmental conditions and regeneration patterns for nearly two dozen native tree species that occur in mountain riparian forests across western Oregon. Our objectives were to: (1) analyze the regeneration behavior of a broad suite of native riparian trees and (2) report how regeneration behavior of native species responds to natural variation in the regeneration environment.
- **Study**: It is important to acknowledge that the spatial patterns in seedling abundances we observed tell only a partial story of the forest regeneration process. A comprehensive understanding will await more long-term studies of temporal dynamics of disturbance, establishment, and forest development.
- **Background**: Riparian forests are among the most dynamic and complex ecosystems in nature and add disproportionately to landscape diversity where they occur (Naiman et al., 1993; Acker et al., 2003; Sabo et al., 2005).
- **Background** Background: Recent work by Pabst and Spies (1998, 1999) and Sarr and Hibbs (2007a,b) have demonstrated that riparian vegetation composition, diversity, and structure vary substantially across sites in geographically complex regions such as western Oregon. For long-lived tree species, as are many of the conifers occurring in riparian forests of the Pacific Northwest, the distribution of adult trees may not be a strong predictor of conditions for current regeneration. Rather, regeneration is likely favored by an opportunistic interaction between seed availability and near-ground regeneration environment.
- **Background**: Seed size and tolerances of shade, drought, heat, and flooding are attributes that often differentiate establishment of species along environmental or successional gradients (Huston and Smith, 1987). Where several species share life history traits, they likely will show similar functional responses to their environment (e.g., regenerate in similar environments).
- **Background**: In the Pacific Northwest (USA), streamside forests occupy a central role in landscape conservation, containing a disproportionate share of landscape biological diversity and directly influencing the integrity of stream ecosystems, including anadromous fish and amphibian species (Gregory et al., 1991; Bury, 2008). Due to the rugged topography of the region, most riparian forests are embedded in steep, forested landscapes and directly influenced by upslope land uses. They provide an important buffering role between upland land uses and aquatic life and provide corridors for dispersal of riparian-dependent wildlife.

- **Finding**: See table 1 for riparian tree species encountered in the four study watersheds, western Oregon, with four letter species codes, and functional group membership. Life history attributes are ranked from 1 (lowest tolerance or seed size) to 10 (highest) for each species.

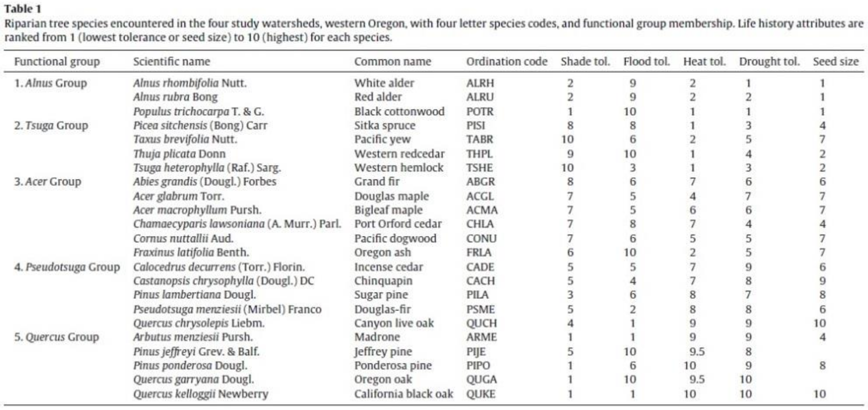
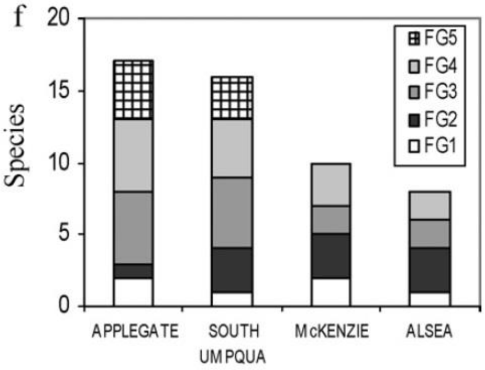


Table 1
Riparian tree species encountered in the four study watersheds, western Oregon, with four letter species codes, and functional group membership. Life history attributes are ranked from 1 (lowest tolerance or seed size) to 10 (highest) for each species.

Functional group	Scientific name	Common name	Ordination code	Shade tol.	Flood tol.	Heat tol.	Drought tol.	Seed size
1. *Alnus* Group	*Alnus rhombifolia* Nutt.	White alder	ALRH	2	9	2	1	1
	Alnus rubra Bong	Red alder	ALRU	2	9	2	2	1
	Populus trichocarpa T. & G.	Black cottonwood	POTR	1	10	1	1	1
2. *Tsuga* Group	*Picea sitchensis* (Bong) Carr	Sitka spruce	PISI	8	8	1	3	4
	Taxus brevifolia Nutt.	Pacific yew	TABR	10	6	2	5	7
	Thuja plicata Donn	Western redcedar	THPL	9	10	1	4	2
	Tsuga heterophylla (Raf.) Sarg.	Western hemlock	TSHE	10	3	1	3	2
3. *Acer* Group	*Abies grandis* (Dougl.) Forbes	Grand fir	ABGR	8	6	7	6	6
	Acer glabrum Torr.	Douglas maple	ACGL	7	5	4	7	7
	Acer macrophyllum Pursh.	Bigleaf maple	ACMA	7	5	6	6	7
	Chamaecyparis lawsoniana (A. Murr.) Parl.	Port Orford cedar	CHLA	7	8	7	4	4
	Cornus nuttallii Aud.	Pacific dogwood	CONU	7	6	5	5	7
	Fraxinus latifolia Benth.	Oregon ash	FRLA	6	10	2	5	7
4. *Pseudotsuga* Group	*Calocedrus decurrens* (Torr.) Florin.	Incense cedar	CADE	5	5	7	9	6
	Castanopsis chrysophylla (Dougl.) DC	Chinquapin	CACH	5	4	7	8	9
	Pinus lambertiana Dougl.	Sugar pine	PILA	3	6	8	7	8
	Pseudotsuga menziesii (Mirbel) Franco	Douglas-fir	PSME	5	2	8	8	6
	Quercus chrysolepis Liebm.	Canyon live oak	QUCH	4	1	9	9	10
5. *Quercus* Group	*Arbutus menziesii* Pursh.	Madrone	ARME	1	1	9	9	4
	Pinus jeffreyi Grev. & Balf.	Jeffrey pine	PIJE	5	10	9.5	8	
	Pinus ponderosa Dougl.	Ponderosa pine	PIPO	1	6	10	9	8
	Quercus garryana Dougl.	Oregon oak	QUGA	1	10	9.5	10	
	Quercus kelloggii Newberry	California black oak	QUKE	1	1	10	10	10

- **Finding**: Twenty-three tree species were classified by life history traits into five functional groups that differed in shade and drought tolerance; distribution and abundance of tree regeneration were analyzed by group. For most groups, seedling abundance varied substantially across the large scale climate gradient. In particular, drought tolerant species decreased sharply in abundance from the drier to wetter watersheds. Overall seedling frequency and diversity also decreased from the driest to wettest watersheds, while nurse log use increased. Regeneration of most, but not all, species was greater in gaps.
- **Finding**: Each functional group is hereafter designated by its functional group abbreviation, and, for ease in interpretation, the generic name of the most common species in the group:
  - Functional Group 1 (FG1), the Alnus Group, is a distinctive drought and shade intolerant group of broadleaved deciduous riparian species. The species in Functional Groups 2–5 show tradeoffs in shade and drought tolerance; the most drought tolerant species have low shade tolerance and vice versa (Fig. 2).
  - Functional Group 2 (FG2), the Tsuga Group, is a drought intolerant, but very shade tolerant group of coniferous species.
  - Functional Group 3 (FG3), the Acer Group, is a moderately drought tolerant, shade tolerant group of broadleaved deciduous and coniferous species.
  - Functional Group 4 (FG4), the Pseudotsuga Group, is composed of drought tolerant, moderately shade tolerant coniferous and broadleaved evergreen tree species.
  - Lastly, Functional Group 5 (FG5), the Quercus Group, is a group of very drought tolerant, shade intolerant conifers (pines) and both broadleaved deciduous and evergreen trees.
- **Finding**: We recorded major shifts in composition, frequency, and abundance of tree regeneration from southwest to northwest Oregon, i.e., from the Applegate, South Umpqua, McKenzie, and Alsea watersheds, respectively (Fig. 3). The frequency of regenerating trees in sampling plots decreased south to north. Frequency was 82.3%, 70.1%, 57.6%, and 14.9%, respectively, in the four watersheds, while the number of species recorded in each was 17, 16, 11, and 8 (Fig. 3f).

- **Finding**: Seedlings of the Alnus Group were most frequent and abundant near streams in all four watersheds (Fig. 3a, Table 3).
- **Finding**: In contrast to alders (Alnus spp.) which were relatively common along all streams in the region, we saw relatively few P. trichocarpa seedlings at our study sites along mountain streams. Those we saw were primarily at open, very disturbed areas, where local conditions (well-lit gravelly and cobbly terraces) appeared similar to those found along the larger alluvial rivers where the species is common (Dykaar and Wigington, 2000).
- **Finding**: Abundances for Tsuga Group species were highest in the South Umpqua and McKenzie watersheds, where the group, especially T. heterophylla, composed the majority of all tree regeneration (Fig.3b).
- **Finding**: After Acer macrophyllum, Abies grandis (Dougl.) Forbes was the most frequently regenerating species of the Acer Group (Table 3). Trees in this group showed a pronounced decline in seedling frequency and abundance from south to north. These species were most frequent close to streams in the Applegate and McKenzie watersheds and rarest on terraces in the Alsea watershed (Fig. 3c).
- **Finding**: Pseudotsuga Group species regenerated most frequently in the two southern watersheds (Fig. 3d, Table 3). Pseudotsuga menziesii and Castanopsis chrysophylla (Dougl.) DC. regenerated in all four watersheds, but were much more abundant in the south (Table 3). Quercus chrysolepis Liebm. was the most abundantly regenerating tree in the Applegate watershed, but was absent elsewhere (Table 3). Pinus lambertiana Dougl. and Calocedrus decurrens (Torr.) Florin regenerated sporadically in all three southern watersheds (Table 3).
- **Finding**: Regeneration of the Quercus Group was limited to the Applegate and South Umpqua watersheds and typically occurred at higher topographic positions (Fig. 3e, Table 3). No species was abundant. Quercus kelloggii Newberry was the most common, followed by Quercus garryana Dougl. and Arbutus menziesii Pursh. Pinus ponderosa Dougl. and Pinus jeffreyi Grev. & Balf. were uncommon and occurred primarily at high microelevations.



Species richness by functional group

- **Finding**: Nurse logs were important regeneration surfaces for conifers, principally those in the Tsuga Group, and secondarily in Pseudotsuga Group, but were typically used less than 10% of the time by the remaining species (Fig. 5a–e). The proportion of total seedlings on logs differed strongly among conifer species, from >75% for P. sitchensis and T. heterophylla, 20–35% for T. plicata, T. brevifolia, and P. menziesii, to 0% for Pinus spp. Among hardwood species, the proportions on logs were much lower, with a high of 11% for C. chrysophylla and less than 2% for all other species. Nurse log use was greatest in the Cascades watersheds, where down logs were prevalent and Tsuga dominated the regeneration layer.

- **Finding**: This study provided compelling evidence that riparian tree regeneration is an outcome of highly interactive factors operating at a multiple spatial scales. A central finding of this paper was that the frequency and composition of regenerating riparian trees can vary greatly across a geographically complex region such as western Oregon. To our surprise, the riparian forests in the relatively harsh, summer dry climates of the Applegate and South Umpqua watersheds of southwest Oregon had a much higher frequency of tree regeneration than wetter forests in the Alsea and McKenzie watersheds of northwest Oregon, although total seedling abundances were comparable (Fig. 2, Tables 3 and 4).
- **Finding**: Why should the frequency and abundance of regeneration decline in the highly productive riparian forests of the wetter climates? Although alternate explanations, such as local effects of pathogens or seed limitations are undoubtedly important for some species, we believe that interplant competition poses the primary limitation on riparian tree regeneration in the wetter, more productive Alsea and McKenzie watersheds.
- **Finding**: In the McKenzie watershed, where T. heterophylla cast deep shade on the floodplains of many streams, even species of reportedly high shade tolerance (e.g., A. grandis, Cornus nuttallii Aud.) regenerated only in gaps (Table 4). However, these same sites often had abundant T. heterophylla regeneration under the forest canopy (Table 3), suggesting that through shading, litter accumulation, and soil acidification, T. heterophylla modifies sites to its own advantage
- **Finding**: Riparian forest gaps yielded higher density of regeneration than nongaps for most species, suggesting such fine scale disturbances provide potentially important regeneration opportunities in these riparian forests, as in forests elsewhere (Hibbs, 1982; Veblen, 1989; Whitmore, 1989). However, species showed considerable variation in their dependence upon gaps for regeneration.
- **Finding**: This study confirmed the importance of organic substrates such as nurse logs as regeneration sites for conifers in wet riparian forests, but also demonstrated that that they are much less important in drier riparian forests of the Applegate watershed (Fig. 4).
- **Finding**: In all watersheds, the regeneration of trees in the Alnus Group was strongly linked to wet streamside environments with ample light and mineral soils and showed a strong affinity with forest gaps, confirming that these species are ruderal (Grime, 1977) or pioneer (Whitmore, 1989) species that are adapted to establish in fluvially disturbed environments.
- **Finding**: Trees in the Tsuga group showed the opposite pattern with respect to shade and seedbed preferences as the Alnus Group, commonly regenerating under conifer canopies and on organic seedbeds. Tsuga Group trees employ the continuous regeneration mode (Veblen, 1992) characteristic of climax species (Whitmore, 1989), being less dependent upon disturbance than the other species measured.
- **Finding**: Trees in Acer, Pseudotsuga, and Quercus Groups, together containing 16 species, fell between Whitmore's (1989) pioneer and climax typologies. Tree species in the Acer Group showed the strongest evidence of context-dependent regeneration

behavior. Although species in the Acer Group are typically described as shade tolerant, climax species in mixed conifer and mixed evergreen forests (Waring and Major, 1964; Minore, 1979; Burns and Honkala, 1990a,b), they showed a marked decrease in abundance in forests with the heavily shade tolerant trees of the Tsuga Group, or with clonal shrubs such as R. spectabilis, adopting pioneer behavior in such settings. Regeneration of both A. macrophyllum and A. grandis in the Acer Group also appeared to occur most frequently on floodplains in the South Umpqua and Applegate watersheds, suggesting that the moist, deep soils in those summer dry climates allow suitable establishment conditions for these moderately drought tolerant species.

- Finding: The drought tolerant and less shade tolerant species in the Pseudotsuga and Quercus groups showed sharp drops in regeneration frequency and abundance from driest to wettest watersheds, and a strong association with gaps wherever they occurred. These tree species appear to be the stress tolerators of these riparian forests (Grime, 1977). Because several of the species in these groups (e.g., Q. chrysolepis) showed southern affinities, their lower abundances in the northern watersheds may reflect seed source as well as ecological limitations.
- Finding: In contrast, dominant, reproductively mature P. menziesii were present in most of the stands we sampled in northwest Oregon, suggesting ecological factors, such as competition, are driving the low levels of regeneration we observed. The microsites where these species regenerated, often with thin, rocky, soils, and on steep, hot south-facing slopes with considerable summer drought stress, are abundant in the Applegate watershed, but become less widespread in the wetter watersheds.
- Finding: The general impression is that regeneration behavior is relatively complex and strongly opportunistic; species will regenerate wherever local conditions fall within their environmental tolerances and they can effectively compete for space.
- Management: Management or restoration of riparian forests, therefore, requires knowledge of site conditions, the life history of the riparian trees present, and in particular an understanding of the species' environmental tolerances, disturbance responses, and competitive abilities relative to one another.
- Management: What can a riparian forest manager learn from this study of natural tree regeneration? First, that there is no blueprint for riparian restoration. Riparian environments in western Oregon show great variation from place to place, with corresponding changes in the regeneration behavior of the majority of species present. Because these mountain riparian forests are embedded in the upland watersheds, they are closely coupled to regional climate patterns (Sarr and Hibbs, 2007a,b), and they also contain many upland trees mixed with the familiar "riparian" trees we associate with alluvial rivers.
- Management: Second, because the riparian forests in all the watersheds we studied contain a rich array of tree species, amanager interested in riparian forest establishment has excellent opportunities to match one or more of the native species with local riparian conditions. Challenges will vary by locale. Across the dry to wet gradient we studied, drought and competition appear to shift in importance as the primary constraints on the frequency and abundance of the species in the regeneration layer. In

the drier climates of the Applegate and South Umpqua watersheds, summer drought is a major factor. Sarr and Hibbs (2007b) demonstrated that the streamside to hillslope gradient in the drier watersheds is associated with much greater changes in summer plant moisture stress than in the wetter watersheds. Consequently, selection of species with a range of drought tolerances will be necessary for riparian restoration, and survival of naturally regenerating and planted seedlings is likely to be quite sensitive to height above the stream channel, aspect, and soil depth.

  - Seedlings of species in the Alnus Group, in particular, are likely to survive only at lowest microelevations adjacent to the active stream channel. Species in the Acer and Tsuga Groups are also most likely to regenerate and thrive in lower topographic positions such as floodplain terraces, and perhaps lower north facing slopes, with species in the latter group likely to benefit from filtered shade. Drought adapted species in the Pseudotsuga, and Quercus Groups, although not typically considered riparian, compose a large proportion of the biomass and the natural regeneration in such dry forests, and should be considered in restoration projects.

- **Management**: In contrast, in the wetter climates of the McKenzie and especially Alsea watersheds, summer drought is less of a concern, but variation in light availability and soils may nonetheless drive some topographic segregation of species. Vigorous growth of understory vegetation, especially clonal shrubs, probably will limit the success of slow growing or shade intolerant species. Generally, the conditions in the wettest watershed strongly favor dominance by the Alnus Group near streams and in disturbed areas and by the Tsuga Group in older forest settings or less frequently disturbed upper floodplains and hillslopes. Slower growing species in the Acer, Pseudotsuga, and Quercus Groups are unlikely to regenerate in such forests without sizable disturbance gaps, and may not be suitable at all in some settings.
- **Management**: Third, managers pursuing conifer establishment in riparian forests, which is a common riparian restoration goal in the Pacific Northwest (Stolnack and Naiman, 2010), will need to recognize the important variation in life history traits of the common riparian conifer species. Two of the conifers in the Tsuga Group, T. heterophylla and T. brevifolia appear to demonstrate continuous regeneration under conifer canopies, and retention of mature seed trees should be adequate to foster regeneration of these two species in northwest and southwest Oregon riparian forests, respectively.
- **Management**: The remaining conifer species in this study, especially those in the Pseudotsuga and Quercus Groups, tended to regenerate in midslope and hillslope positions in gap environments. This suggests that their regeneration is strongly influence by upland disturbance regimes, such as fire.

Serra-Diaz et al. 2017. Disequilibrium of fire-prone forests sets the stage for a rapid decline in conifer dominance during the 21st century. doi: http://dx.doi.org/10.1101/163899

- **Finding**: Using a landscape simulation model, we estimate that 1/3 of the Klamath could transition from conifer forest to shrub/hardwood chaparral, triggered by an enhanced fire activity coupled with lower post-fire conifer establishment.
    - Such shifts were more prevalent under higher climate change forcing (RCP 8.5) but were also simulated under the climate of 1950-2000, reflecting the joint influences of early warming trends and historical forest legacies.
- **Finding**: Our results demonstrate that there is a large potential for loss of conifer forest dominance—and associated carbon stocks and biodiversity-- in the Klamath before the end of the century, and that some losses would likely occur even without the influence of climate change.
- **Finding**: Thus, in the Klamath and other forested landscapes subject to similar feedback dynamics, major ecosystem shifts should be expected when climate change disrupts key stabilizing feedbacks that maintain the dominance of long-lived, slowly regenerating trees.

Skinner et al. 2006.

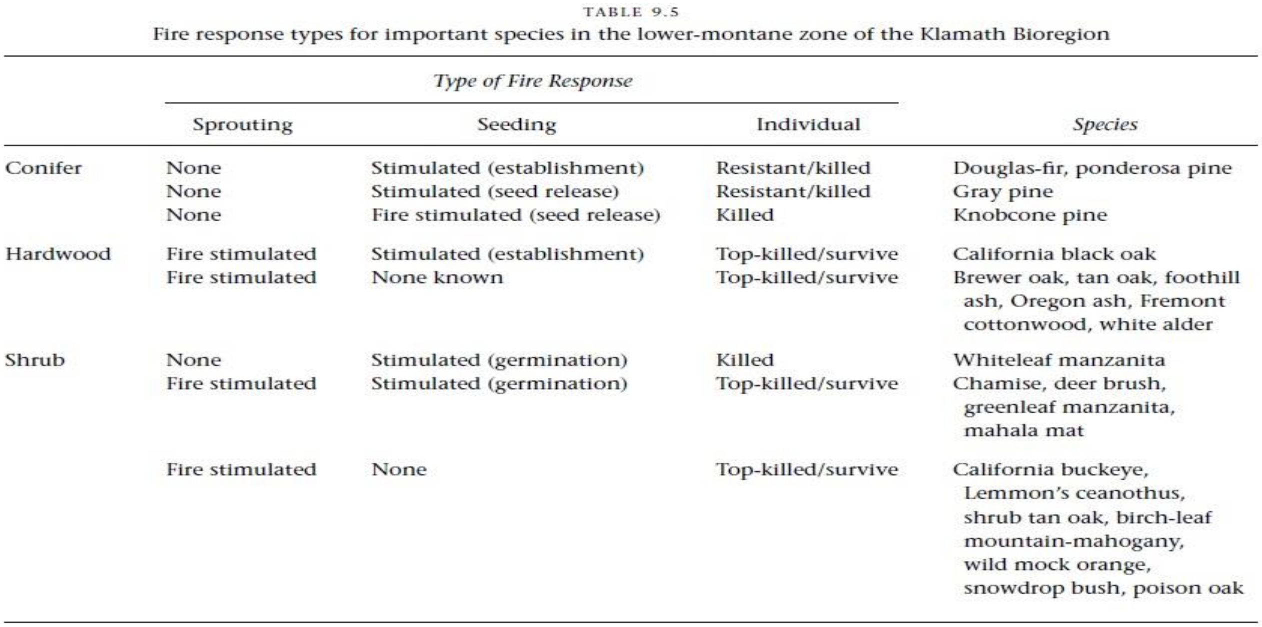
- **Background**: The very steep and complex terrain of the Klamath Mountains covers approximately 22,500 km2 (8,690 mi2), or 6% of California. The bioregion includes the Klamath and Trinity River systems, the headwaters of the Sacramento River, the most extensive exposure of ultramafic rocks in North America (Kruckeberg 1984), and the most diverse conifer forests in North America (Cheng 2004) (Map 9.1).
- **Background**: The Klamath Mountains have been deeply dissected by the Klamath, McCloud, Sacramento, and Trinity Rivers with no consistent directional trends. Only two sizable alluvial valleys, Scott Valley and Hayfork Valley, occur here (Oakeshott 1971, McKee 1972). Elevations in the Klamath Mountains range from 30 m (100 ft) to 2,755 m (9,038 ft). From north to south, several prominent ranges or ridge systems comprise the Klamath Mountains with Mt. Eddy being the highest peak (Oakeshott 1971, McKee 1972). The crests of these ridge systems are usually between 1,500 m (4,900 ft) and 2,200 m (7,200 ft) (Irwin 1966).
- **Background**: The complexity of the geology and terrain has a strong influence on the structure, composition, and productivity of vegetation in the Klamath Mountains (Whittaker 1960). The topography and vegetation influence fire regimes. Spatial variation in soil productivity combined with steep gradients of elevation and changes in slope aspect across landscapes control the connectivity, structure, and rates of fuel accumulation.
- **Background**: The climate of the Klamath Mountains is mediterranean, characterized by wet, cool winters and dry, warm summers. However, the local expression of this climate regime is remarkably variable due to a strong west to east moisture and temperature gradient caused by proximity to the Pacific Ocean and steep elevation gradients that influence temperature and the spatial pattern of precipitation via orographic effects. The contemporary climatic phase appears to have become established about 3,500–4,000 years ago (West 1985, 1988, 1989, 1990; Mohr et al. 2000).
- **Background**: Although most precipitation falls between October and April, there is considerable local and regional geographic variation in the amount of annual precipitation. Generally, less precipitation falls in valleys and canyons than in the surrounding uplands with strong gradients over short horizontal distances. Precipitation declines with distance from the coast in both the northern and southern Klamaths.
- **Background**: Overall, critical fire weather is associated with any weather condition that creates sustained periods of high-velocity winds with low humidity. In the Klamath Mountains, critical fire weather conditions are created by three different weather patterns described by Hull et al. (1966): (1) Pacific High–Post-Frontal (Post-Frontal), (2) Pacific High–Pre-Frontal (Pre-Frontal), and (3) Subtropical High Aloft (Subtropical High).
  - Post-Frontal conditions occur when high pressure following the passage of a cold front causes strong winds from the north and northeast. Temperatures rise and humidity declines with these winds.
  - Pre-Frontal conditions occur when strong, southwesterly or westerly winds are generated by the dry, southern tail of a rapidly moving cold front. Strong winds

  are the key here because temperatures usually drop and relative humidity rises as the front passes.
  - Subtropical High conditions occur when the region is under the influence of descending air from high pressure that causes temperatures to rise and humidity to drop. In the Klamath Mountains, these conditions lead to fires controlled mostly by local topography. Subtropical High conditions also promote the development of strong temperature inversions that inhibit smoke from venting out of the canyons and valley bottoms. The combination of smoke and lack of vertical mixing created by strong inversions, especially following initiation of widespread lightning-caused fires, reduces fire intensity.
- **Background**: Lightning is common in the Klamath Mountains with 12.8 strikes (range 6.4–26.4)/yr/100 km2 (33.7 strikes [range 16.8–69.4]/yr/100 mi2). Lightning-caused fires have accounted for most area burned in recent decades (e.g., 1977, 1987, 1999, and 2002). Lightning may ignite hundreds of fires in a 24- hour period.
- **Background**: Lightning occurrence increases with distance from the coast and with increasing elevation (van Wagtendonk and Cayan 2007).
- **Background**: Storms that produce lightning-caused fires are associated with higher instability and higher dew point depression (drier air) than storms that produce the most lightning strikes (Rorig and Ferguson 1999, 2002). Additionally, in both 1987 and 1999, a single storm episode was responsible for nearly all of the area burned by lightning-caused fires.
- **Background**: The Klamath Mountains are thought to be of central importance in the long-term evolution and development of western forest vegetation because of this diversity and the mixing of floras from the Cascade/Sierra Nevada axis and the Oregon/California coastal mountains that intersect in the Klamath Mountains (Whittaker 1961, Smith and Sawyer 1988). Vegetation and species diversity generally increases with distance from the coast and species diversity is highest in woodlands with a highly developed herb strata (Whittaker 1960).
- **Background**: The rugged, complex topography and resulting intermixing of vegetation in the Klamath Mountains defies a simple classification of ecological zones by elevation. Nevertheless, this chapter discusses three general zones:
  - (1) a diverse lower montane zone of mixed conifer and hardwood forests, woodlands, and shrublands;
  - (2) a mid-upper montane zone where white fir (Abies concolor) is abundant and hardwoods are less important;
  - (3) a subalpine zone where white fir, Douglas-fir (Pseudotsuga menziesii var. menziesii), sugar pine (Pinus lambertiana), and ponderosa pine (Pinus ponderosa) drop out and are replaced by upper montane and subalpine species such as Shasta red fir (Abies magnifica var. shastensis), mountain hemlock (Tsuga mertensiana), western white pine (Pinus monticola), Jeffrey pine (Pinus jeffreyi), whitebark pine (Pinus albicaulis), lodgepole pine (Pinus contorta spp. murrayana), foxtail pine (Pinus balfouriana), and curl-leaf mountain-mahogany (Cercocarpus ledifolius).

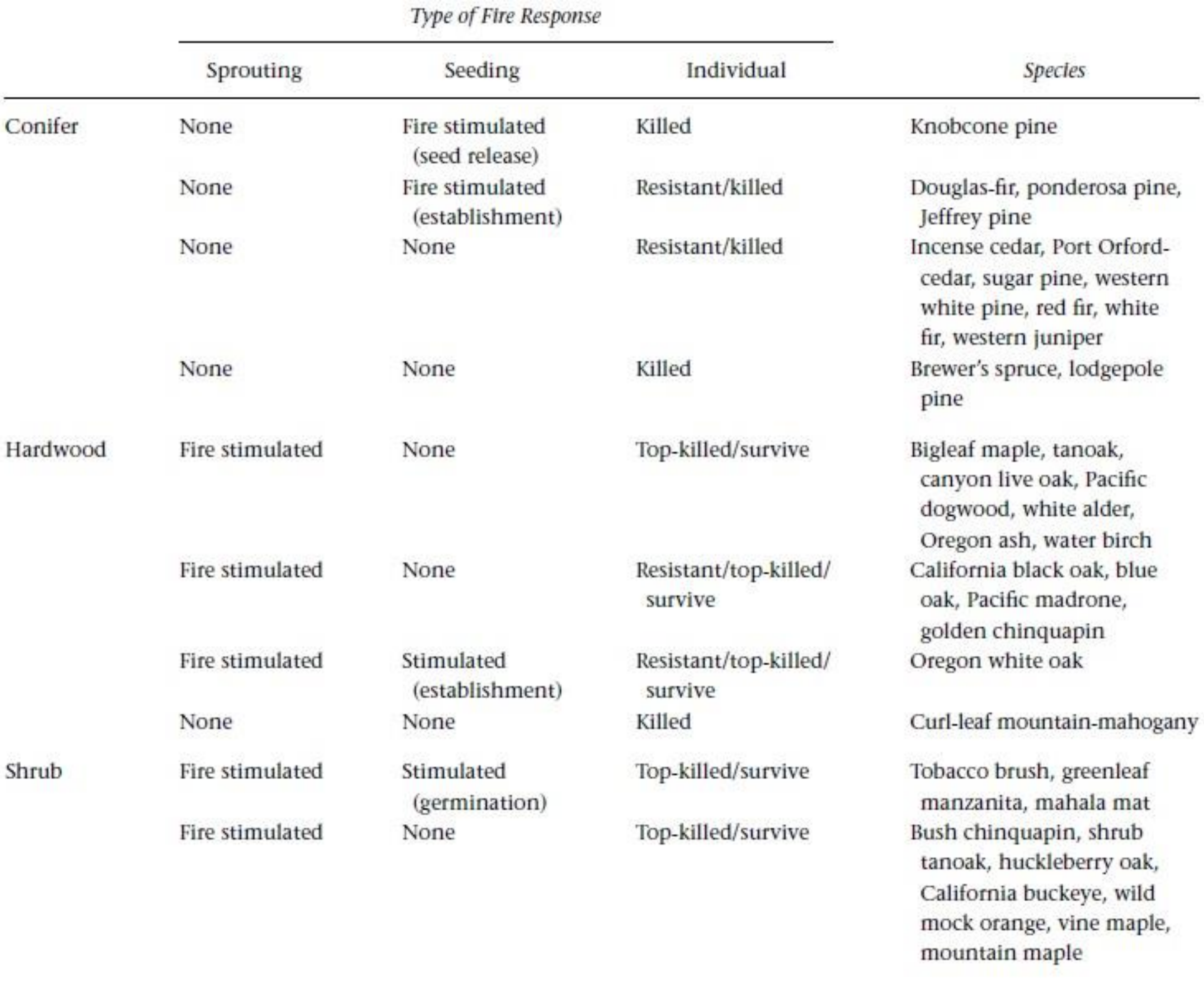
- **Background**: Contemporary vegetation assemblages coalesced approximately 3,000 to 4,000 years ago when the climate cooled and became moister compared to the previous several millennia (West 1985, 1988, 1989, 1990; Mohr et al. 2000). Because the dominant tree species have potential life spans of 500 to 1,000+ years (Brown 1996, 2002), the current forest assemblages have existed for only a few life spans of the dominant tree species.
- **Background**: Fire regimes characteristic of the pre-settlement period (i.e., 1600 A.D.–1850 A.D.) have been in place for approximately the last 1,000 years (Mohr et al. 2000).
- **Background**: Native people of the Klamath Mountains used fire in many ways:
    - (1) to promote production of plants for food (e.g., acorns, berries, roots) and fiber (e.g., basket materials);
    - (2) for ceremonial purposes;
    - (3) to improve hunting conditions (Lewis 1990, 1993; Pullen 1995).
    - Though native ignitions appear to have been widespread, we do not know the extent of their influence on fire regimes and vegetation at broad scales.
- **Background**: Several fire history studies describe fire regimes in parts of the Klamath Mountains over the last few centuries (Agee 1991; Wills and Stuart 1994; Taylor and Skinner 1997, 1998, 2003; Stuart and Salazar 2000; Skinner 2003a, 2003b; Fry and Stephens 2006).
    - These studies indicate there are two periods with distinctly different fire regimes:
        - (1) the Native American period, which usually includes both the pre-historic and European settlement period, and
        - (2) the fire suppression period.
    - Though there is variation among sites as to when fire suppression became effective, the temporal patterns of fire occurrence in the pre–fire suppression period indicate that most stands experienced at least several fires each century.
    - This suggests a general fire regime of frequent, low- to moderate- intensity fires.
- **Background**: Before fire suppression, fires of higher spatial complexity created openings of variable size within a matrix of forest that was generally more open than today (Taylor and Skinner 1998). This heterogeneous pattern has been replaced by a more homogenous pattern of smaller openings in a matrix of denser forests (Skinner 1995a). Thus, spatial complexity has been reduced. The ecological consequences of these changes are likely to be regional in scope, but they are not yet well understood.
- **Background**: A typical pattern of fire severity is illustrated in Figure 9.7 (Taylor and Skinner 1998). Generally, the upper third of slopes and the ridgetops, especially on south- and west-facing aspects, experience the highest proportion of high-severity burn.
- **Background**: Douglas-fir, once mature, is very resistant to low- to moderate-intensity surface fires due to a variety of characteristics. Douglas-fir has very thick bark, a deep rooting habit, high crowns (Agee 1993), short needles, heals fire wounds rapidly, and does not slough bark. In fact, Douglas-fir is the most fire-resistant tree species in the Klamath Mountains. Its common conifer associates, ponderosa, Jeffrey, and sugar pine, are also fire resistant and have thick bark, root deeply, and have high, open crowns.

TABLE 9.5

Fire response types for important species in the lower-montane zone of the Klamath Bioregion



	Type of Fire Response			
	Sprouting	Seeding	Individual	*Species*
Conifer	None	Stimulated (establishment)	Resistant/killed	Douglas-fir, ponderosa pine
	None	Stimulated (seed release)	Resistant/killed	Gray pine
	None	Fire stimulated (seed release)	Killed	Knobcone pine
Hardwood	Fire stimulated	Stimulated (establishment)	Top-killed/survive	California black oak
	Fire stimulated	None known	Top-killed/survive	Brewer oak, tan oak, foothill ash, Oregon ash, Fremont cottonwood, white alder
Shrub	None	Stimulated (germination)	Killed	Whiteleaf manzanita
	Fire stimulated	Stimulated (germination)	Top-killed/survive	Chamise, deer brush, greenleaf manzanita, mahala mat
	Fire stimulated	None	Top-killed/survive	California buckeye, Lemmon's ceanothus, shrub tan oak, birch-leaf mountain-mahogany, wild mock orange, snowdrop bush, poison oak



	Type of Fire Response			
	Sprouting	Seeding	Individual	*Species*
Conifer	None	Fire stimulated (seed release)	Killed	Knobcone pine
	None	Fire stimulated (establishment)	Resistant/killed	Douglas-fir, ponderosa pine, Jeffrey pine
	None	None	Resistant/killed	Incense cedar, Port Orford-cedar, sugar pine, western white pine, red fir, white fir, western juniper
	None	None	Killed	Brewer's spruce, lodgepole pine
Hardwood	Fire stimulated	None	Top-killed/survive	Bigleaf maple, tanoak, canyon live oak, Pacific dogwood, white alder, Oregon ash, water birch
	Fire stimulated	None	Resistant/top-killed/survive	California black oak, blue oak, Pacific madrone, golden chinquapin
	Fire stimulated	Stimulated (establishment)	Resistant/top-killed/survive	Oregon white oak
	None	None	Killed	Curl-leaf mountain-mahogany
Shrub	Fire stimulated	Stimulated (germination)	Top-killed/survive	Tobacco brush, greenleaf manzanita, mahala mat
	Fire stimulated	None	Top-killed/survive	Bush chinquapin, shrub tanoak, huckleberry oak, California buckeye, wild mock orange, vine maple, mountain maple

- **Background**: White fir has thin bark when young, but its bark is not shed and thickens with age, making it more fire tolerant when mature. Shasta red fir is similar but appears to be more sensitive than white fir at all ages. Port Orford cedar stands often include trees more than 300 years old with open, charred wounds (cat faces) indicating they commonly survived low to moderate-intensity surface fires (Table 9.7).

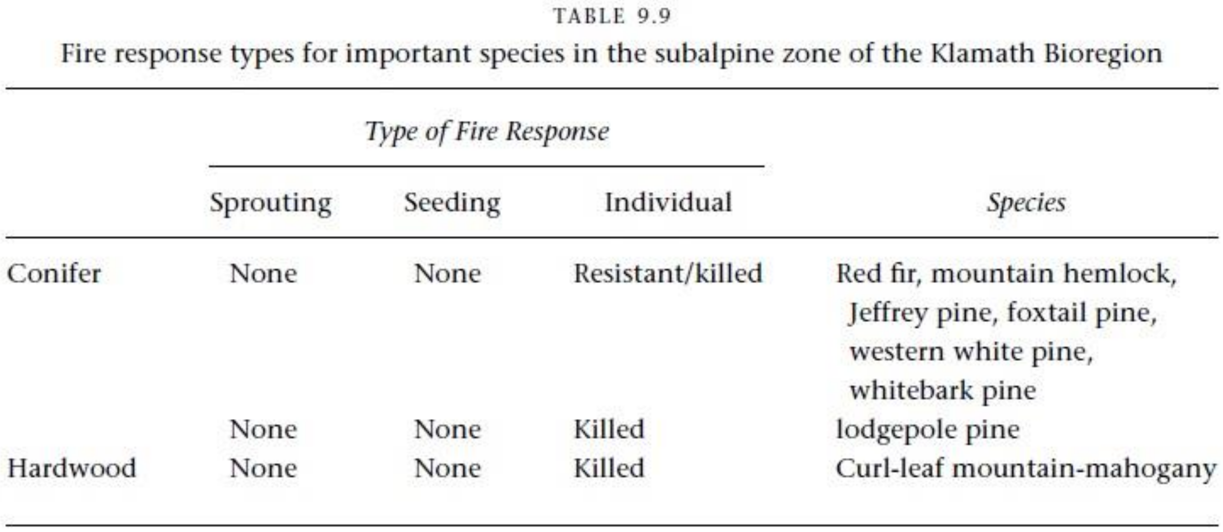


TABLE 9.9

Fire response types for important species in the subalpine zone of the Klamath Bioregion

	Type of Fire Response			
	Sprouting	Seeding	Individual	*Species*
Conifer	None	None	Resistant/killed	Red fir, mountain hemlock, Jeffrey pine, foxtail pine, western white pine, whitebark pine
	None	None	Killed	lodgepole pine
Hardwood	None	None	Killed	Curl-leaf mountain-mahogany

- **Background**: Most tree species in the subalpine zone, including mountain hemlock, Shasta red fir, white bark pine, western white pine, foxtail pine, lodgepole pine, and curl-leaf mountain mahogany have thinner bark than species found at lower elevations and are easily damaged or killed by moderate-intensity fire or the consumption of heavy surface fuels at the base of the tree.
- **Background**: More-recent management activities, such as logging and replacement of multi-aged old-growth forests with even-aged forest plantations and continued fire suppression have reduced forest heterogeneity, increased the proportion of even-aged forests, and altered habitat conditions for forest-dwelling species compared to conditions in the pre–fire-suppression landscape (USDAs-USDI 1994).
- **Background**: Primarily due to the annual summer drought and ample winter precipitation, fires were historically frequent and generally of low to moderate and mixed severity in most vegetation assemblages, especially those that cover large portions of the Klamath Mountains. Fire exclusion and other management activities have led to considerable changes in Klamath Mountain ecosystems over the last century. Of all management activities that have contributed to altering ecosystems in the Klamath Mountains, fire suppression has been the most pervasive since it alone has been ubiquitously applied.
- **Management**: Recent studies suggest that vegetation patterns and conditions generated by pre–fire-suppression fire regimes (Taylor and Skinner 1998, 2003) may be advantageous for wildlife species of concern such as the northern spotted owl (Strix occidentalis caurina) (Franklin et al. 2000) and several species of butterflies (Huntzinger 2003).
- **Management**: Hardwoods, especially oaks, provide important habitat elements for many species of wildlife. As a result, managers may use prescribed fire to inhibit conifer encroachment into oak stands as well as to improve acorn crops (Skinner 1995b).

- **Management**: Quantities of large woody material for standards and guidelines were developed from contemporary old-growth forests that had experienced many decades of fire suppression. These quantities of woody material were probably unusually high compared to typical pre–fire-suppression values. Consequently, a management emphasis on meeting or exceeding standards and guidelines for dead woody material has and will increase fire hazard over time and threatens the very habitat the standards and guidelines were designed to improve (Skinner 2002b).
- **Management**: Though there is much current discussion of the need for restoring fire as an ecological process, or at least creating stand structures that would help reduce the general intensity of fires to more historical levels, there are many competing social/political concerns and objectives (e.g., fine filter approaches to managing wildlife habitat and air quality) that make doing anything problematic (Agee 2003).

Spittlehouse and Stewart. 2003.

- **Study**: The objective of this paper is to encourage the forestry community to evaluate the long-term impacts of climate change and determine what the community might do now and in the future to respond to this threat.
- **Study**: We focus here on a framework for planning adaptive actions.
- **Climate Change Impacts**: By the end of the 21st century, the mean annual temperature for western North America could be 2–5°C above the range of temperatures that have occurred over the last 1000 years.
- **Climate Change Impacts**: An increase in winter precipitation and a decrease in summer precipitation may also occur. These changes would significantly affect human society and ecosystems (McCarthy et al. 2001).
- **Background**: Predictions of biological changes over the next century range from large-scale biome shifts (Aber et al. 2001; Scott et al. 2002) to relatively less extensive disruptions in forest growth (Loehle 2000). Responses will be at the species level with the movement of species ranges northward and up in elevation, and the occurrence of new assemblages of species in space and time (Hebda 1997; Kirschbaum 2000; Hansen et al. 2001).
- **Governance**: Adaptation is not something to be applied only in the future; actions are needed now in anticipation of future conditions.
- **Finding**: We focus here on a framework for planning adaptive actions. The framework consists of four steps (see Table 1). The first is defining the issue. The second involves the assessment of the vulnerability to change (sensitivity, adaptive capacity) of the forest, forest communities, and society. This allows the development of adaptive actions to be taken now (step 3) and those required for the future (step 4) as change occurs.
- **Finding**: The precautionary principle advocates taking steps by implementing strategies that are useful now, but would also reduce the risk of unacceptable losses in the future. Many actions required to adapt to climate change benefit the present as well as the future (e.g., provenance trials). Forest policy needs to be assessed to ensure it encourages adaptation (Duniker 1990; Parker et al. 2000; Burton et al. 2002).
- **Finding**: Existing forests are quite resistant to climate variability (Noss 2001)—it is the regeneration phase that will initially be susceptible to the changed climate.
- **Finding**: Adaptive actions include: Identifying drought-tolerant genotypes (Farnum 1992). Assisting the migration of commercial tree species from their present to future ranges through artificial regeneration (Parker et al. 2000). The northward movement of certain species will, in some instances, be hindered by the lack of suitable soil conditions, such as nutrients, soil depth, and mycorrhizae. Planting provenances that grow adequately under a wide range of conditions and (or) planting stock from a range of provenances at a site (Ledig and Kitzmiller 1992). Controlling undesirable plant species, which become more competitive in a changed climate, through vegetation management treatments (Parker et al. 2000).
- **Finding**: In the case of most non-timber resources, management will likely be limited to minimizing impediments to autonomous adaptation through: Minimizing fragmentation

of habitat and maintaining connectivity (Peters 1990; Noss 2001). Maintaining representative forest types across environmental gradients and protecting primary forests (Holling 2001; Noss 2001; Carey 2003). Established forests are often able to survive extensive periods of unfavourable climates and this inertia could extend the time period over which adaptation could take place. Maintaining diversity of functional groups as well as species within groups (Holling 2001; Noss 2001).

Staus et al. 2002. Rate and pattern of forest disturbance in the Klamath-Siskiyou ecoregion, USA between 1972 and 1992. Landscape Ecology 17: 455-470.

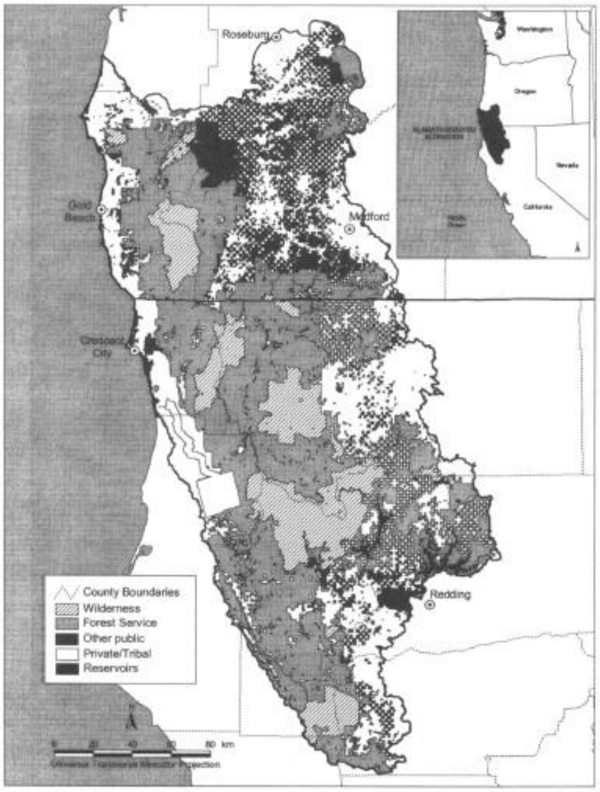
- **Study**: We classified NALC (North American Landscape Characterization) imagery to forest-nonforest and examined forest change between 1972 and 1992 in the Klamath-Siskiyou ecoregion (USA) in relation to land ownership and fifth level watersheds.
- **Study**: We also analyzed changes in forest patterns by land ownership for three major river basins within the ecoregion (Eel, Klamath, and Rogue) using FRAGSTATS.
- **Study**: Therefore, we used satellite remote sensing data to examine the rates and patterns of coniferous forest landscape change over a 20-yr period in the Klamath- Siskiyou with special attention to land ownership. We first examined changes in the ecoregion as a whole to understand landscape changes at the regional level.
- **Background**: When landscapes are disturbed naturally or by humans, forest patches are often divided into smaller units that can become isolated in the surrounding nonforest matrix leading to fragmentation of the original vegetation communities (Franklin and Forman 1987).
    - This fragmentation can have far-reaching effects on the structural and functional characteristics of a landscape and can have serious consequences for maintaining native biodiversity (Harris 1984).
- **Background**: Spatial characteristics of forested landscapes such as patch size and abundance, amount of edge, and habitat connectedness directly influence organisms within the landscape (Harris 1984; Franklin and Forman 1987).
- **Finding**: Overall, forests covered 66.8% of the ecoregion in 1972 and 62.1% in 1992. Approximately 10.5% of the forest area was disturbed overall, translating into an annual disturbance rate of 0.53%. Although public lands accounted for a slightly higher total area of forest disturbance, private lands were cut at a slightly higher rate. Forest disturbance within fifth level watersheds averaged 13.2%, but reached as high as 93.2%.
- **Finding**: For the three river basins where spatial pattern of forest disturbance was analyzed, private lands were already more fragmented than public lands in 1972.
- **Finding**: Over the 20- year time period, forest fragmentation increased on all ownerships. Fragmentation rates on public lands were high for all basins especially the Rogue.
- **Finding**: Clear-cut logging on private lands was generally in larger adjacent tracts, whereas cuts on public lands were generally smaller and more dispersed.
- **Finding**: Our results illustrate the importance of considering landscape change history when planning for effective biodiversity conservation in forested ecoregions and when formulating ecologically sustainable forest management strategies.
- **Finding**: Although forest disturbance in the Klamath-Siskiyou was moderate compared to many other temperate forest regions, the fact that forest area continues to decline and fragmentation measurements continue to increase regardless of ownership is cause for concern. Some subregions showed particularly high disturbance rates (e.g., Rogue Basin).
- **Finding**: Spatial characteristics of the Klamath-Siskiyou forests have changed in important ways between 1972 and 1992. Overall, forest disturbance has outpaced regeneration and forest patches have decreased in size and connectivity.

Stralberg et al. 2009.

- **Study**: We used a multivariate approach borrowed from paleoecology to quantify the potential change in California terrestrial breeding bird communities based on current and future species-distribution models for 60 focal species.
- **Study**: We used a representative subset of terrestrial breeding birds to evaluate the potential for no-analog assemblages as a result of projected climate disruption. We chose birds for this analysis due to their high trophic position, relatively high visibility and detectability during the breeding season, and high mobility, which we assume allow them to track environmental change rapidly [25,26]. We used high-quality, breeding-season datasets from multiple sources to develop intermediate-scale (800-m pixel resolution) spatial models to predict current and future probabilities of occurrence for each of 60 focal species selected to represent avian communities of five major habitat types: oak woodland, coniferous forest, chaparral/scrub, grassland, and riparian [27].
- **Study**: Our analysis assumes that species interactions do not constrain current or future species distributions. This is one of the chief limitations of an empirical SDM approach, which necessarily models the realized, rather than fundamental niche of a species
- **Background**: current community dynamics such as predator-prey or competitive interactions may become affected as species assemblages are reshuffled in new ways [9]. New species interactions that develop within these no-analog assemblages may result in the decline or extirpation of species as they adjust or adapt to changing climates, especially when the climate is changing at a rapid rate.
- **Background**: Entirely unique combinations of species and the new interactions that occur among those species may lead to even greater rates of local extirpation if species cannot adapt quickly enough [19].
- **Background**: the high frequency of no-analog bird communities that may occur over the next century can be said to reflect the individualized nature of climate-change impacts on different species and the transient nature of current ecological communities as we know them [43,44].[12].
- **Climate Change Impacts**: Climate models generally concur in projections of significant warming for California over the next century, with small changes in precipitation but potentially large declines in snow accumulation [22,23].
- **Finding**: Projections of future no-analog communities based on two climate models and two species-distribution-model algorithms indicate that by 2070 over half of California could be occupied by novel assemblages of bird species, implying the potential for dramatic community reshuffling and altered patterns of species interactions.
- **Finding**: The expected percentage of no-analog bird communities was dependent on the community scale examined, but consistent geographic patterns indicated several locations that are particularly likely to host novel bird communities in the future.
- **Finding**: Our analysis suggests that, by 2070, individualistic shifts in species' distributions may lead to dramatic changes in the composition of California's avian communities, such that as much as 57% of the state (based on the scales of communities that we examined) may be occupied by novel species assemblages.

- **Finding**: although net changes in the distributions of common species may be relatively small due to the combination of local decreases and increases, the cumulative effect on community composition is likely to be great due to variation in individual species' responses to climate disruption and resulting differences in geographic shifts.
- **Finding**: Based on the most refined delineation of communities, our analysis revealed several no-analog ''hotspots,'' primarily in arid inland portions of the state. These patterns may reflect the greater climatic variability of inland areas with continental climates and little or no moderating maritime influence, which are also likely to be more influenced by climate disruption [21].
- **Finding**: In addition, regions of high geologic diversity such as the Klamath Mountains in northern California, which represent the convergence of three mountain ranges [40], may also have high bird community heterogeneity and thus greater potential for the re-shuffling of species.
- **Management**: The likely emergence of novel, no-analog communities over the coming decades presents enormous conservation and management challenges. These challenges will be exacerbated in the high proportion of landscapes that are dominated by intensive human management [46,47], where it will be more difficult for species to move to new climatically suitable areas.
- **Management**: Managers and conservationists will be faced with difficult choices about how, where, and on which species to prioritize their efforts and investments. Traditional management approaches that focus on maintaining the status quo will not likely be successful; novel approaches will be needed to manage novel communities [48]. Adaptive management will become even more important as conservation targets shift and new ones emerge in unanticipated ways. Successful adaptive management will depend on rapid transfer of information from the scientific community to resource managers so that decisions can be made quickly.

Strittholt and DellaSala. 2001.



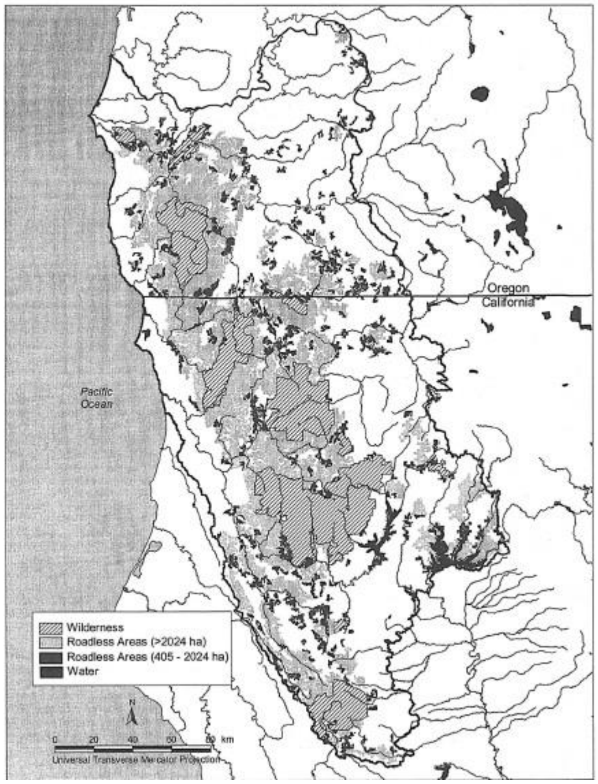
- **Study**: We examined the ecological attributes of mapped roadless areas for the Klamath-Siskiyou ecoregion of northwestern California and southwestern Oregon (U.S.A.).
  - Attributes examined include
    - special elements (such as natural heritage, serpentine geology, late-seral forests, Port Orford cedar [Chamaecyparis lawsonianal),
    - key watersheds;
    - elevation and habitat representation;
    - overall landscape connectivity.
- **Study**: We compared designated wilderness to roadless areas, giving special attention to the relative importance of small roadless areas (405-2024 ha). We mapped nearly 500 roadless areas of >405 ha.
- **Study**: we sought to evaluate the ecological attributes of existing roadless areas in a forest ecoregion, the Klamath- Siskiyou. The ecological attributes we examined included five special elements of conservation concern, two representation evaluations, and regional landscape connectivity.
- **Background**: Roads allow access to pristine areas and fragment native ecosystems into smaller and smaller patches of various sizes and shapes (Dickman 1987; Atkinson & Cairns 1992).
- **Background**: According to the National Research Council (1997), there are approximately 4 million miles of roadway in the United States. That covers about 1% of the conterminous United States, but the negative ecological effects of the "road-effect zone" are often much greater-18-22% (Forman 2000).
- **Background**: Roads constructed to gain access to resources on public lands have been substantial, and in some cases extremely heavy, over the last 50 years. It is difficult to determine the number of all roads currently on public lands, but agency estimates exist. The U.S. Forest Service (USFS) maintains approximately 440,000 miles of roads, nearly 10 times the total length of the interstate highway system.
- **Background**: Roads and the maintenance of roads affect natural terrestrial and aquatic environments in many ways. Increased erosion, air, and water pollution, spread of invasive exotics, road mortality and avoidance, and habitat fragmentation all

accompany roads (reviewed by Andrews 1990; Spellerberg 1998; Jones et al. 2000; Trombulak & Frissell 2000). Roads directly fragment natural ecosystems (Reed et al. 1996), but -more importantly- they also provide access to areas, which leads to subsequent human disturbances from activities such as logging, mining, grazing, agriculture, and urban development. These disturbances result in substantial declines in native species and an overall degradation of ecosystem integrity.

- **Background**: As large unroaded lands disappear, a minimum size of 405 ha is now being examined for wilderness designation. (Was originally a min size of 2024 ha in 1964.)
- **Background**: The World Conservation Union (IUCN) considers the Klamath-Siskiyou an area of global botanical significance (Wagner 1997), and the World Wildlife Fund chose it as a global 200 ecoregion, meaning that it is of high biodiversity value and under considerable threat (Ricketts et al. 1999). The ecoregion, as we define it, covers over 43,000 km2, of which approximately 63% is in public ownership (83% of this by the USFS). Nearly 13% of the ecoregion is considered strictly protected, primarily through a number of relatively large, scattered wilderness areas (Fig. 1).
- **Background**: The Klamath-Siskiyou ecoregion is noted for its abundance of serpentine bedrock geology (13%, or 575,550 ha of the ecoregion). Serpentine is a metamorphic rock upon which ultramafic soils are built. Ultramafic soils are unique in many of their physical and chemical properties: they are low in exchangeable calcium and high in magnesium, and they tend to be deficient in many soil nutrients. Many of these soils contain high levels of heavy metals, such as nickel, chromium, and cobalt, that impede normal plant growth and development (Cole- man & Kruckeberg 1999). For these reasons, serpentine geology is one of several known factors that have contributed to species endemism in the Klamath-Siskiyou (DellaSala et al. 1999; Strittholt et al. 1999).
- **Background**: Based on interpretation of mid-1990s satellite images, approximately 22% of the Klamath-Siskiyou ecoregion contained late-seral forest (928,356 ha), and 80% of it was on public land (Strittholt et al. 1999). Late-seral forest, which once dominated much of the Pacific North- west, has been in significant decline since the end of World War II. Many species and natural processes depend upon older forests, and they are of special conservation concern in the Klamath-Siskiyou. Late seral was defined as any forest older than 100 years.
- **Background**: Late-seral condition is not equally important among the various forest types found in the Klamath-Siskiyou. For example, some globally imperiled forest types are found in the ecoregion, including white fir (Abies concolor), Port Orford cedar, Brewer spruce (Picea breweriana), and huckleberry oak (Quercus vaccinifolia), and these are of particular concern (DellaSala et al. 1999),
- **Background**: Port Orford cedar is an important southwestern Oregon-northwest California endemic tree species (Lang 1999) that grows primarily in riparian areas, where it provides channel stabilization, shade for waterways, and microhabitat for numerous aquatic species (Jimerson & Creasy 1997). In an area where migratory species-most notably salmon-make up the bulk of the region's fish fauna, streamside integrity is of paramount importance, and Port Orford cedar is one of the dominant riparian tree species throughout the western sections of the Klamath- Siskiyou ecoregion. These

cedars are at risk because of their value in Asian markets (there is no major domestic market for Port Orford cedar) and, more important, from an imported root-rot fungus (Pbytopbtbora lateralis) (Lang 1999). This fungus is water-borne and is usually associated with the building and use of roads for logging, mining, and recreation (imerson & Creasy 1997). Spores are easily picked up from infected sites and transported to uninfected ones on the tires of vehicles. Infestation usually results in mortality (Zobel et al. 1985)

- **Background**: The extensive literature on the importance of intact natural habitats makes a compelling case for the potential role of roadless areas as refugia for native biodiversity and as areas crucial to forest integrity and function. Equally impressive is the mounting body of evidence showing the ecological costs of roads.
- **Finding**: Roadless areas occupied more than twice the land area of wilderness (approximately 27% of the entire ecoregion) and contained approximately 36% of the known occurrences of heritage elements, 37% of the mapped serpentine habitats, 36% of the remaining late-seralforests, 60% of Port Orford cedar strongholds, and 42% of key watersheds for aquatic biodiversity.
- **Finding**: In addition, roadless areas were composed of significant amounts of low- and mid-elevation sites and a substantial number of the 214 mapped physical-biological habitat types with strong complementarity with designated wilderness.
- **Finding**: Fragmentation analyses showed that roadless areas contributed to regional connectivity in important ways. Also, small roadless areas were an important component of the roadless-areas conservation assessment.
- **Finding**: For the Klamath-Siskiyou ecoregion, roadless areas and designated wilderness provide an important foundation upon which to develop a comprehensive regional conservation strategy.
- **Finding**: The total road length of all surface types for the Klamath- Siskiyou mapped at 1:100,000 scale was 44,522 km.
- **Finding**: Designated wilderness in the ecoregion covered 533,700 ha in several large, scattered patches. We mapped nearly 500 roadless areas of >405 ha on public lands of the Klamath-Siskiyou ecoregion area, which totaled 1,186,422 ha, approximately 27% of the ecoregion and more than twice the area of designated wilderness (Fig. 2).
- **Finding**: We mapped 131 large roadless areas covering 871,815 ha and 367 smaller roadless areas covering 314,607 ha, or 26% of the total roadless area. The USFS lands accounted for most (92%) of the roadless area mapped, followed by Bureau of Land



Management (7.6%) and other public lands (e.g., National Park Service, 0.4%).

Table 1. Frequency of heritage-element occurrence records for existing wilderness and mapped roadless areas within the Klamath-Siskiyou ecoregion.

Element category	*No. of records*	*No. in wilderness*	*No. in roadless areas (≥405 ha)*	*No. in roadless areas (405–2,024 ha)*	*Wilderness (%)*	*Roadless areas (%)*	*Combined (%)*
Plants	3837	389	1306	341	10.1	34.0	44.1
Vertebrates	4652	212	1749	562	4.6	37.6	41.2
Invertebrates	132	2	80	26	1.5	60.6	62.1
Community	8	0	6	2	0.0	75.0	75.0
Aquatic	6	0	0	0	0.0	0.0	0.0
Special feature	158	36	36	0	22.8	22.8	45.6
Total	8793	639	3177	931	7.3	36.1	43.4

- **Finding**: Roadless areas contained nearly four times more heritage elements than designated wilderness areas; the largest gains occurred in the plant and vertebrate categories (Table 1). In general, roadless areas captured approximately 36% of all known heritage elements. When added to those within designated wilderness, the total number increased to 3816 records, or 43% of all known records (Table 1). Small roadless areas accounted for 931 element records, or 29% of the total roadless-area records, adding substantially more plant, vertebrate, and invertebrate occurrences.
- **Finding**: We found 209,051 ha (36%) of the existing serpentine geology in the Klamath-Siskiyou ecoregion in roadless areas. The contribution from the smaller roadless-area class was 47,090 ha, 22% of the roadless-area total. Designated wilderness areas captured 100,170 ha (17%) of serpentine geology in the ecoregion.
- **Finding**: Of the 928,356 ha of late-seral forest mapped for the Klamath-Siskiyou, 337,180 ha (36%) were in roadless areas. Small roadless areas accounted for 93,508 ha, or 28% of the roadless-area total. In comparison, designated wilderness areas contained only 16% (149,386 ha) of the remaining late-seral forest. We found no difference in the average density of late-seral forest between wilderness and roadless areas: both contained approximately 28% late-seral forest.
- **Finding**: Key watersheds covered 1,157,812 ha, or 26% of the Klamath-Siskiyou ecoregion. Over 42% of the key water- shed area (491,954 ha) was also roadless. The contribution from smaller roadless areas was 89,506 ha, or 18% of the roadless area total. Of the 333 key watersheds, 190 (57%) were 80% contained (54 were completely contained) within wilderness and roadless areas. Only 13 (4%) contained no roadless area.
- **Finding**: Wilderness and roadless areas showed a marked difference in elevation representation (Fig. 3). When compared to wilderness, roadless areas captured much more of the low- and medium-elevation classes (<1525 m) (Table 3). The small roadless areas made up about the same proportion (approximately 26%) of each elevation class, providing additional representation of low and medium elevations. Roadless areas did proportionally better than designated wilderness at representing low and medium elevations. Most of the existing high-elevation sites in the Klamath-Siskiyou were in designated wilderness.
- **Finding**: Roadless areas also contained many different habitat types than designated wilderness, with 96 new types (45%) represented at the -25% level (Fig. 4). When

combined, designated wilderness and roadless areas complimented each other well, with 64% (138/214) of the classes represented at the >25% representation level. Although not visible in Fig. 4, smaller roadless areas made important contributions to 148 different habitat types, including 24 not found in any designated wilderness or large roadless areas.

- **Finding**: On numerous scientific grounds, our analyses strongly support protecting roadless areas in the Klamath-Siskiyou ecoregion. Roadless areas contained many known locations of species of concern, including rare and endangered species, many more than could be explained by additional land area alone, and the contribution by small roadless areas was noteworthy.
- **Finding**: We also suspect that many more rare species are present in roadless areas than are presently known because of the remoteness of roadless areas, a lack of organized biological surveys, and a current sampling bias toward areas with road access. The actual importance of roadless areas with regard to this criterion may actually be higher than the current data analysis indicates.
- **Finding**: The amount of late-seral forest in roadless areas is considerable, but the percentage is about that found in wilderness areas (both are around 28% late seral). What is important is that these forests are part of relatively large, intact blocks of habitat representing important ecological values. Larger patches of forest that can support a wider range of species, including those requiring large home ranges, are more secure from human-induced effects and are large enough to allow natural processes such as fire to operate without human interference.
- **Finding**: The contribution roadless areas made to Port Orford cedar conservation was particularly significant. The road- less area and designated wilderness components of the best-condition category were high; when combined, they accounted for nearly 88% of the best remaining areas of uninfected cedar.
- **Finding**: Our representation analyses suggest that an important role of roadless areas is adding low and medium elevations and many combined physical-biological habitat classes to the reserve network.
- **Finding**: Lower elevations contained most of the region's biological richness (DellaSala et al. 1999), and roadless areas were well represented at these elevations.
- **Finding**: Wilderness areas are concentrated on most of the forested and non- forested ecosystems at high elevations, including most of the red fir (Abies magnifica) and white fir (A. con- color) forests and much of the higher Jeffrey pine (Pinus jeffreyi), ponderosa pine (P. ponderosa), montane- hardwood conifer, and Klamath mixed-conifer forest types. Roadless areas added additional area to some of these habitat types, and-more important-picked up different physical zones for the same plant community types as well as totally new habitat types, including forests of Douglas-fir, montane hardwood, and Sierra mixed conifers growing under various physical zones defined and mapped for the region (Strittholt et al. 1999; Vance- Borland 1999). Smaller roadless areas were particularly important in contributing to 54 different habitat types and were exclusively responsible for capturing 24 habitat types not encountered at all in wilderness or the larger roadless areas.

- **Finding**: Small roadless areas in the Klamath-Siskiyou did not equally address all conservation issues examined, but they address many of them significantly, especially heritage elements, late-seral forests, elevation representation, habitat-type representation, and overall landscape connectivity
- **Finding**: Most biologically productive lands are already developed, and opportunities are limited to design effective protected-area networks without the necessity for substantial restoration. Roadless areas provide the remaining building blocks toward this end, so it is important to understand the contribution these areas make to an overall conservation strategy.

Strittholt et al. 2006.

- **Study**: Our objectives were to (1) determine the areal extent of old (>150 years) and mature (50–150 years) conifer forests based on 2000 Landsat 7 ETM+ imagery, (2) examine levels of protection, (3) determine the degree of additional protection afforded to old and mature conifer forests if late-successional reserves (LSRs) and inventoried roadless areas (IRAs) were fully protected, and (4) review management options to achieve greater protection of older forests.
- **Background**: For Douglas-fir forests, the definition of old growth ranges from 150 to 200 years (Haynes 1986). These forests are characterized by high densities of large (>100 cm in diameter) conifers, a broad array of tree sizes, a high percentage of trees with broken and dead tops, high densities of shade-tolerant trees, and high levels of snags and downed wood (Old-Growth Definition Task Group 1986; Spies & Franklin 1991; Wimberly et al. 2000).
- **Background**: Other forest types, including subalpine fir (Abies lasiocarpa [Hook.] Nutt.), white fir/grand fir (A. concolor [Gord. & Glend.] Lindl. ex Hildebr./A. grandis [Dougl. ex D. Don] Lindl.), and ponderosa pine (Pinus ponderosa P. & C. Lawson), have been assigned old growth age thresholds of 150 years, whereas others such as Pacific silver fir (A. amabilis [Dougl. ex Loud.]) are not considered old growth until they are 260 to 360 years old (Fierst 1993).
- **Background**: For Douglas-fir, mature forests are defined as being between 80 and 200 years of age, a period between the culmination of maximum growth and the development of old-growth characteristics (Franklin & Spies 1991b). These forests are also characterized by lower levels of snags and down wood than young, naturally regenerating forests and older age classes (Spies & Franklin 1991); the mature stage, however, represents an important intermediate age class from which old-growth conditions are likely to develop over time (Spies & Franklin 1991; Franklin et al. 2002).
- **Background**: Decades of research in the Pacific Northwest have documented the many values of old-growth forests, including their importance as wildlife habitat, regulation of hydrologic processes, sequestration of carbon, and maintenance of soil and nutrient processes (Norse 1990; Franklin & Spies 1991a; Thomas 1991; NRC 2000; Lindenmayer & Franklin 2002).
- **Background**: The Forest Ecosystem Management Assessment Team (FEMAT 1993) responded to concerns about the management of old-growth forests within the range of the federally threatened Northern Spotted Owl (Strix occidentalis caurina) and determined that approximately 1084 species were associated with older forests, including 10 species on the federal endangered species list.
- **Background**: salvage logging obscures the distinction between timber production and old-growth forest protection because this activity is virtually always damaging to regenerative processes following fire (Lindenmayer et al. 2004).
- **Finding**: The historical extent of old-growth forest in the Pacific Northwest was roughly two-thirds (16,672,976 ha) of the total land area. Since the time of European

settlement, approximately 72% of the original old-growth conifer forest has been lost, largely through logging and other developments.

- **Finding**: Of the remaining old growth, the Central and Southern Cascades and Klamath-Siskiyou account for nearly half. Mature conifer area (4,758,596 ha) nearly equaled the amount of old conifer. More than 78% of the old growth and 50% of mature forest were located on public lands. Approximately one-quarter (1,201,622 ha) of the old-growth conifer (or 7% of the historical old-growth area) was classified as GAP status 1 (strictly protected) or GAP status 2 (moderately protected).
- **Finding**: The total area of LSRs was slightly more than 3 million ha, approximately 36% (1,073,299 ha) of which contained old-growth conifer forest. Combined old and mature conifer within LSRs was approximately 59% of the total LSR area. The total amount of IRA for the Pacific Northwest was approximately 1,563,370 ha; of this, 526,912 ha (34%) was old growth. The combined area of old-growth conifer forest accounted for by protected areas (GAP 1 and 2), LSRs, and IRAs was 2,401,780 ha, which accounts for 66% of the old-growth conifer forests on public land, 51% of the old conifer in the region, and 14% of the amount that occurred historically.
- **Finding**: Outside these land designations, an additional 1,240,271 ha of old growth are on other public land and another 1,023,392 ha are on private lands throughout the Pacific Northwest. Our results indicate the need to periodically monitor status and condition of older forests and strengthen protections of old growth in the region.
- **Management**: Strengthening protection requirements for the LSRs and including IRAs, however, can greatly improve the functionality of the reserve network. This combination of increased LSR and IRA protections would add 1.3 million ha of old conifer forest to the reserve network, increasing the total protection of older forests to 2,533,456 ha (or 69% of the old forest on public lands) and, because these areas are close to existing protected areas, increasing functional connectivity across the region as well.
- **Management**: the reserve network can be managed more effectively to accommodate largescale disturbances by (1) increasing the redundancy and connectivity of reserves by protecting remaining older forests, (2) increasing the size of the reserves to withstand large disturbances (although this may not be practical because many large fires eclipse the size of individual reserves), and (3) building fire resiliency into the reserves through restorative actions. Reducing fuel loads in firesuppressed forests through low-density thinning (small trees and ladder fuels) and using prescribed burning are ways to increase resiliency (Brown et al. 2004; Spies et al. 2006).
- **Management**: If all the remaining old growth on public land were protected, roughly 21% of the historical area of old growth would not be subjected to industrial development. And although 21% seems like a luxury compared with many regions, it still may be insufficient to maintain all of the old-growth forest values present in the region.
    - This research and the growing public interest in protecting older forests support the conservation need to set aside old-growth forests on federal lands and to manage the maturing conifer forest to reach old-growth condition to ensure that

the many biological values associated with older forests are maintained in perpetuity.

Taylor and Skinner 2003.

- **Study**: The goal of this study is to better understand the spatial and temporal patterns of, and controls on, fire regimes and forest structure in mixed conifer forests of the Klamath Mountains.
- **Study**: Our study was conducted in a 2325-ha area of two small watersheds in the Shasta-Trinity National Forests, 8 km west of Hayfork, California in the south-central Klamath Mountains (Fig. 1). Elevations range from 640 to 1360 m. The climate is characterized by warm, dry summers and cool, wet winters.
- **Background**: Fire exclusion in mixed conifer forests has increased the risk of fire due to decades of fuel accumulation.
- **Background**: Nearly a century of fire exclusion in forests that once experienced frequent low- and moderate-severity fires has reduced compositional and structural diversity in forest stands and forested landscapes. For example, in California's mixed conifer forests the reduction in the frequency and extent of fire has caused an increase in forest density, a compositional shift to more fire-sensitive species, and a shift from coarse to fine grain forest mosaics (Vankat and Major 1978, Parsons and DeBenedetti 1979, Skinner 1995, Taylor 2000). Reduced fire frequency has also caused unprecedented accumulations of surface and aerial fuels and dramatically increased the risk of high-severity fires (Weath- erspoon et al. 1992).
- **Background**: Variation in fire frequency and fire severity vary with topographically related variables such as aspect, species composition, elevation, and soil type in some mixed conifer landscapes (Caprio and Swetnam 1995, Fites-Kauffman 1997, Taylor and Skinner 1998, Taylor 2000, Beaty and Taylor 2001, Bekker and Taylor 2001) but not in others (Heyerdahl et al. 2001).
- **Background**: Forests in the study area are diverse and any of six conifer species: ponderosa pine (Pinus ponderosa) (nomenclature follows Hickman 1993), Douglas-fir (Pseudotsuga menziesii var. menziesii), incense cedar (Calocedrus decurrens), sugar pine (Pinus lambertiana), Jeffrey pine (Pinus jeffreyi), and white fir (Abies con- color) may co-occur and share dominance in a stand depending on site conditions and stand history (Bar- bour 1988, Parker 1994). A subcanopy of the evergreen hardwoods Pacific madrone (Arbutus menziesii), gold- en chinquapin (Chrysolepis chrysophylla), and canyon live oak (Quercus chrysolepis) and the deciduous hard- woods California black oak (Quercus kelloggii), big- leaf maple (Acer macrophyllum), Oregon white oak (Quercus garryana), and dogwood (Cornus nuttallii) occur beneath the mixed conifer canopy. Stand com- position is strongly influenced by elevation, site mois- ture availability, and substrate.
- **Background**: A fire suppression policy was introduced in 1905 when the Trinity Forest Reserve was established as part of the National Forest Reserve System (Shrader 1965). Small-scale logging along ridge- tops began in the 1960s and extensive clear-cut logging occurred between 1980 and 1990.
- **Background**: Five forest compositional groups were identified from the cluster analysis of species importance values and the groups are segregated by elevation and potential

soil moisture ($P < 0.05$, Kruskal-Wallis H test) (Table 1). The ponderosa pine-sugar pine group (n = 18) occupies mainly south- and west-facing slopes and xeric upper slopes and ridgetops. The two pines share codominance and canyon live oak and Douglas-fir are important associates. The Douglas-fir group (n = 30) occupies mesic north-facing slopes at mid-elevations and is strongly dominated by Douglas-fir with sugar pine and hardwoods as important associates. The Douglas- fir-ponderosa pine-incense cedar group (n = 17) occupies mainly east-facing slopes at low and midelevation and is a variable mixture of the three species. The Douglas-fir-sugar pine group (n = 41) is compositionally variable and occupies midslope positions on north- and east-facing slopes. Ponderosa pine is the most important associate and a diverse assemblage of hardwoods is character tic of this group. The Douglasfir-white fir group (n = 13) occupies higher elevation sites on north- and east-facing slopes with sugar pine and ponderosa pine as the most important associates.

- **Background**: The prevalence of Douglas-fir and the diversity of hardwood species distinguish mixed conifer forests in the Klamath Mountains from those elsewhere in the Cascade Range, Sierra Nevada, San Bernardino Mountains, and Sierra San Pedro Martir (Whittaker 1960, Barbour 1988).
- **Background**: features (i.e., streams, riparian zones, sharp changes in aspect, changes in parent material) that act as impediments to fire spread.
- **Background**: Even small streams and narrow riparian strips with water, higher humidity, and vegetation with high live fuel moisture are effective barriers to fire spread in forests that experience frequent, low-intensity surface fires (Skinner 1997). Moreover, differences in fuel bed characteristics that occur at abrupt changes in aspect, in riparian areas, or at parent material boundaries are sufficient to inhibit the spread of fire under typical conditions (e.g., Taylor 2000, Stephens 2001). Parent materials, especially where ultramafic rock is interspersed with other rock types as in our study area, may affect fire spread patterns due to different levels of fuel production. Historically, even bare foot paths were reported to stop many fires in the vicinity of our study area (Wilson 1904).
- **Background**: Variation in fire severity is an important source of structural diversity in forested landscapes because burns may kill all trees in some stands and few in others.
- **Background**: Stands that have experienced high-severity fires are even-aged or several aged with stems in relatively few age classes while those that experience mainly low- and moderate-severity fires have stems in a wide range of age classes because fires kill few trees in the stand (Agee 1993). Forest stands in our study area were multiaged and virtually all stands had stems >250 yr old, and many included older stems of relatively fire-sensitive white fir. This suggests that burns were mainly low or moderate in severity and patchy enough to allow white fir to grow to a fire-resistant size (e.g., Agee 1993).
- **Background**: The age structure of mixed conifer forests, however, are not uniformly multiaged. In the Klamath Mountains and southern Cascades, large (>100 ha) mainly even-aged patches of trees are present indicating that high-severity burns played an integral role in shaping forest structure at stand and landscape scales at least in some areas (e.g., Taylor and Skinner 1998, Beaty and Taylor 2001, Bekker and Taylor 2001).

- **Background**: Forest changes caused by fire suppression have been documented in the mixed conifer forests in the Sierra Nevada (Vankat and Major 1978, Parsons and DeBenedetti 1979), the San Bernardino Mountains (Min- nich et al. 1995, Savage 1997), and southern Cascade Range (Dolph et al. 1995, Taylor 2000). Overall, forests have increased in density and shifted in composition from more fire-resistant to more fire-sensitive species, reducing the structural diversity of forests at both stand and landscape scales (Vankat and Major 1978).
- **Finding**: Forests were multiaged and burned frequently at low and moderate severity, but forest age structure did not vary with aspect, elevation, or topographic position.
- **Finding**: Recently there has been an increase in forest density and a forest compositional shift to shade-tolerant species.
- **Finding**: Median fire return intervals (FRI) ranged from 11.5 to 16.5 yr and varied with aspect but not with forest composition or elevation. The median area burned was 106 ha, and the pre-Euro-American fire rotation of 19 yr increased to 238 yr after 1905.
- **Finding**: Median site Fire Return Intervals (FRIs) were statistically longer on north-facing slopes than on other aspects ($P < 0.05$, Kruskal-Wallis H test) (Table 2).
- **Finding**: the median area burned in the pre-Euro-American (128 ha, range 25-1541 ha) and settlement (106 ha, range 25-1188 ha) periods were similar. Median area burned was smaller (25 ha) in the fire suppression period.
- **Finding**: Fire rotation for the pre-Euro-American periods was 20 yr. Fire rotations were shorter during the 19th century (15 yr) and settlement period (18 yr) due to the proportionately greater area burned during these periods.
- **Finding**: The ordination of - 100-yr-old and >100-yr-old stems shows that Douglas-fir and white fir have regenerated more successfully than other conifer species during the fire suppression period
- **Finding**: Ponderosa pine, sugar pine, and canyon live oak were most abundant on dry south-facing slopes and ridgetops while white fir was most abundant on high elevation mesic sites. In contrast, Douglas-fir, California black oak, Pacific madrone, and golden chinquapin were most abundant on more mesic north-facing slopes at low elevation.
- **Finding**: fuel production rates on warmer, low-elevation, pine-dominated sites are higher than on cooler, higher elevation, fir-dominated sites (Agee et al. 1978, Stohlgren 1988; J. W. van Wagten- donk, personal communication). Consequently, fuel recovery after fire is faster so a low elevation site can burn again sooner. Second, fuels dry out sooner each year on low elevation sites so the period fires can burn each year is longer than at higher elevation.
- **Finding**: In the Hayfork study area, spatial variation in fire frequency was associated with aspect and not elevation or forest species composition. Fires were less frequent on north-facing slopes than on other slope aspects. Al- though this difference was statistically significant, the small difference in median FRI between north-facing and other aspects may not be significant from a man- agement perspective.
- **Finding**: What may be more important is the greater variation in median Fire Return Intervals (FRIs) on the north- and west-facing aspects compared to the south- and east-facing aspects. The variation in FRIs on the west-facing aspects may be due to the dry,

shallow soils of low productivity associated with them (cf. USFS 1983). Indeed, these slopes were more likely to have a greater component of canyon live oak. Where canyon live oak makes up a major portion of the canopy, it is often associated with sites of low productivity (USFS 1983) characterized by sparse, discontinuous surface fuels that do not carry fire well except under more extreme conditions (Skinner and Chang 1996). Instead of more humid, mesic conditions inhibiting fires, the xeric, steep, west-facing slopes may not have been able to consistently produce fuels to carry fires as often as the south- or east-facing slopes.

- **Finding**: the coincidence of fire occurrence group boundaries with topographic features known to affect fire behavior suggests that topography is the primary control on the spatial pattern of fire in the highly complex terrain in our study area
- **Finding**: Even-aged stands in the Klamath Mountains and southern Cascade Range, are proportionately more abundant on upper slope positions suggesting that topography may also be an important control on fire severity and stand age structure at landscape scales (Skinner 1995, Taylor and Skinner 1998, Beaty and Taylor 2001). Mid- and upper-slope positions often experience higher fire intensities than lower slopes due to preheating of fuels, higher effective windspeeds, and lower canopy cover (Rothermel 1983, Weatherspoon and Skinner 1995, Taylor and Skinner 1998).
- **Finding**: Our understanding of the influence of topography on patterns of fire severity is currently insufficient to untangle the potential long- term effects of topography from the short-term effects of extreme fire weather on fire severity and forest age structure patterns.
- **Finding**: The predominant increase in density in Klamath Mountains with fire suppression was for Douglas-fir or a mixture of Douglas-fir and white fir. Douglas-fir is shade tolerant on drier sites in the Klamath Mountains (Herman and Lavender 1990), and Douglas-fir and white fir are more fire-sensitive than the pines when they are small. But Douglas-fir is as fire tolerant as the pines when it matures due to its thick bark, which prevents injury by low- and moderate-intensity fires (Agee 1993).

Tepley et al. 2017. Vulnerability to forest loss through altered postfire recovery dynamics in a warming climate in the Klamath Mountains. Global Change Biology 2017: 1-16.

- **Abstract**: In the context of ongoing climatic warming, certain landscapes could be near a tipping point where relatively small changes to their fire regimes or their postfire forest recovery dynamics could bring about extensive forest loss, with associated effects on biodiversity and carbon-cycle feedbacks to climate change. Such concerns are particularly valid in the Klamath Region of northern California and southwestern Oregon, where severe fire initially converts montane conifer forests to systems dominated by broadleaf trees and shrubs. Conifers eventually overtop the competing vegetation, but until they do, these systems could be perpetuated by a cycle of reburning. To assess the vulnerability of conifer forests to increased fire activity and altered forest recovery dynamics in a warmer, drier climate, we characterized vegetation dynamics following severe fire in nine fire years over the last three decades across the climatic aridity gradient of montane conifer forests. Postfire conifer recruitment was limited to a narrow window, with 89% of recruitment in the first 4 years, and height growth tended to decrease as the lag between the fire year and the recruitment year increased. Growth reductions at longer lags were more pronounced at drier sites, where conifers comprised a smaller portion of live woody biomass. An interaction between seed-source availability and climatic aridity drove substantial variation in the density of regenerating conifers. With increasing climatic water deficit, higher propagule pressure (i.e., smaller patch sizes for high-severity fire) was needed to support a given conifer seedling density, which implies that projected future increases in aridity could limit postfire regeneration across a growing portion of the landscape. Under a more severe prospective warming scenario, by the end of the century more than half of the area currently capable of supporting montane conifer forest could become subject to minimal conifer regeneration in even moderate-sized (10s of ha) high-severity patches.

Welsh and Lind. 2002.

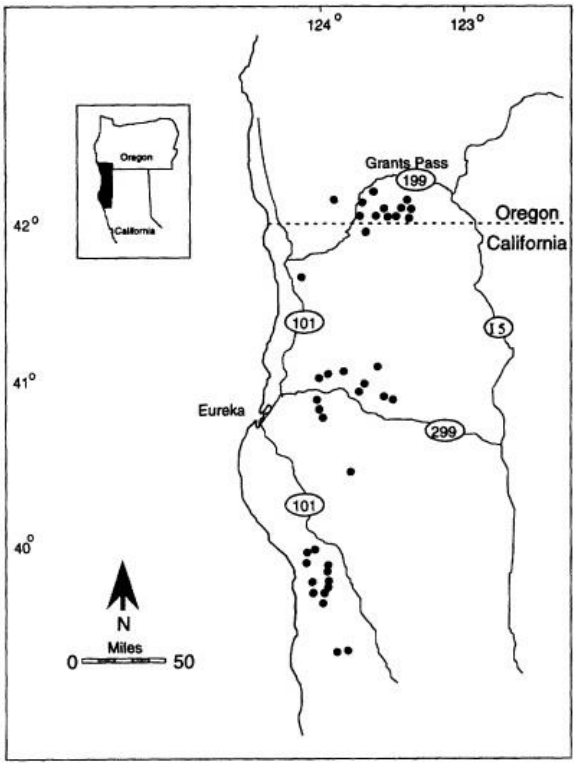


Fig. 1. Locations of 39 streams in southwestern Oregon and northwestern California, USA (the Klamath–Siskiyou Region), sampled during summers 1984 and 1985.

- **Study**: We sampled amphibians in 39 second- and third-order streams in the conifer-hardwood forests of northwestern California and southwestern Oregon, USA (the Klamath-Siskiyou Region) during 1984 and 1985. We concurrently measured spatial, structural, compositional, and climatic attributes of the forest and stream environment-attributes representing landscape, macroenvironment, and microenvironment scales-to determine key habitat relationships.
- **Study**: forest sites were systematically selected to represent both the range of geographic variation across the mixed Douglas-fir-hardwood forests of the KS Region and the seral continuum from young to old-growth forest.
- **Background**: Bury and Pearl (1999) reported that stream amphibian populations in the Oregon Coast Range had not recov- ered 35-50 years after clearcut harvesting
- **Background**: Welsh (1993) analyzed data from 156 sites, and from a greater proportion of the range of the Pacific giant salamander in California, and reported both a higher incidence and higher relative abundance of salamanders both nearer the Pacific Coast and northward. He interpreted this pattern as resulting from the direction of the prevailing cooler, moister, maritime-modified climate (Froehlich et al. 1982), which creates and sustains the region's temperate rainforests and provides optimum conditions for D. tenebrosus in the northwest portions of the state.
- **Background**: Patch dynamics of the surrounding landscape directly affect the stream network within by influencing hydrologic patterns, microclimates, sediment loads, and energy inputs, and thus affect the incidence and abundance of the associated riparian and stream biota (Schlosser 1991, Zwick 1992, Malanson 1993, Gregory 1997, Jules et al. 1999, Naiman et al. 2000).
- **Finding**: We captured 7 species, 97% of which were larval and paedomorphic Pacific giant salamanders (Dicamptodon tenebrosus) and larval and adult tailed frogs (Ascaphus truei).
- **Finding**: Streams in late seral forests supported both the highest diversity of amphibians and the highest densities of A. truei. Overall, A. truei distribution was patchy in

occurrence, while D. tenebrosus distribution was widespread throughout the region at all scales.

- **Finding**: The incidence of A. truei was assessable at the landscape, macroenvironment, and microenvironment scales; however, variation in density was most predictable at the microenvironment scale. Changes in density of D. tenebrosus were detected only at the microenvironment scale.
- **Finding**: Tree size class and plant species composition variables distinguishing younger from older, more structurally complex forests, and forest microclimates and in-stream attributes best determined the presence and density for both life stages of A. truei.
- **Finding**: However, only in-stream conditions were good predictors of D. tenebrosus density. A. truei occupied a narrower range of habitat conditions than D. tenebrosus, exhibiting an ecological dependence on lotic and riparian environments found more reliably in late seral forests.
- **Finding**: We captured 1,400 individuals of 7 species in 39 streams. Amphibian diversity (SDI) was greater in streams traversing stands with greater forest age; 21% of the variance was explained by this single variable (Fig. 2).

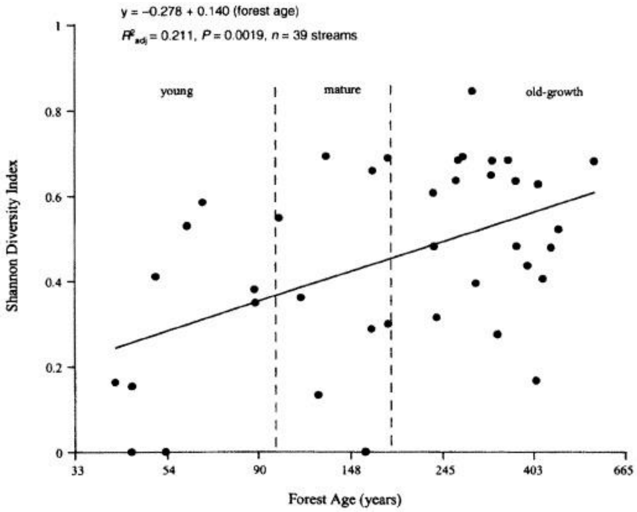


Fig. 2. Amphibian diversity (Shannon Diversity Index) of the stream amphibian assemblage relative to forest age in the Douglas-fir–hardwood forests of the Klamath–Siskiyou Region. Data and regression equation reflect natural log transformation of forest age; X-axis was back-transformed to show actual forest age.

- **Finding**: Five of the 7 species occurred in relatively low numbers (0.1-1.5% of total obser- vations). We found 2 California slender salamanders (Batrachoseps attenuatus), 6 black salamanders (Aneides flavipunctatus), 11 southern torrent salamanders (Rhyacotriton variegatus), 23 adult foot- hill yellow-legged frogs (Rana boylii), and 3 rough-skinned newts (Taricha granulosa). The 2 remaining species constituted 96.9% of all cap- tures. Tailed frogs (Ascaphus truei; larvae and adults, n = 487) were present in 21 of 39 streams. We found A. truei larvae in 21 streams and 50 of 117 reaches, and adult frogs in 16 streams and 38 of 117 reaches. Pacific giant salamanders (Dicamptodon tenebrosus; larvae and paedomorphs, n = 870) were present in all but a single stream, and in 109 of 117 reaches.
- **Finding**: While our approach to understanding the multiscale habitat relationships of A. truei and D. tenebrous was primarily descriptive, our analyses demonstrated that distinct distribution patterns were present and detectable and that a substantial amount of variation in incidence and density (34-69%) could be explained by habitat variables, though our predictions of absence were more accurate than our predictions of presence (Table 3)

- **Finding**: The key difference between landscape scale models for the 2 life stages of A. truei was the addition of rainfall (cm/yr) for the mostly terrestrial adult frogs. Higher annual rainfall, a good indicator of moister sites, also is a good predictor of forest that can better support adult A. truei, which require high environmental moisture to frequent terrestrial microenvironments (Claussen 1973a,b). Given that A. truei larvae are strictly aquatic, the negative association with air temperature probably reflects the close correspondence between air and stream temperature (Mitchell 1999).
- **Finding**: There is a much more compelling explanation for increases in A. truei with elevation at the landscape scale in the KS Region (and elsewhere; see Hawkins et al. 1994). This explanation lies in the pronounced physiological limitations of this unique frog species. Experiments with adult A. truei indicated that their tolerance to desiccation was lower than 17 other North American frog species tested (Claussen 1973a,b). Brown (1975, 1989) found this species to have the narrowest tolerance range (5-18.5 'C), and the lowest upper limit temperature for development (18.5 'C) of any frog in North America. Our study was conducted at the southern end of the range of A. truei (Metter 1968, Stebbins 1985). In this region, the incidence of A. truei is patchy (Bury 1968). This patchy distribution probably results from the limited capacity of this cold-adapted, moisture- dependent frog to tolerate the dry, warm conditions found throughout this portion of its range.
- **Finding**: The negative relationships between salamander numbers and density of understory hardwoods and grass cover suggest that a relatively closed overstory and lack of disturbance (where young hardwoods and grass are precluded) may be attributes of the upland environment adjacent to streams sup- porting higher densities of D. tenebrosus
- **Finding**: The positive associations between adult tailed frogs and pools, and tailed frog larvae with cobble and waterfalls, is an expression of morphological and physiological adaptations unique to each life stage. A. truei tadpoles, with rock-gripping, sucker-disk mouths, and associated feeding and breathing structures, are highly adapted to life in the fast-moving water (Gradwell 1971, Altig and Brodie 1972). Turbulence created by high water velocities over coarse substrates provides protection from predators such as D. tenebrosus (Metter 1963). Tadpoles attach readily to rock surfaces in strong currents, where potential predators have to fight currents and contend with the visual impairment of "white water" which serves to hide the larvae (Welsh 1993:80).
- **Finding**: Correlative evidence from earlier work on adult A. truei showed that they were found mostly under cobbles and boulders in slower water than tadpoles (Metter 1964, Nussbaum et al. 1983, Bury et al. 1991). We demonstrated that adult A. truei select pool habitats and cobble-sized rock cover more frequently than do other life stages, possibly as summer refuge from desiccating temperatures in terrestrial environments.
- **Finding**: The association of giant salamander larvae with narrow, shaded stream reaches dominated by pools and coarse substrates (see also Parker 1991) may be related to their foraging strategy. D. tenebrosus larvae are predominantly sit-and-wait predators (Parker 1994), and these conditions provide both cover and an abundance of ambush foraging sites.

- **Finding**: Our multivariate models suggest that for predicting A. truei presence, stream temperature is more important than aspects of forest structure; however, conditions of forest structure and microclimate are closely linked (Chen et al. 1993, 1999).
- **Management**: Timber harvesting near streams can have a profound effect on the nature and availability of substrate interstices (Waters 1995), which are important microhabitat for tailed frogs (Welsh and Ollivier 1998). Depending on the competency of the bedrock materials, stream conditions can change dramatically following nearby tree removal (Waters 1995).
- **Management**: In the case of A. truei, although present in some streams in younger forests (e.g., Diller and Wallace 1999, Aubry 2000, Wilkins and Peterson 2000), their populations often are reduced or eliminated by timber harvest and related activities through direct perturbations to the forest and stream environment. Given that habitat conditions for A. truei are optimized in late-seral forests (Corn and Bury 1989; Welsh 1990, 1993; Welsh and Lind 1991), the long-term viability of this frog throughout the region of our study probably is linked to the presence and spatial accessibility of these forests and the interior microclimatic conditions they provide.
- **Management**: Based on our research, we expect D. tenebrosus to continue to be widely distributed and abundant, while A. truei likely will continue to decline across the landscapes of the KS Region (and the greater Pacific Northwest) in response to these relatively new, more intensive anthropogenic disturbance regimes (e.g., Corn and Bury 1989, Dupuis and Steventon 1999, Welsh 2000

Wright. 2016. News Release.

- **Background**: The USDA Forest Service and the Oregon Department of Forestry have been doing an annual aerial tree mortality detection survey in Oregon since 1951. We can be confident that the data derived from the aerial survey provides us with good information on mortality trends over time; these data, maps, reports and related information are posted on the internet at http://www.fs.usda.gov/main/r6/forest-grasslandhealth/.
- **Finding**: The drought of 2013 followed by the snow drought of 2014 diminished tree defenses in the interior areas of Southwest Oregon, especially in very dense stands. Subsequently, tree mortality due to insects and plant pathogens has increased.
- **Finding**: in the Applegate Adaptive Management Area (AMA), which encompasses the entire Applegate River watershed, the 2015 overview aerial detection survey results illustrate a large increase in conifer mortality --- pines, firs and Douglas-fir --- as compared with previous years.
- **Finding**: These surveys and a number of studies have shown that particular types of tree mortality occur in pulses, often in response to drought or other weather conditions.
- **Finding**: Although last winter brought ample precipitation, it is likely that 2016 will be another year of elevated conifer mortality in Southwest Oregon. This is due, in part, to the enlarged beetle populations that exist within currently infested conifers and the life cycle length of the beetle species involved.