



Hotter, Drier, No Less Wild

Protecting Public Land and Biodiversity in the
Klamath-Siskiyou Region in the Era of Climate Change



A Report from KS Wild
The Klamath-Siskiyou Wildlands Center
October 2017



PHOTO: SHANE STILES

Hotter, Drier, No Less Wild: Protecting Public Land and Biodiversity in the Klamath-Siskiyou Region in the Era of Climate Change

Prepared by Brandon M. Breen
October 2017

For the Klamath-Siskiyou Wildlands Center
P.O. Box 102
Ashland, Or 97520
(541) 488-5789 · info@kswild.org



KS Wild takes all responsibility for errors and omissions.

Special thanks to the Charlotte Martin Foundation for supporting the production and distribution of this report.

Front cover photo by Bob Wick

KS Wild's mission is to protect and restore wild nature in the Klamath-Siskiyou region of southwest Oregon and northwest California. We promote science-based land and water conservation through policy and community action.

For more information please visit: kswild.org.

Hotter, Drier, No Less Wild

Protecting Public Land and Biodiversity in the Klamath-Siskiyou Region in the Era of Climate Change

- 2 Executive Summary
- 4 The Klamath-Siskiyou: Land of Treasures
- 6 Climate Projections for the Klamath-Siskiyou
- 8 Vulnerable Wildlife in the Klamath-Siskiyou
- 10 The Klamath-Siskiyou: Climate Refuge
- 12 Understanding Ecological Resilience
- 14 Understanding Wildfire in the Klamath-Siskiyou
- 17 Carbon Storage and Emissions in Forests
- 20 Valuable Old Forests
- 22 Valuable Roadless Areas
- 24 Climate Change Impacts on Forests
- 26 Salmon, Streams, and Climate Change
- 28 Serpentine and Climate Change
- 30 An Overview of Thinning and Logging
- 32 Land Management Solutions
- 36 References

PLEASE NOTE: In addition to the references section at the end of this report, an annotated and interactive bibliography is available online. The bibliography provides references in alphabetical order and by topic. Annotations on individual papers are also provided. The annotated bibliography can be found at:

<https://tinyurl.com/KS-climate-bibliography>

Executive Summary



PHOTO: KS WILD

The Klamath-Siskiyou is one of the wildest places left on the U.S. West Coast and is home to the most diverse conifer forests in North America.

The Klamath-Siskiyou along the Oregon-California border is one of the wildest regions remaining on the U.S. West Coast. World-class biodiversity, stunning wild rivers, and an incredible eight million acres of public lands are spread across the eleven-million-acre region. Due to the diversity of plants and animals in the region and its central location between the Sierra, Cascade, and Coastal Mountains, this region may act as a refuge for nature in a changing climate. Like many regions, the “KS” is already feeling significant impacts from global climate change. Yet, there are important steps we can take to ensure that the forests, rivers, and wildlife in this region survive in a changing climate.

Reducing carbon emissions is essential to reduce the overall magnitude of impacts from climate change. Even so, many of the effects are already here and we must adapt. Protecting the region’s natural systems requires the concerted efforts of public land managers and engaged residents from across the region. This report draws on expert research on the likely impacts of climate change and summarizes the most critical efforts we can take to ensure continued diversity and resilience of our natural systems in a changing climate.

The Challenge of Climate Change is Only Beginning

On average, the Klamath-Siskiyou region is already hotter and, consequently, drier than historical norms. In the future, more precipitation will come in the winters and less in the summers. More win-



PHOTO: SHANE STILES

ter precipitation will come as rain, resulting in less snowpack, important to feeding streams throughout the summer. Warmer temperatures will more quickly dry the landscape. As the region becomes hotter and drier, stream levels in summers will decrease and water temperatures will increase. With longer and much hotter summer seasons, soil moisture decreases, trees become stressed, and vegetation will dry out. A future of bigger, hotter, longer-lasting fires is likely.

These trends can create knock-on effects. Climate change generally will reduce tree growth and make forests more susceptible to insects and fire. This is especially true at drier sites and lower elevations. Forest types could change completely, for example, from conifers to hardwoods, or even to scrublands and grasslands.

A variety of species, from trees to wildflowers, from big predators to insects will shift in composition, seasonal timing, and range. The KS is especially well-suited to maintaining biodiversity under such pressures, because of the diverse topography, microclimates, and habitats available to species in this area. Some species are more vulnerable than others, however. Especially vulnerable are high elevation species that cannot shift upslope. Similarly, in a hotter, drier KS, wet and cold-loving species at all elevations will often find nowhere to survive. This situation could lead to the local disappearance of many species or even complete species extinction. Most vulnerable are certain rare plants,

Forests and Fire

The KS is a region that has long adapted to fire. Despite climate change's amplification of fire impacts, the region's forests often thrive after fire. Species composition and density is often maintained or even increased with fire. This is true even after big, severe fires, and fires repeating after short intervals.

Forests reduce atmospheric carbon levels through storage in trees and soils. The latest science shows that, generally, the best way to store the most carbon in forests is to protect them, because mature and old growth forests are the least likely forests to burn. This is especially true in the KS where forests are among those that store the most carbon of any in the U.S.

amphibians, and perhaps most tragically, that most iconic of species, salmon.

Salmon are in particular danger from changes in flow timing, reduced flow overall, and hotter water. These negative impacts come on top of already decimated regional salmon populations.

Protecting Climate Strongholds and Vulnerable Landscapes are Both Critical

The Klamath-Siskiyou has a variety of areas that act as small climate refuges ("refugia")—places where species can escape to survive the worst effects of climate extremes. Protecting these areas is critical to the resiliency of the region. At the same time, the region also has areas particularly vulnerable to climate change. Reducing non-climate stressors, such as roads, livestock, and logging, gives them a fighting chance in a hotter and drier future.

Old-growth and mature forest (about 80 years old or older) is the most important overarching climate refuge. Only 28% of this type of forest remains in the Klamath-Siskiyou and little more can afford to be lost. Among older forests, the most important forests possess one or more of the following characteristics: north or northeast-facing slopes, long forested gradients across elevations, forested canyons, low to mid-elevation forests, and forests with abundant fog or precipitation.

At almost three million acres, **the region's roadless areas** are key landscapes to protect as refugia. They contain disproportionate amounts of old-growth, rarer intact low and mid-elevation habitat types, rare plants, and key watersheds. Cooler streamside forests that shade streams, and areas that provide connectivity between regions are also key targets for protection.

Among ecosystems most vulnerable to climate change, **reducing non-climate impacts is critical**. Key examples of impacts to prevent include habitat fragmentation, erosion from roads, loss of keystone species, introduction of invasive species, livestock overallocation, floodplain and coastal development, over allocation of water, inappropriate fire management, and post-fire logging.

Because of its rich diversity of species and large, fairly intact landscapes, **the Klamath-Siskiyou is better positioned to fend off climate impacts than many regions in the West**. The region will only do so if public land managers and an engaged public take climate change threats and proposed solutions seriously now, before it is too late.



The Klamath-Siskiyou has acted as a refuge for nature during past climatic events, owing to its complex terrain and a wide variety of habitats.

The Klamath-Siskiyou: Land of Treasures



MAP: KS WILD

The Klamath-Siskiyou region covers almost 17,000 square miles of mountainous terrain in southern Oregon and northern California. This region—home to Pacific fisher, black bear, mountain lion, northern spotted owl, bald and golden eagles, osprey, salmon—has received extensive attention owing to its biological diversity and natural wealth.

Now, the region faces challenges from a changing climate. Many native species could disappear and ecosystem services (i.e., benefits people obtain from nature) could diminish in the coming decades. There is room for optimism, however, because the region acted as a refuge for nature during past climatic events, owing to its complex terrain and a wide variety of habitats with favorable temperatures and conditions. With science-based public lands management, the Klamath-Siskiyou may function again as a climate refuge and sustain minimal losses to its unique values.

Ecosystem Services of the Klamath-Siskiyou^{1,11-19}

- Nutrient recycling.
- Soil formation.
- Primary production.
- Wild foods (salmon, mushrooms, etc.).
- Wood products.
- Genetic resources.
- Carbon storage and climate regulation.
- Water and air purification.
- Medicinal resources.
- Pest and disease control.
- Waste decomposition.
- Pollination.
- Recreation.
- Ecotourism.
- Scientific discovery.
- Cultural, spiritual opportunities.



PHOTO: SHANE STILES

With eight of the eleven million acres of the Klamath-Siskiyou managed by the Bureau of Land Management and Forest Service, federal land managers play a critical role in addressing climate impacts.

Exceptional Habitat & Biodiversity

- 36 species of conifer trees.
- 3,500 plant species (281 endemics).
- 120 butterfly species.
- 5 salmonid species.
- More than 4,000 miles of fish-bearing tributary streams in the Rogue River Basin.¹
- Nearly 13% of region is considered strictly protected, mostly via large scattered wilderness areas.²
- 13% of region is serpentine bedrock geology.²
- Approximately 22% of the Klamath-Siskiyou (as of the mid-1990s) contained late seral (>100yrs) forest (80% of this on public land).
- Exceptional reptile, amphibian, and mollusc richness and endemism.
- Exceptional diversity of genetically distinct populations (high beta diversity).

Region Distinctions

- Global Botanical Area of Significance (IUCN).
- Proposed World Heritage Site and Biosphere Reserve (UNESCO).
- The Rogue River was one of the original eight rivers named in the Wild and Scenic Rivers Act of 1968.
- Contains first U.S. national monument set aside for the protection of its rich biological diversity (Cascade-Siskiyou National Monument).
- Provides key habitat linkages among Cascades, Great Basin, Siskiyou Mountains, Klamath Mountains, and Sierra Nevada, and is therefore thought to be of central importance in the long-term evolution and development of western forest vegetation.⁴
- Provided refuge for wildlife during past climate change events.⁵
- Conifer forests here are the most diverse in North America,⁶ and among the most diverse of their kind in the world.⁷
- Region's high-biomass forests are among the world's most carbon dense forest ecosystems.^{8,9}
- Region contains the most extensive exposure of ultramafic rocks (serpentine) in North America.¹⁰

The high-elevation Siskiyou Crest is home to a large number of rare and endemic plants, that is, plants found nowhere else in the world. These high-elevation plants are under an increased threat from climate change.



PHOTO: KS WILD



The Rogue Valley could transition to climate conditions similar to those of Sacramento, California.



PHOTO: KS WILD

Climate Projections for the Klamath-Siskiyou

Climate change is here—the average annual temperature in the Siskiyou Mountains has increased 3.5°F from 1950–2010³⁰—and its impacts will only escalate throughout the century. The present rate of warming is higher than previous rates over at least the past 10,000 years.²⁸ By the end of the century, the temperature for western North America could be 3.5–9°F above the range of temperatures that have occurred over the last 1,000 years.²⁴

Climate change will impact our natural systems in profound—and sometimes unexpected—ways. The threat is especially severe given that habitat fragmentation, extensive road-building, invasive species, and other causes of ecosystem degradation have already weakened the resilience of our lands and waters to new stresses such as climate change.¹³

Climate change will lead to a significant increase in the frequency and severity of wildfires, including large, high-intensity wildfires.



PHOTO: MIKE DICKENSON

What to Expect

Temperature

▲ 1–3°F by 2040.¹⁸

▲ 4–8°F by 2080.¹⁸

▲ 7–15°F by 2080 (summers).¹⁸

Many more days likely to exceed 90 or 100°F.²¹

Models agree on significant warming for California.¹⁶¹

Precipitation

Shifting to mid-winter and away from spring, summer, and fall.¹⁸

Shifting from snow to rain in winter.

Declining in September.²⁸

More severe storm events.¹⁸

More flooding.^{21,18}

Decrease in coastal fog.¹⁶²

Snowpack

Decreasing snowpack.^{21,161}

▼ 75% by 2040.¹⁸

▼ to negligible by 2080.¹⁸

Earlier snowmelt.²¹

Snow turns to rain at lower elevations.^{21,18}

Wildfires

Significant ▲ in frequency and severity of wildfires.^{21,18,163}

▲ risk of large, high-intensity wildfire.¹⁶³

Drought

▲ frequency and severity of drought.^{1,21,18}

Higher temps will lead to increased drying.¹⁸

Streams & Flows

▲ stream temperatures.²¹

Shift of timing of peak streamflow to earlier in year.²¹

Large ▼ in summer flows in streams that depend on snowmelt.²

▼ dissolved oxygen.²¹

Sediment and mineral build-up in streams due to increased erosion from storms and wildfires.²¹

By 2080, snowpack in the Klamath-Siskiyou may be negligible.

Key Risks

Declines in water quality and quantity,^{21,69} severe wildfire,²¹ increases in stream temps,²¹ loss of snowpack—and thus water supply during dry summers.²

A New Sacramento

The Rogue Valley could transition to climate conditions similar to those of Sacramento, California.¹⁸

Ecological Impacts

- Species population reductions and extirpations.¹⁶⁴
- Species range shifts (generally northward and upslope).^{21,30,165}
- Phenology shifts (timing of flowering, aquatic insect emergence, etc.).¹⁶⁶
- Non-native species invasions.^{18,166}
- Tree die-offs.¹³
- Amphibian declines.¹⁶⁷
- Increased prevalence of disease and disease vectors given warmer temperatures,^{13,18,21} combined with greater susceptibility of wildlife to disease due to increased stress from climate change and other stressors¹⁸ (collapse of the Klamath fall Chinook population).
- Increased outbreaks of mountain pine beetle leading to more tree mortality.^{9,13}
- Potential jump of mountain pine beetle to non-pine species.¹⁴³
- Community reorganization.^{166,168}
- Current community dynamics such as predator–prey or competitive interactions may become affected as species assemblages are reshuffled in new ways.¹⁶⁹
- By 2070 over half (57%) of California could be occupied by novel assemblages of bird species, implying the potential for dramatic community reshuffling and altered patterns of species interactions.¹⁶⁸
- Regions of high geologic diversity, such as the Klamath-Siskiyou region, may have high community heterogeneity and thus greater potential for the re-shuffling of species.¹⁶⁸
- Increases in warm-adapted and decreases in cold-adapted organisms²³ (Increased mortality for fall migrating adult salmon).
- Increased summer evapotranspiration.²⁸
- Unanticipated changes to natural system.¹³



Two out of every three rare California plants surveyed were classed as vulnerable to climate change.

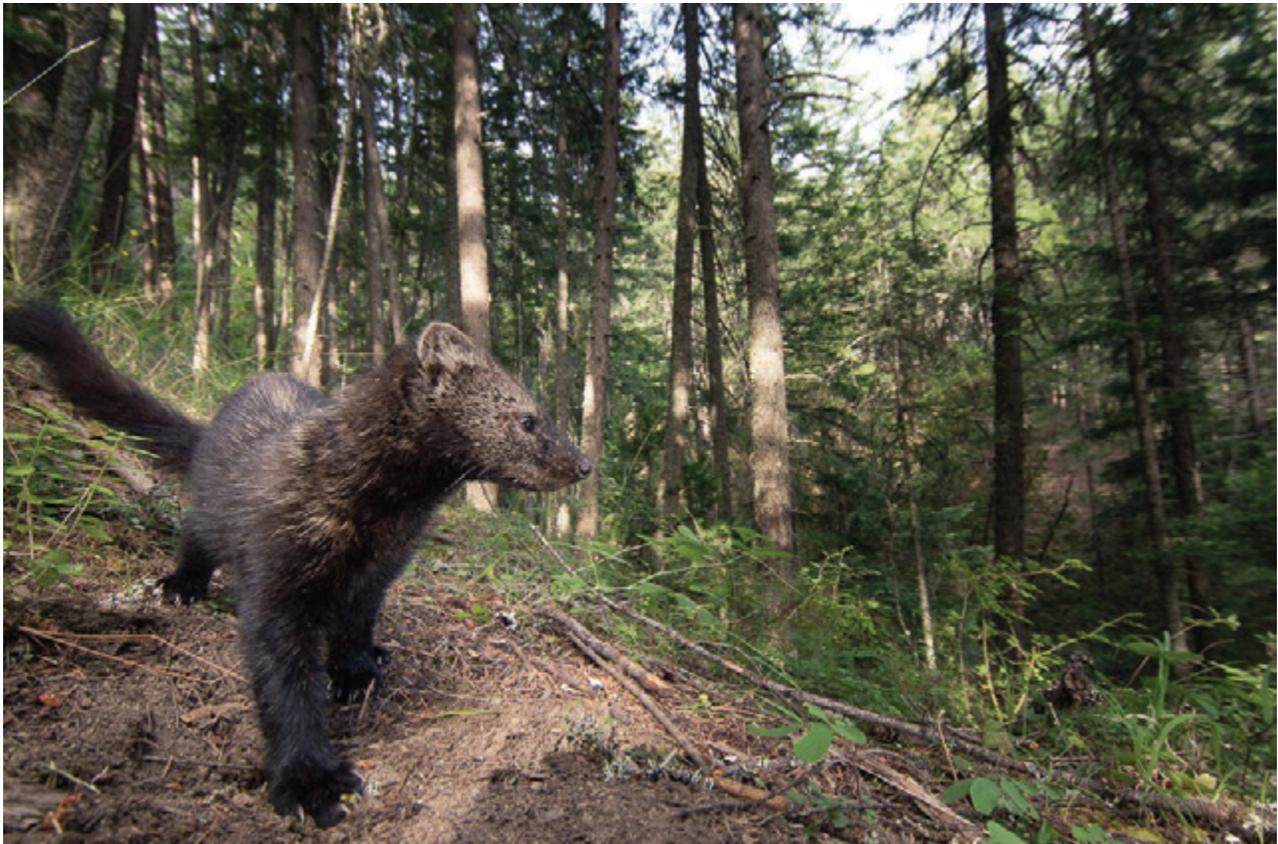


PHOTO: US FISH & WILDLIFE

Vulnerable Wildlife in the Klamath-Siskiyou

Hundreds to thousands of species in the Klamath-Siskiyou region may be at risk due to climate change.⁴¹ Especially vulnerable are species that depend on habitats that may disappear in the future (e.g., high-elevation specialists) and species that may be unable to move to new, suitable habitats due to low dispersal abilities or barriers such as roads (e.g., salamanders).

Moreover, forest types themselves may change with consequences for entire wildlife communities—birds, mammals, amphibians, invertebrates, fungi, and non-vascular plants. Here is a look at some of the Klamath-Siskiyou wildlife facing an uncertain future.



The Klamath-Siskiyou is a stronghold for the forest dwelling Pacific fisher (*Pekania pennanti*). Maintaining forest cover is important for this species.

PHOTO: JONNY ARMSTRONG



PHOTO: STEVEN JOHNSON

Many endemic species found no-where else on earth live in the Klamath-Siskiyou, such as the Siskiyou Mountains salamander pictured here. This lungless salamander is low mobility and lives under the shade of forest canopy and burrows deep into rocky talus slopes to avoid temperate extremes.

Vulnerable Wildlife and Communities

High-elevation plants and animals: may be unable to migrate higher to suitable habitat^{20,27} and as snowpack diminishes water-limitation may become important at higher elevations.²⁷

Amphibians: could suffer from increased drying combined with an inability to migrate to suitable sites.^{1,20} This is on top of the fact that amphibian declines in the U.S. have continued unabated since at least the late 1960s, averaging 3.8% per year, with declines more severe on the West Coast.³⁵

Species requiring cool, moist habitats: including local endemic and relict species, may disappear from region (e.g., lichen; bryophytes; fungi; Plethodon and Dicamptodon salamander species and subgroups; molluscs including land snails; insects, harvestman, millipedes, trapdoor spiders; Brewer spruce, Engelmann spruce, Foxtail pine; additional plants).^{41,44}

Salmon and other aquatic wildlife: face a suite of threats from climate change, including from ocean warming. See below for further details.

Long-distance migratory birds: could have lower access to primary foods due to changes to timing of flowering or insect emergences.²⁰

Endemic serpentine flora: may be highly vulnerable to increases in drying and warming.^{23,46} See below for further details.

Coastal areas: at high risk.⁴¹

Forests: may experience reduced growth and survival, in general.²⁵ See below for further details on forests.

Globally imperiled forest types: in the region include White fir, Port Orford cedar, Brewer spruce, huckleberry oak (*Quercus vacciniifolia*).⁴⁷

Regenerating trees: are most vulnerable (to heat, soil drying, etc.) during the regeneration phase.^{25,29}

Drought-stressed vegetation could be more susceptible to insect outbreaks, disease.^{20,25,27}

Rare plants: 99 out of 156 California rare plants surveyed (~2 out of every 3) were classed as vulnerable to climate change.⁴²

Traits Associated with Vulnerability

- Poor dispersal ability (e.g., small forest vertebrates, flightless invertebrates).^{30,42}
- Narrow microclimatic preferences (e.g., tailed frog).⁴²
- Habitat specialization.⁴²
- Dependence on other species (e.g., pollinator).⁴²
- Low genetic diversity.⁴²
- Dependence on a particular disturbance regime.⁴²

Drought-related Tree Mortality

A 2013 drought followed by a 2014 snow drought in southwestern Oregon led to lowered tree defenses (especially in dense stands) and greater tree mortality from insects and pathogens of pines, firs, and Douglas firs.⁴³



The protection of “climate refuges” represents a vital line of defense against the negative impacts of climate change.



PHOTO: AMY SCHLOTTERBACK

The Applegate Valley, like most of the KS, has complex landscapes shaped by the mosaic of past fire severity.

The Klamath-Siskiyou: Climate Refuge

The protection of “climate refuges” represents a vital line of defense against the negative impacts of climate change. Climate refuges are places with favorable conditions (often cool and moist) where species can persist despite an increasingly unfavorable regional or global climate.^{55–59,62}

Climate refuges tend to occur within complex, mountainous landscapes because this terrain produces an abundance of microhabitats and thus opportunities for species to find favorable climates within small geographic areas.^{1,20,38,55,62,63} The temperatures in rough mountain terrain can vary by up to 16°F^{23,65} and evapotranspiration by >20% between nearby sites.⁶⁶

Mature and old-growth forests are key habitats to protect given their ability to maintain stable climates and function as climate refuges;^{23,55,59,67,68} studies show that well-shaded understory communities have changed little under recent decades of climate warming compared to more open habitats.^{23,69} Also, reducing non-climate anthropogenic stressors (e.g., mining, logging, road-building, etc.) is a critical step that will help climate refuges function most effectively.⁵⁵



PHOTO: NOAH ELHARDT, WIKIMEDIA COMMONS

History as a Climate Refuge

The Klamath-Siskiyou region functioned as a climate refuge for species of a shrinking warm-temperate community (e.g., Siskiyou Mountains salamander, Port Orford cedar, weeping spruce) following the increased aridity of the Miocene.⁷⁰ Past refuge locations tend to occur on or near the coast and overlap with areas of high precipitation.³⁸ Also, the Russian Wilderness contains an extraordinary assemblage of conifer species whose co-occurrence may reflect past climate refuge conditions.⁵⁵

Terminology: Large areas containing clusters of climate refuges—or microrefugia—are known as mesorefugia.⁵⁵

Locations of Climate Refuges

Near coasts: (lessens temperature extremes, abundant rain and fog, low stratus clouds).^{38,55,59}

In forests: especially old-growth, mature, and complex forests; especially forests on north and north-east-facing slopes; especially mesic lowland and mid-elevation forests (stable climate; shady; cool; retain moisture, especially old-growth).^{55,59,67,68}

On north- and northeast-facing slopes: (lower frequency of fire; less solar heating; shaded areas; lower evaporative demand).^{59,62,67,76}

Persistently wet areas: wetlands, rock glaciers, talus slopes, groundwater-fed seeps and springs, bogs (persistent wet soil conditions).^{38,55,59,71,74,75}

Riparian corridors: (climate stability, cool, low evaporative demand).⁵⁹

Near large bodies of water, deep persistent pools: (air warms more slowly due to high heat capacity of water).⁵⁹

Near cold groundwater inputs: (produce local cold-water refuges).⁵⁹ Where cold air pools—valley bottoms, steep canyons, sinks, local depressions, coves, basins (shady, lower minimum temps, cool, accumulate water and soil).^{59,62,76}

Where deep snow drifts form: (water source late in season, insulation to surface below).⁵⁹

Mature and old-growth forests are key habitats to protect given their ability to maintain stable climates and function as climate refuges.

Conditions in Climate Refuges

Stable climate: (free from temperature extremes).^{38,55,59,71–73}

Persistently wet or moist: (high rainfall/fog, water accumulates, wet soil conditions).^{38,55,59,67,68,71,74}

Shady: (buffers against temperature extremes).^{55,59,68}

Cool: (presence of cold air pools, lower minimum temperatures, temperatures drop rapidly after sunset, lower evaporative demand).^{59,62,67}

Cold stream temperatures.⁵⁹

Accumulation of soil: (which helps retain water).⁶²

Improving Refuge Effectiveness

Absence of anthropogenic land use stressors (mining, logging, livestock grazing, damming of rivers, human-caused alterations of fire regimes).⁵⁵

Contiguous habitat along elevational and environmental gradients.⁵⁵

Minimized spread of invasives and pathogens—which are associated with roads.⁵⁵

Areas that are protected from climate-related disturbance—such as increasingly severe fires and extreme floods, also can be considered climate change refugia.^{60,61}

Valuable Resource

See Olson et al. 2012⁵⁵ for a provisional set of 22 highest- and 40 high-priority climate refuges that occur mostly outside of existing protected areas and along wetter and lower elevations of the region.



When already stressed and experiencing low resilience, the significant stress of climate change can cause an ecosystem to undergo a fundamental change or “regime shift.”

Understanding Ecological Resilience

Climate Change may dramatically disrupt the structure and functioning of the Klamath-Siskiyou region with negative consequences for wildlife and humans.^{2,18,21} Efforts should be taken immediately to maximize ecological resilience in the region through science-based natural resource management. Increasing resilience will increase the likelihood that wildlife will adapt or migrate to suitable locations as the climate changes, and decrease the likelihood of ecosystem collapse.

Federally designated wilderness areas, which make up 13% of the KS, will be key climate refuges.



PHOTO: KS WILD

How Does Ecological Resilience Work?

The structure and functioning of an ecosystem depends on (a) interactions among species (e.g., pollination, seed dispersal, predation) as well as (b) the diverse functions performed by species (e.g., regulation of biogeochemical cycles, impacts on disturbance regimes, modification of the physical environment).⁷⁷

In general, the resilience of a given ecological function—such as soil decomposition, for instance—increases with the number of substitute species that can perform that function.^{13,77,80–83} Thus, soil decomposition may maintain consistent performance while populations of the individual species that perform soil decomposition fluctuate.¹⁴ Resilience also increases as diversity within species and populations increases.^{13,77,84,85}

Species vary in the strength of their contributions to ecological functions and structure. Those that contribute most strongly may be considered “drivers” whereas species having less pronounced ecological impacts may be considered “passengers.”⁷⁷ Drivers may be ecological engineers (e.g. beavers⁸⁶ or gopher tortoises⁸⁷) or keystone species (e.g., sea otters⁸⁸ or asynchronously fruiting trees⁸⁹), both of which have strong interactions with multiple species.⁷⁷ There is also evidence that the resilience of ecosystems is further supported when species within a given functional group (e.g., pollinators) operate at different geographic scales. The result is a cross-scale reinforcement of the ecological function.⁷⁷

When an ecosystem with low resilience experiences significant stress and disturbance, the ecosystem can undergo a fundamental change or “regime shift.” Such shifts are often attributed to human actions that have undermined ecosystem resilience.⁹⁰ For example, the Everglades have transitioned from a sawgrass-dominated habitat to one dominated by cattails as a result of increased phosphorus in the soils due to human agricultural activities.⁹¹

As wildlife populations decline, species’ ranges contract, and species go extinct or become locally extirpated, the result is an ecosystem that is more vulnerable to collapse and ultimately replacement by an alternative ecological organization.⁷⁷

Definition

Ecological resilience is the amount of disturbance an ecosystem can withstand without fundamentally changing its structure or function.^{78,79} Resilient ecosystems are better able to handle stress and disturbances, such as climate change.

Resilience Demonstrated

- Grasslands that had higher functional group species richness were more resistant to invasion by other species.³⁶
- Diverse communities achieved more stable ecological function even with large fluctuations in populations of individual species.⁸⁵
- More diverse natural grass communities recovered faster following drought.⁹³
- In experimental ecosystems, carbon dioxide consumption, vegetative cover, and productivity increased with species richness.⁹⁴
- More diverse experimental plots achieved greater plant cover and more efficiently utilized nitrogen.⁸⁵
- Lightly-stressed desert grasslands showed greater resilience to drought than heavily-stressed desert grasslands (stress: grazing by domestic livestock).⁹²



Fire size has increased in recent decades, but fire severity proportions are in line with historic fire.... Wildfires in the region provide numerous benefits.



PHOTO: HIGH CASCADES COMPLEX

Understanding Wildfire in the Klamath-Siskiyou

Mixed-severity wildfires have shaped the Klamath-Siskiyou region for millennia. Variability in burn patterns and severity creates habitat patchiness in vegetation that contributes to the high biological diversity of the region^{14,31,33,34,95,96} because different wildlife species are adapted to the different habitat types that result from fires.^{97,98}

Wildfires in the region provide numerous benefits. They recycle nutrients,¹⁴ increase the abundance of early successional and fire-adapted broadleaf plants (fires of shorter intervals, such as every 30 years, create canopy gaps that allow persistence of these generally shade-intolerant species⁹⁹),^{31,33} and increase fine-scale, structural diversity within habitat types because many or few trees in a stand may survive a fire depending on its severity.^{31,97}

It is hard to believe, but the variety and the abundance of Klamath-Siskiyou plants and animals is not reduced even after multiple large fires.



PHOTO: KS WILD

The widespread 20th century policy of fire suppression in the region (the median area burned per wildfire decreased from 128 ha before Europeans arrived to 25 ha during the fire suppression period⁹⁷) has resulted in major effects on landscape structure, biodiversity, and ecosystem functioning,^{14,101} especially in dry, low-elevation forests characterized by more frequent fire return intervals.¹⁴

Some research shows the region's forested landscapes were generally more open due to fire prior to the 20th century than they are today¹⁰⁰ and today's landscape is characterized by denser forests, less structural diversity, more fire-sensitive species, fewer coarse-grained vegetation mosaics, and a greater likelihood of high-severity fire (particularly in previously open ponderosa pine forests).^{34,97,101} Douglas-fir, and white fir to a lesser extent, increased the most under fire suppression and both are more sensitive to wildfire when young than pines.⁹⁷

Other research shows fires in the region have increased in size in recent decades^{34,102} but have maintained fire-severity proportions in line with contemporary and historic fires: 59% low-severity, 29% moderate, and 12% high-severity.³⁴ Many fires that do show high-severity effects are related to infrequent, severe drought,¹⁰³ but fire exclusion practices have had minimal impact on these fires.¹⁴

Determinants of Fire Behavior and Severity

Topography: a primary control on fire behavior (evidenced by consistent relationships between fire boundaries and topographic features in complex terrain);^{35,97} likelihood of high-severity fire on ridgetops and upper topographic positions (due to preheating of fuels, higher winds, and lower canopy cover).^{31,97,99,101}

Weather: can override topography and be a main driver of fire behavior.^{31,34,105,106}

Impediments to Fire Spread: streams, riparian zones (canopy and soil damage lower in riparian areas compared to uplands in Biscuit Fire¹⁰⁷), sharp changes in aspect, changes in vegetation.^{97,106}

Vegetation: drier vegetation, especially untreated post-logging slash and debris, is more likely to combust,^{14,31,35,97} and stressed and dying vegetation allows more and bigger fires.¹⁸

Shrub cover: there was a positive relationship between shrub cover and canopy damage in the Biscuit Fire.¹⁰⁵

Mature and Old Forests: the long absence of fire (>75 years) results in lower likelihood of high-severity fire^{34,99,108} (due to decreased abundance of combustible understory fuels from shading [e.g., shrubs, evergreen hardwoods] and increased height-to-crown with forest age),^{31,34,109} (due to lower understory temperatures from shading),¹¹⁰ (due to large trees and downed logs functioning as heat sinks).¹⁰⁹

Plantations: tend to experience higher-severity fires,^{34,111} more combustible than co-occurring forests,^{34,111} experienced twice as much severe fire as multi-aged-forests.³⁴

Closed forests: lower fire severity in forests where fire had been absent for 57 years (compared to forests that had experienced more recent fire),³⁴ much lower severity fire than open forest and shrubby non-forest habitats.³⁴

Serpentine: low-productivity, high shrub cover sites with few trees experienced among the highest rates of conifer crown damage in the Biscuit Fire.¹⁰⁵

Mountain Pine Beetles: outbreaks do little if anything to increase fire severity.^{9,112-118}

North-facing slopes: longer times between fires (because wetter conditions inhibit fire)⁹⁷ but can be high-severity fire when fire occurs (because of high tree densities).⁹⁷

South-facing slopes: more frequent fires (because drier conditions),^{14,97} likelihood of high-severity burn on upper third of slope and ridgetops.¹⁰¹

West-facing slopes: longer times between fires (may be due to low productivity soils),⁹⁷ likelihood of high-severity burn on upper third of slope and ridgetops.¹⁰¹

Southwesterly slopes: likelihood of high-severity fire (because drier conditions), especially in upper topographic positions.³¹

East-facing slopes: more frequent fires.⁹⁷

Fire Resistance in Trees

Douglas fir, once mature, is extremely fire-resistant thanks to its thick bark, deep roots, and high crowns.¹⁰¹ Similarly, mature ponderosa, Jeffrey, and sugar pine are also fire-resistant. In contrast, most trees of the much rarer subalpine zone have thinner bark and are easily damaged or killed by fire. These include mountain hemlock, Shasta red fir, white bark pine, western white pine, fox-tail pine, lodgepole pine, and curl-leaf mountain mahogany.¹⁰¹

Community Resilience

A consistent finding from the Biscuit Fire, and other nearby fires, was the high resilience of plant and animal community composition in the aftermath of fire, even in areas burned twice within 15 years.³¹ Both conifer- and hardwood-dominated riparian plant communities returned in similar states following the Biscuit Fire due to abundant regeneration.³¹ Following a repeat high-severity burn, bird community richness remained level or increased and bird densities increased.^{31,33} Small mammal richness and community structure was similar between twice-burned and once-burned areas, but densities were higher in twice-burned areas.³³ Lastly, plant species richness actually increased after a repeat burn due to increases in ephemeral fire-adapted plants in combination with minimal species extirpation.^{31,121}

Burn Patterns of Sequential Fires

In general, areas that burned at high-severity are likely to burn again at high severity if fire returns within a short time period (<30 years).^{31,34,99} This time period can be extended if severe fire reduces soil carbon and site productivity and therefore slows tree growth and lengthens the time when highly flammable shrubby vegetation dominates.⁹⁹ Early successional, non-forest vegetation experiences much higher fire severity than forests, and this tends to favor the persistence of early-successional

habitat.³⁴ In locations where the mixed-severity Biscuit Fire re-burned over the 15-year-old Silver Fire, low-severity patches tended to burn at low-severity and high-severity patches tended to re-burn at high-severity.¹²²

Fire Severity & Return Intervals

High-severity fire has played a role, at least in some areas, in shaping the structure of the region according to the presence of large (>100 ha), even-aged patches of trees in the Klamath Mountains and southern Cascades.^{97,100} The recurrence of fires in western forests varies widely, from once per decade in a few dry pine forests to cycles of 250–400 years (or more) in coastal forests.¹⁴

Birds and Wildfire

Many birds depend on disturbances such as fire.³³ In general, the following types of birds increase in abundance following a wildfire: cavity-nesting birds, aerial insectivores, and ground- and shrub-nesting birds.¹⁷ Early hardwood cover following a fire can be moderate-to-high and this provides good habitat for open-cup nesting birds while aiding soil function and mycorrhizal networks.³¹ The black-backed woodpecker depends heavily on burned forests and their populations often increase dramatically following a fire.^{31,119,120} After high-severity fire, abundant birds were those associated with dead wood (hairy woodpecker), bare ground (dark-eyed junco), and aerial foraging (Townsend's solitaire).³³ The presence of shrubs helped predict both avian abundance and composition, and presence of snags helped predict bird community composition.³³ It appears once-burned areas and twice-burned areas may converge in bird community composition over time.³³

Avian Indicators of Post-fire Habitats³³

Recent burn (2–3 years post-burn): hairy woodpecker, Townsend solitaire, dark-eyed junco.

Repeat burn (2–3 years post-burn): lazuli bunting, rufous hummingbird, spotted towhee, fox sparrow, white-crowned sparrow, nashville warbler.

Old burn (17–18 years post-burn): wrentit, orange-crowned warbler, black-headed grosbeak, Macgillivray's warbler.



Protecting older forests and allowing young forests to regrow for longer periods are two ways to increase regional carbon storage.



PHOTO: GREG VAUGHN

Lower summer streamflows have lower water quality and warmer temperatures that harm juvenile salmon, and the lower flows may prevent spawning salmon from entering some smaller streams.

Carbon Storage and Emissions in Forests

Climate Change is a major threat to wildlife¹²³ and action to minimize the extent of climate change through carbon uptake and storage by vegetation is important.¹²⁴ Protecting older high-biomass forests and allowing young forests to re-grow for longer periods are two ways to increase regional carbon storage.^{4,18,32,38} Additionally, forests that regenerate after disturbance store carbon rapidly—and for long periods—if left undisturbed through the stages of succession.^{4,5}

Wildfires and Carbon

Wildfires can release huge amounts of carbon into the atmosphere²¹ and they are the largest source of carbon losses on federal lands.³²

Most carbon losses from wildfires come from the combustion of surface fuels (as opposed to canopy fuels) because surface fuels burn abundantly in almost all fire types whereas canopy burns, when they occur, tend to be patchy;⁵³ consequently, high-severity fires (>80% canopy combustion) produce only 30% more emissions than low-severity fires (0–10% canopy combustion).^{53,64}

For example, in the 2002 mixed-severity Biscuit Fire that burned in the Siskiyou National Forest in southern Oregon and northern California, less than 20% of the carbon emissions came from canopy combustion.¹²⁵

From a management perspective, efforts to minimize canopy mortality (and subsequent plant material decay with its additional carbon release) are limited in their ability to reduce overall wildfire carbon emissions because most wildfires experience significant combustion of surface fuels and this is what drives total wildfire emissions.^{31,53}

More carbon is stored by forests that burn less often; long-term simulations indicate that forests experiencing a low-frequency, high-severity fire regime store more carbon than forests with a high-frequency, low-severity fire regime.⁵³

In the first decade (or two) following a forest-replacing fire, it is likely that carbon emissions from the decay of fire-killed trees will exceed the carbon sequestered by new vegetation.⁵³

Forest stands that experience high tree mortality from fire experience higher carbon and nitrogen losses from mineral soil.³¹



Protecting older high-biomass forests and allowing young forests to re-grow for longer periods are two ways to increase regional carbon storage.

PHOTO: SHANE STILES

Both logging and wildfires produce significant carbon emissions.^{13,21,32} It is important to note that fuel-reduction treatments aimed at preventing future high-severity wildfires emit more carbon into the atmosphere than they ultimately save from combustion.^{53,54} Also, they do not have a major impact on total wildfire carbon emissions because high-severity fires release only moderately more carbon (~30%) than low-severity fires.^{53,64}

Good News for Climate Mitigation: Regional forests in the Pacific Northwest have shifted from a net source to a net sink of carbon under the Northwest Forest Plan (1994–Present) due to reduced logging and forest regrowth.⁴

Logging and Carbon

Logging can release huge amounts of carbon into the atmosphere.¹³ Logging (mostly on non-federal lands) is the primary source of land-use related carbon emissions.³² Carbon emissions from fuel-reduction treatments generally exceed the carbon savings that would occur if the treated area were to burn.⁵³ For example, simulations of conifer forests in Oregon indicate that removing three units of carbon in treatment will protect one unit of carbon from wildfire combustion.⁵⁴

The average aboveground carbon losses from fuel-reduction treatments in semiarid conifer forests (western U.S.) are 10% for prescribed fire only, 30% for thinning only, and 50% for thinning followed by prescribed fire.⁵³ By comparison, aboveground carbon losses from wildfires on comparable fire-suppressed forests averaged 12–22%.^{64,125}

There is a low likelihood that forest stands that receive fuel-reduction treatments will be exposed to fire.⁵³

If fuel-reduction treatments could possibly result in greater carbon storage overall, it would require the treatments to increase maximum achievable biomass on the plot (e.g., through decreased non-fire tree mortality, protection of soil fertility from losses sometimes incurred from high-severity fire, etc.).⁵³

Over a period of seven years, plots that received fuel-reduction treatments did not store more carbon than comparable fire-suppressed control plots.¹²⁷ Typically, carbon emissions from the decay of dead plant material in logged forests exceeds the carbon sequestered from the growth of new vegetation.¹²⁶ The fossil fuel costs of fuel-reduction treatments range from ~1–3% of aboveground carbon stock.^{128–130}



PHOTO: SHANE STILES

Regional forests in the Pacific Northwest have shifted from a net source to a net sink of carbon under the Northwest Forest Plan (1994–Present) due to reduced logging and forest regrowth.



In the Pacific Northwest, most forest types begin developing mature/old-growth characteristics at 80 years.



PHOTO: TIM PALMER

While protecting all mature and old-growth forest is important, climate change makes it vital in middle and low elevations, on north- and northeast-facing slopes, in canyon bottoms, and in coastal mountains.

Valuable Old Forests

Old-growth and complex mature forests are immensely valuable owing to their wildlife habitat, provision of ecosystem services (including carbon storage), and their role as climate refuges (i.e., places where species can persist despite an increasingly unfavorable regional or global climate).^{15,55} The mature forests that will function most effectively as climate refuges are mesic lowland and mid-elevation mature forests, those located on north- and northeast-facing slopes, in canyon bottoms, along elevational gradients, or in areas with abundant fog and precipitation (e.g., in coastal mountains).^{55,74} Cultivating additional older forests will also help alleviate the negative impacts of climate change and align with the growing public interest in older forest protection.^{15,55} The Klamath-Siskiyou region contains only 28% of its historic old-growth forests,⁵⁵ adding further to the rationale for their protection.



PHOTO: KS WILD

Forests as Sanctuaries in a Changing Climate

Mature and old-growth forests are important climate refuges for wildlife because they maintain a stable climate; their canopy cover—especially when dense and complex—buffers temperature extremes by keeping temperatures cooler in summer and warmer in winter.^{20,23,59,69} Maximum springtime temperatures are 4.5°F lower in old-growth than in structurally simple forest plantations.²⁰ Old-growth forests exhibit year-to-year consistency in site-level conditions despite sizable fluctuations in annual climates.²⁰

Complex canopy cover also increases relative humidity in the understory²³ and this, in combination with the greater litter and understory vegetation of mature and old-growth, helps retain moisture and protect wildlife from the stress of desiccation during summer droughts.⁶⁸ The climate buffering characteristics of mature forests can provide a critical lifeline (a safe haven, plus extra time to adapt or migrate) for temperate forest diversity in a warming climate—this may be essential for the many known slow-colonizing forest herbs.¹³²

Recent studies show that mature forests are in fact functioning as climate refuges for wildlife. Community change data from southern Oregon demonstrate that well-shaded understory communities changed less over six decades of climate warming than more open understory communities.⁶⁹ Similarly, a multi-decadal study of temperate deciduous forests in 29 regions in Europe and North America found that thermophilization (i.e., the increase of warm-adapted species and the decrease of cold-adapted species) was lowest in the densest forests.²³

Ecosystem Services of Old Forests

Older forests—especially high-biomass older forests¹⁷⁰—provide a wealth of ecosystem services. These include wildlife habitat, carbon storage, clean air, clean water, primary productivity, regulation of hydrologic processes, soil formation,

Mature and old-growth forests are important climate refuges for wildlife because they maintain a stable climate; their canopy cover—especially when dense and complex—buffers temperature extremes by keeping temperatures cooler in summer and warmer in winter.

nutrient cycling, pollination, medicinal resources, wild foods, salmon productivity, cultural and spiritual opportunities, and recreation.^{23,133–139,170}

Old-Growth Ages, Features, & History

In the Pacific Northwest, most forest types begin developing mature/old-growth characteristics at 80 years.⁶ Old-growth forests are characterized by high tree size diversity at the stand level and high densities of large live trees, large snags, and downed wood cover.⁷ Douglas-fir forests are classified as mature at >80 years and as old-growth at 150–200 years.¹⁵ Subalpine fir, white/grand fir, and ponderosa pine become old-growth at 150 years,¹⁵ and upper elevation subalpine fir and Pacific silver fir reach old-growth at 260–360 years.¹⁵

Historically, old-growth forest once covered about two-thirds (41 million acres) of the Pacific Northwest.¹⁵ Today, about 28% remains.¹⁵ Within the Klamath-Siskiyou region the same percentage—about 28%—of historic old-growth forest remains.⁵⁵ Since the adoption of the Northwest Forest Plan in 1994, most losses of old-growth on federal lands in the region are due to large wildfires.¹²

Valuable Roadless Areas

The KS still includes nearly three million acres of roadless acres at least 1000 acres in size. That's over one-quarter of the region. These areas are essential to protect in the face of climate change.

Roadless areas in the Klamath-Siskiyou region avoid the negative impacts of roads while simultaneously increasing habitat connectivity and protecting numerous elements of special conservation interest. Existing roadless areas, in combination with protected lands and waters (e.g., wilderness areas), provide an important foundation upon which to build an overall regional conservation strategy⁴⁰ to maintain ecological resilience and integrity in the face of climate change.



Roadless Areas in the Klamath-Siskiyou and their Contributions to Conservation

In 2001, Strittholt and DellaSala⁴⁰ mapped nearly 500 roadless areas (each >1000 acres) in the Klamath-Siskiyou region. These roadless areas (totaling more than 2,930,000 ac) combine to cover ~27% of the region—an area twice as large as that covered by designated wilderness—and they contain valuable conservation elements that complement what is protected in wilderness areas.⁴⁰

Klamath-Siskiyou wilderness areas are concentrated at high elevations and protect non-forested habitats as well as most of the region’s red fir and white fir forests, and significant portions of the region’s higher Jeffrey pine, ponderosa pine, montane-hardwood conifer, and Klamath mixed-conifer forests.⁸ Roadless areas augment the acreage of some of these habitats, but more importantly they add new physical zones for the same plant community types as well as new habitats; in fact, adding roadless areas to wildernesses resulted in 96 new habitat types (note: 214 total habitat types in the region) being captured at a level of >25% of their total occurrence in the region;⁴⁰ together, roadless areas and wildernesses protect 64% (138 out of 214) of Klamath-Siskiyou habitat types at the >25% level.⁴⁰

Roadless areas represent low- and mid-elevations (<5000 feet) better than wilderness areas.⁴⁰ This is significant because lower elevations contain the most biological diversity in the region.¹⁴⁰ Roadless areas also made important contributions to regional habitat connectivity,⁴⁰ a critical landscape component that will allow species to adapt and migrate when faced with stresses from a changing climate.

Negative Impacts of Roads

Negative impacts of roads on terrestrial and aquatic environments include the following: increased erosion, air and water pollution, the disruption of the natural infiltration of water to the soil, the spread of invasive species and pathogens, wildlife mortality and avoidance, restricted wildlife movement and dispersal, forest fragmentation, and an increase in human-caused forest fire.^{9,40} Additionally, roads



PHOTO: KS WILD

Once roads are built, a landscape is more susceptible to landslides, the fouling of streams, the spread of noxious weeds, and an increase in human-caused forest fires.

increase access to natural areas which often leads to human activities—such as logging, mining, and grazing—that degrade ecosystems and result in native species declines.⁴⁰ As of 2001, the total road length (all road surface types) for the Klamath-Siskiyou region was ~28,000 miles.

KS Roadless Areas⁴⁰ (In Brief)

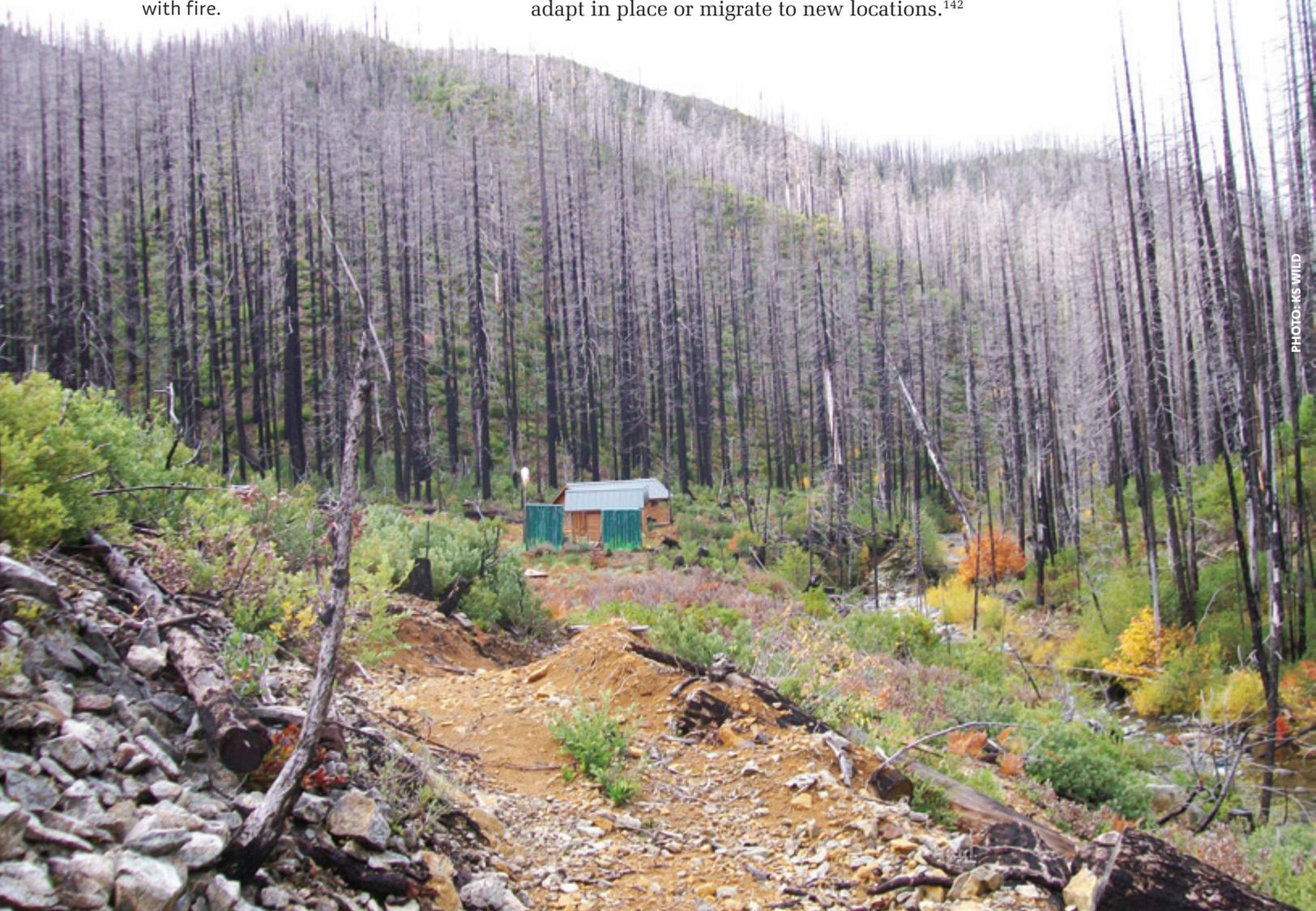
- 498 mapped roadless areas.
 - 367 smaller roadless areas (1000–5000 ac).
 - 131 large roadless areas (>5000 ac).
- Roadless areas cover 27% of the region (2,930,000 ac) and contain high percentages of the region’s
 - remaining mature and old forests (36%).
 - known occurrences of heritage-elements (i.e., point locations for plant and animal species of special conservation interest; 36%).
 - mapped serpentine habitat (37%).
 - key watersheds for aquatic biodiversity (42%).
 - Port Orford cedar strongholds (60%).
- 92% of roadless areas occur on US Forest Service land, 7.6% on BLM land, and 0.4% on National Park Service land.

Climate Change Impacts on Forests

Protection from the numerous stressors caused by climate change increases dramatically right at a wilderness boundary, here, in the Kalmiopsis Wilderness which has evolved for thousands of years with fire.

Forests in General

- Reduced forest growth and survival (in general), due to adverse effects of higher temps and drought stress.¹
- May be positive forest responses in growth and productivity where there is sufficient moisture or where growth is limited by cold.¹
- Changing forest structure and composition.^{1,141}
- Rapid climate change may challenge the capacity of tree species to adapt in place or migrate to new locations.¹⁴²



- Greater forest susceptibility to insects, disease.¹
- Beetle conditions will be enhanced, increasing the threat to native forests.²¹
- Potential jump of mountain pine beetle to non-pine species.¹⁴³
- Forest changes will lead to impacts on the terrestrial communities that depend upon them.
- Mature forest communities may be vulnerable to increases in wildfires and lengthened fire seasons.¹

Lower Elevation Forests

- Increased drought stress at lower elevations.²
- Drought-related vegetation die-off in warm and water-limited low to moderate elevations.³⁰
- Areas that are moisture-limited are particularly vulnerable (e.g., low elevations in the Klamath and Siskiyou Mountains).¹
- Douglas-fir associations will be reduced.²¹
- Warming and drying will favor oaks and other hardwoods at lower elevations.²¹
- Chaparral, dry pine forests, oak, and broadleaved hardwood forests will replace wetter temperate forests—this transition could happen rapidly via wildfires.
- Grassland and scrublands are likely to expand as forest conditions diminish.²¹
- Increase in fire-adapted vegetation communities.²¹

High Elevation Forests

- Increase in high elevation plant productivity and species richness, with losses of high-elevation specialists.^{1,30}
- Increased establishment and growth at higher elevations.²
- Higher elevation spruce/fir/hemlock communities will be compromised or eliminated.²¹



PHOTO: KS WILD ARCHIVES

The speed at which the climate changes matters. Rapid climate change may challenge the capacity of plant species to adapt in place or migrate to new locations.

Maritime Forests

Projections show significant declines in maritime evergreens, and two models show an increase in maritime needleleaf and temperate deciduous broadleaves.²¹

Plant Physiology & Climate Change

Warmer temperatures tend to improve plant physiological processes so long as moisture is sufficient and optimal temperatures are not exceeded.¹

Whether plants benefit from elevated carbon dioxide concentrations may depend on nutrient availability, especially nitrogen.¹ There may be little benefit on nutrient-poor sites.

Plants may be able to accommodate some degree of drought with minimal negative effects because higher atmospheric carbon dioxide increases water conservation in plants.¹⁴⁴ As plants open their stomata (tiny openings on leaves) to draw in carbon dioxide molecules to build their bodies, they lose moisture; but with higher atmospheric carbon dioxide they need to open their stomata for shorter time periods and consequently lose less moisture.



Trees grow up to three times as fast when salmon are plentiful.



PHOTO: US FISH AND WILDLIFE

Coho and other salmon are simultaneously one of the most culturally and ecologically important species in the region. They are also some of the most threatened, even before the full impacts of climate change are felt.

Salmon, Streams, and Climate Change

Benefits of Salmon and Salmon Habitats

Salmon populations support the health and functioning of ecosystems in multiple ways. Salmon are the primary food source for many wildlife species^{145,146} and they bring marine-derived nutrients—such as carbon, nitrogen, phosphorus, and micronutrients—to inland communities.^{147–150} In fact, trees grow up to three times as fast when salmon are plentiful.¹⁵¹ They also create new in-stream habitats for other wildlife when they alter streambeds and sediment composition during spawning.¹⁵¹ Salmon are a keystone species that interact



PHOTO: WIKIPEDIA OREGON DEPARTMENT OF FORESTRY

(directly and indirectly) with many species in an ecosystem; thus, their decline or extirpation from a region affects many wildlife species.^{21,145}

Ecosystems capable of supporting robust salmon populations—such as intact and functional wetlands, floodplains, streams, rivers, and riparian systems—also provide regulating ecosystem services including water purification, flood control, more consistent stream flows, temperature regulation, and abundant fish populations.¹⁴⁷ Additionally, salmon hold cultural significance for many people and bring economic vitality to regions where they occur.²¹

Climate Threats to Salmon and Streams

Hotter temperatures—warmer air temperatures will increase water temperatures and cause thermal stress and possibly death to salmon.^{18,26}

Reduced summer streamflows—lower summer streamflows have lower water quality and warmer temperatures that will compromise the survivorship of juvenile fish, and the lower flows may prevent spawning salmon from entering some smaller streams.²⁸

Altered timing of natural events—warmer temperatures could lead to earlier emergences of aquatic invertebrates and a possible decoupling of the availability of fish food sources from seasonal fish needs.^{18,21}

Increased storms and wildfires—more intense storms combined with more frequent and severe wildfires will harm aquatic systems by increasing runoff of sediment, nutrients, persistent organic pollutants, and other contaminants into streams and tributaries.¹⁸ Increased sedimentation to streams caused by runoff from roads after a severe fire (and by post-fire logging if present) may continue for years¹⁴ and may push aquatic systems into a less desirable ecological states altogether.¹⁵²

Increased disease prevalence—the combination in summers of warmer stream temperatures, lower streamflows, and reduced dissolved oxygen concentrations increases the potential for disease spread and fish mortality.¹⁸

The surrounding landscape—patch dynamics on the greater landscape affect waterways by influencing hydrology, sediment and contaminant loads, and water temperatures.²⁵

Notable: Due to widespread salmon declines, current salmon populations bring only 6% or 7% of the historical amount of marine-derived nitrogen and phosphorus to rivers and inland terrestrial communities in the Pacific Northwest.¹⁴⁸

Sample of Aquatic Species in the Rogue Valley¹⁵³

- Coho salmon.
- Chinook salmon.
- Steelhead.
- Cutthroat Trout.
- Amphibians, including tailed frog.
- Pacific lamprey.
- Green sturgeon.
- White sturgeon.
- Klamath smallscale sucker.
- Speckled dace.
- Prickly sculpin.

Valuable Riparian Habitats

Riparian habitats alongside streams and rivers are dynamic and complex environments that contain high biological diversity compared to surrounding landscapes,^{27,154} provide dispersal corridors for wildlife, especially fish migration,²⁷ and directly influence the health and integrity of stream habitats and their dependent wildlife communities (including birds, salmon, amphibians, aquatic invertebrates, molluscs, etc.).¹⁵⁴

Serpentine and Climate Change



PHOTO: US FOREST SERVICE

The high metal content in serpentine soils has led to an explosion of unique and wonderful plant species throughout the Klamath-Siskiyou, including lady slipper orchid above, and the carnivorous cobra lily or *Darlingtonia*, to the right.

An Introduction to Serpentine

Serpentine rocks are found throughout the world, primarily where oceanic crust and mantle appear on the earth's surface, and soils weathered from these rocks contain high magnesium, low calcium, possibly low macronutrients (especially phosphorus and potassium), possibly high heavy metals (such as, nickel, chromium, and cobalt), and sometimes high rock content.⁶⁷ Plant communities on serpentine soils have traits that reflect harsh living conditions: small stature, low specific leaf area, more roots than shoots, and overall sparse canopy cover.¹⁵⁵ Low canopy cover in combination with the high rock content of the soils can lead to higher temperatures and water scarcity.^{67,155} Serpentine communities have evolved



PHOTO: KS WILD

to tolerate the stresses of their environment and in the Klamath-Siskiyou region, where 13% of the soil is serpentine,⁴⁰ these communities have contributed to the region's high level of plant species endemism.^{140,155}

Are Serpentine Communities Vulnerable to Climate Change?

An important question is whether serpentine plant communities, with their stress-tolerant traits, will be more or less vulnerable than other communities to the changes brought by climate change. There is evidence on both sides:

Serpentine communities will be more resilient to climate change:

- In the Klamath-Siskiyou region, shrub and tree abundances (insufficient data on herbs) have varied less on serpentine compared to granitic substrates over the past 15,000 years,¹⁵⁶ suggesting greater tolerance to climate changes on serpentine soils.
- Serpentine grassland communities in northern California responded less to variation in annual precipitation than non-serpentine, in terms of species richness and composition.¹⁵⁷
- Generally, serpentine communities vary less than non-serpentine across climate gradients.^{155,158}
- Three out of four studies suggest serpentine communities will be less sensitive to climate change, while the fourth indicates serpentine communities will be just as sensitive as communities on "normal" soils.¹⁵⁵
- In a 15-year observational study as the climate has become more arid, grassland species diversity declined but less so on serpentine soils.¹⁵⁹
- Balance of evidence seems to support hypothesis, that low soil fertility results in stress-tolerant plant traits that confer higher resistance to climate change.⁶⁹

Serpentine communities have evolved to tolerate the stresses of their environment and in the Klamath-Siskiyou region, where 13% of the soil is serpentine, these communities have contributed to the region's high level of plant species endemism.

Serpentine communities will be more vulnerable to climate change:

- Greater shifts in Klamath-Siskiyou region from 1949–2007 in plant species richness and cover on serpentine compared to non-serpentine soils.¹⁶⁰
- Serpentine endemics had greater declines in cover than soil generalists in Klamath-Siskiyou from 1949–2007.¹⁶⁰

It is important to note that even if serpentine communities are more resilient to climate change, they can still suffer species loss and other negative impacts.⁶⁹ Their sparser canopy cover means they will experience more heating than forests, which could undermine their greater tolerance of water stress.⁶⁹ Additionally, stress-tolerant invasive species could become established and outcompete native species.⁶⁹ Serpentine sites that retain wet soil conditions, such as those located in or near seeps and fens, may be important climate refuge locations for serpentine flora.³⁷



Post-fire logging and associated road-building can increase future fire risk and severity and are nearly always harmful to natural regenerative processes after fire.



PHOTO: KS WILD

Careful thinning in dense, second growth stands and on south facing slopes can reduce fire hazards and lessen drought stress. The Nedsbar Timber Sale, pictured below, proposed logging large trees in older forest stands and was stopped by community action.

An Overview of Thinning and Logging

A century of fire exclusion policies in the western U.S. has resulted in forests that differ both structurally and compositionally from historic forests.⁵³ Tree removal and prescribed fire (i.e., fuel-reduction treatments) are common management tools used in fire-prone forests to restore historic functionality, reduce fuel quantity and continuity, and reduce the risk of high-severity forest fire.^{52,53} It is generally accepted that fuel-reduction treatments do reduce fire hazards in forests for short periods,^{53,130} and they are also said to lessen drought stress and likelihood of insect and disease outbreaks.¹



PHOTO: KS WILD

That said, there are also costs associated with fuel-reduction treatments. It takes the treatment of about 10 locations to influence fire behavior in a single location due to the rarity of severe wildfires.⁵³ Carbon emissions from fuel-reduction treatments generally exceed the carbon savings that would occur if the treated area were to burn.⁵³ Logging causes heavy disturbance to the soil that can reduce the abundance of herbs ill-adapted to such disturbance.³⁰ Without careful implementation, treatments often damage remaining trees, compact the soil, and lead to fuel build-up.¹ Finally, logging in riparian areas, which harms these highly valuable wildlife habitats, also can diminish recruitment of wood to instream habitats.⁹

Where to Thin

- The home-ignition zone (up to 100–200 ft outward from home structures).^{9,34}
- In drier forests sites to lessen drought stress and mimic natural fire regimes.^{14,54}
- Dense, young forest stands on south-facing slopes and ridgetops (where fire-severity is typically the greatest).^{14,31,101}

Logging and Beetles

Thinning and logging are said to reduce the risk of future mountain pine beetle outbreaks,¹ however, studies reveal mixed effects on future outbreaks at the stand level and no effects at the landscape scale.^{9,118} Even when thinning reduces an outbreak at the stand level, the negative impacts of thinning (i.e., soil compaction and other impacts to soils, damage and stress to trees, road-building and its associated negative impacts, carbon loss, water quality reductions from soil runoff, spread of invasives, etc.) must be considered.^{9,10}

Post-fire Logging

Post-fire logging—the logging of forests relatively soon after a wildfire event—has many negative impacts on wildlife and ecosystems.^{9,15,131} The logging (and associated road-building, if present) can increase future fire risk and severity⁹ and is nearly always harmful to natural regenerative processes after fire.^{15,131}

Following post-fire logging in ponderosa pine or Douglas-fir forests, there tends to be in the early years greater abundances of ground- and shrub-nesting birds and less prevalence of bird species associated with snags.¹⁷ The black-backed woodpecker is a “sensitive species” in Oregon⁴⁵ that is less abundant in salvaged forest, regardless of whether it is partial or complete logging.¹⁷ Maintaining some burned forests for this post-fire specialist is a management action consistent with maintaining native bird populations.¹⁷

After post-fire logging in the Eastern Cascades, there were lower relative abundances and densities of black-backed woodpecker, hairy woodpecker, brown creeper, western wood-pewee, and yellow-rumped warbler, and higher relative abundances and densities of fox sparrow and dark-eyed junco.¹⁷ Additional studies demonstrate negative impacts on hairy woodpecker with near complete removal of snags, whereas other studies show mixed effects from partial post-fire logging.¹⁷ A separate study found non-significant responses of most bird species to post-fire logging and little effect on community composition.³



PHOTO: KS WILD

Land Management Solutions

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. — REED NOSS

Believing that climate change is happening is not enough. Our public land managers must consistently use the best available climate science in making land management decisions that will affect this region and its people for centuries.

Scientifically-informed land management will be the primary means to stave off the worst effects of climate change for ecological communities. Action must be swift, however. Here we outline the most important land management steps from the scientific literature for protecting the unique biological heritage of the Klamath-Siskiyou region.



PHOTO: KS WILD

1.

Habitats to Protect and Restore

Mature and Old-growth Forests

- Protect remaining old-growth habitat as swiftly as possible.^{8,13,15,18,20,24,37,48}
- Manage for high biomass old forests (because these support more biodiversity and provide more ecosystem services).¹⁹

Climate Refuges

- Immediately identify and protect climate refuges (especially old-growth) at multiple scales, including small scales (see above for details).^{13,20,23,37,38,48,50}
- Identify past refugia (when possible) and protect them because they may act as refugia again.¹³
- Identify and protect thermal refugia in streams (provided by cold ground-water and tributary inflows).^{21,26}

Streams and Rivers

- Restore and maintain critical stream habitats (e.g., high-elevation riparian areas, floodplains, tributary junctions, north-facing streams, stream reaches with gravels and topographic complexity).¹⁸
- Restore native vegetation in riparian zones that provide shade and complex habitat.^{21,26}
- Maintain or increase stream buffers.^{8,21}
- Restore and maintain stream floodplain complexity and connectivity,^{18,21,28,49} restore stream flow regimes,⁴⁹ restore channels,⁴⁹ and raise groundwater tables.²⁸
- Use native beavers and beaver dam analogs to increase water retention on landscape.²⁸
- Ensure highest possible water quality and quantity.²¹
- Protect genetic diversity and life history diversity of fish.¹⁸

Protect missing elements in existing protected area network:

- Areas that add to habitat connectivity¹⁸ (large forest patches;⁴⁰ roadless areas^{18,40}). Protected areas should be expanded (longitudinally, latitudinally) to allow species to shift ranges, especially along elevational gradients^{18,8}).
- Areas containing representative lowland species assemblages.³⁷

Degraded areas

- Undertake ecological restoration in degraded areas.^{37,2}

2. Prevent Additional Climate Change

- Reduce greenhouse gas emissions wherever possible.⁹
- Increase carbon storage in the landscape (protect older, high-biomass forests; allow young forests to regrow for longer time periods because these forests rapidly sequester carbon).^{4,13,18,32,38}
- Do not undertake fuel treatments (thinning and/or prescribed fire) for the purpose of increasing carbon storage on the landscape because fuel treatments aimed at preventing high-severity wildfires emit more carbon into the atmosphere than they ultimately protect from subsequent wildfire combustion.^{53,54}

3. Strengthen Ecosystem Resilience

- Maintain species richness,^{13,36} maintain diversity of functional groups and redundancy of species within functional groups,^{24,36} and maintain genetic diversity within and among populations.^{13,18,24}
- Probably the single most important action land managers can take is to reduce existing non-climate stressors (e.g., habitat fragmentation, erosion from roads and resource extraction, air and water pollution and contamination, loss of keystone species, invasive species, livestock overgrazing, logging of old forests, floodplain/coastal development, over allocation of water, flooding, energy development, human footprint, disease, overfishing, inappropriate fire management, loss of natural habitats).^{1,13,18,24,38,39}
- Target the reduction of non-climate stressors to core habitats, old-growth climate refuges, and adaptation corridors along elevational gradients.³⁷
- Increase habitat connectivity (especially along elevational and environmental gradients).^{13,21,24}
- Maintain native forest types across environmental gradients.²⁴
- Maintain keystone species near ecologically optimal population levels.³⁶
- Minimize impediments to adaptability and resilience.

4. Landscape Planning and Forestry

- Apply ecologically-appropriate, low-intensity fuels reduction where needed (particularly in dry ponderosa pine and dry mixed-conifer forests; and within 100–200 ft of homes^{9,34}) (to reduce competition, drought stress, and risk of high-severity fire).^{13,15,18,21,46}
 - Retain old live trees, large snags, and large logs, and restore native understory plants.¹⁴
 - Minimize the following: soil disturbance and soil compaction, the loss of carbon and mycorrhizae from soil, the introduction of invasive species, road-building, the size of canopy openings, and the removal of biomass.²²
- Prevent conversion of forests to even-aged, single species tree plantations (because they harbor lower biodiversity and are more vulnerable to disturbances such as fire and pest outbreaks).^{13,20,34}
- Restore a diverse mosaic of resilient habitats across the landscape.^{14,21}
 - Restore early successional forests and forests experiencing natural regeneration (because they are scarce on the landscape).^{14,33}
 - Restore young forests (<80 years old) that originate after disturbance in older forests (i.e., complex early seral forest) (because of high species richness, especially forbs and shrubs).^{8,33}

- Retain “snag forests” (because they are very biologically diverse and one of rarest forest types due to prevalence of post-fire logging).^{10,11,33}
- Retain trees killed by mountain pine beetles outbreaks (because ecologically valuable and used by birds, bats, squirrels, etc.).⁸
- Represent forest types across environmental gradients in reserves.¹³
- Increase quality of landscape matrix that exists among habitat patches.⁴²
- Use prescribed fire and thinning to inhibit conifer encroachment into wild-life-rich oak habitats.³⁵
- Reintroduction of fire (prescribed and from natural ignitions).²¹
- Fire suppression may be ecologically warranted if habitat of critically threatened species is at risk, if fire is outside the historical range of variability, or in places where high-severity fire is not viewed as desirable (e.g., old-growth forests).¹⁴
- Do not log after fires (because suites of species depend on large areas of post-fire “snag forest” habitat type, as well as other natural habitats that form through natural succession).^{8,11,12,14}
- Avoid replanting after fire (replanting may reduce natural tree regeneration, may reduce the recovery of native plants and biodiversity, and may not be effective at reducing soil erosion).^{11,14,31}
- Control undesirable plants and invasive species through vegetation treatments.²⁴

5. Monitoring and Identification

- Periodically monitor status and condition of old-growth and mature forests.¹⁵
- Survey old-growth forest invertebrates and non-vascular plants in order to understand distributions of distinct assemblages (to inform identification of representative climate refuges for protection).⁸
- Identify climate refuges for at-risk species.⁸
- Identify species of high ecological importance for all ecosystems, and maintain them.¹³

6. Other Interventions

- Decommission or repair failing roads (to improve water quality).^{8,21,26}
- Create zoning ordinances to prevent development and agriculture within or adjacent to riparian areas.²¹
- Limit stream water withdrawals during periods of low flow and high temperatures.²⁶
- Equip rural residences with tanks to store spring and winter runoff for use in the summer (to lessen withdrawals from low summer streamflows).²⁸
- Incentivize decreased human consumption of water.²⁸
- Increase storage of winter rains in soils (to offset summer drought stress).²

References

PLEASE NOTE: In addition to this references section, an annotated and interactive bibliography is available online. The bibliography provides references in alphabetical order and by topic. Annotations on individual papers are also provided. The annotated bibliography can be found at:

<https://tinyurl.com/KS-climate-bibliography>

- 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.
- Mote et al. 2003. Preparing for climate change: the water, salmon, and forests of the Pacific Northwest. *Climate Change* 61: 45–88.
- Fontaine, J.B., 2007. Influences of high severity fire and post-fire logging on avian and small mammal communities of the Siskiyou Mountains, Oregon, USA. In: Fisheries and Wildlife, Oregon State University, Corvallis, OR.
- Krankina, O.N.; Harmon, M.E.; Schnekenburger, F; Sierra, C.A. 2012. Carbon balance on federal forest lands of western Oregon and Washington: The impact of the Northwest Forest Plan. *For. Ecol. Manag.* 286, 171–182.
- Harmon, M.E.; Ferrell, W.K.; Franklin, J.F. 1990. Effects on carbon storage of conservation of old-growth forests to young forests. *Sci. Febr.* 247, 4943.
- Franklin, J.F.; Spies, T.A. 1991. Ecological Definitions of Old-Growth Douglas-Fir Forests; General Technical Report PNW-GTR-85; U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station: Portland, OR, USA.
- Davis, R.J.; Ohmann, J.L.; Kennedy, R.E.; Cohen, W.B.; Gregory, M.J.; Yang, Z.; Roberts, H.M.; Gray, A.N.; Spies, T.A. 2015. Northwest Forest Plan—The First 20 Years (1994–2013): Status and Trends of Late-Successional and Old-Growth Forests (draft); USDA Forest Service: Portland, OR, USA. Available online: <https://reo.gov/monitoring/reports/20yr-report/LSOG%2020yr%20Report%20-%20Draft%20for%20web.pdf>
- 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.
- 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.
- DellaSala, D.A. et al. 2015. In the aftermath of fire: logging and related actions degrade mixed- and high-severity burn areas. Pp. 313–347, In DellaSala, D.A., and C.T. Hanson (eds), *The ecological importance of mixed-severity fires: nature's phoenix*. Elsevier, UK.
- Swanson, M.E., et al. 2011. The forgotten stage of forest succession: early-successional ecosystems on forested sites. *Frontiers in Ecol. and Environ.* 9:117–125 doi:10.1890/090157.
- Davis, R. J., B. Hollen, J. Hobson, J. E. Gower, and D. Keenum. 2015. Northwest Forest Plan—The first 20 years (1994–2013): Status and trends of Northern Spotted Owl habitats. USDA Forest Service General Technical Report PNW-GTR-000.
- Noss, Reed F. 2001. Beyond Kyoto: forest management in a time of rapid climate change. *Conservation Biology* 15(3): 578–590.
- 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.
- 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.
- Wright, Juanita. 2016 News Release. Southwest Oregon experiencing an increase in drought-related conifer mortality. Pacific Northwest Region Rogue River-Siskiyou National Forest.
- 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.
- 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.
- Carroll, C.; Odion, D.C.; Frissell, C.A.; DellaSala, D.A.; Noon, B.R.; Noss, R. 2009. Conservation Implications of Coarse-Scale Versus Fine-Scale Management of Forest Ecosystems: Are Reserves Still Relevant? Klamath Center for Conservation Research: Orleans, CA, USA. Available online: <http://www.klamathconservation.org/docs/ForestPolicyReport.pdf>
- Frey et al. 2016. Spatial models reveal the microclimatic buffering capacity of old-growth forests. *Sci. Adv.* 2016; 2:e1501392 22 April 2016.
- 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.
- Amaranthus, M. P. 1998. The importance and conservation of ectomycorrhizal fungal diversity in forest ecosystems: lessons from Europe and the Pacific Northwest. General technical report PNW 0(431). U.S. Forest Service, Seattle.
- De Frenne, P., et al. 2013. Microclimate moderates plant responses to macroclimate warming. *PNAS* 110(46): 18561–18565.
- Spittlehouse, D.L. and R.B. Stewart. 2003. Adaptation to climate change in forest management. *BC Journal of Ecosystems and Management* 4(1):1–11.
- 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.
- Mantua, N., I. Tohver, A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change* 102:187–223.
- 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.

28. 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.
29. Carpenter, S. R. and C. Folke. 2006. Ecology for transformation. *Trends in Ecology and Evolution* 21 (6):309–315.
30. Harrison, S., Damschen, E.I. and J.B. Grace. 2010. Ecological contingency in the effects of climate warming on forest herb communities. <http://www.pnas.org/content/107/45/19362.full.pdf?sid=65227b5b-272b-4aa8-ac21-e7ddd1920ada>.
31. Halofsky et al. 2011. Mixed-severity fire regimes: lessons and hypotheses from the Klamath-Siskiyou Ecoregion. *Ecosphere* 2(4): 1–19.
32. Krankina, O.; DellaSala, D.A.; Leonard, J.; Yatskov, M. 2014. High biomass forests of the Pacific Northwest: Who manages them and how much is protected? *Environ. Manag.* 54, 112–121.
33. 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.
34. 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.
35. Skinner, C.N., Taylor, A.H. and J.K. Agee. 2006. Chapter 9: Klamath Mountains Bioregion; In: *Fire in California's Bioregions*.
36. Symstad, A. J. 2000. A test of the effects of functional group richness and composition on grassland invasibility. *Ecology* 81:99–109.
37. Olson et al. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou Ecoregion. *Nature Areas Journal* 31: 65–74.
38. DellaSala et al. 2010. Climate-adapted conservation planning. Powerpoint presentation.
39. Beschta, R.L.; DellaSala, D.A.; Donahue, D.L.; Rhodes, J.J.; Karr, J.R.; O'Brien, M.H.; Fleishcner, T.L.; Deacon-Williams, C. 2013. Adapting to climate change on western public lands: Addressing the impacts of domestic, wild and feral ungulates. *Environ. Manag.* 53, 474–491.
40. 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.
41. Coope, G. R. 1979. Late Cenozoic fossil Coleoptera: evolution, biogeography, and ecology. *Annual Review of Ecology and Systematics* 10:247–267.
42. Fahrig, L.; Merriam, G. 1985. Habitat patch connectivity and population survival. *Ecology* 66, 1762–1768.
43. 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.
44. Stebbins, G.L. and Major, J. 1965. Endemism and speciation in the California flora. *Ecological Monographs*, 35, 1–35.
45. Oregon Natural Heritage Information Center. 2004. Rare, Threatened and Endangered Species of Oregon. Oregon Natural Heritage Information Center, Oregon State University, Portland, OR.
46. Franklin, J. F. and K. N. Johnson. 2012. A restoration framework for federal forests in the Pacific Northwest. *Journal of Forestry* 110:429–439.
47. North, M., B. M. Collins, and S. Stephens. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. *Journal of Forestry* 110:392–401.
48. R. Julliard, F. Jiguet, D. Couvet. 2004. Common birds facing global changes: What makes a species at risk? *Glob. Chang. Biol.* 10, 148–154.
49. Beechie, T., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess. P. Roni, J. Kimball, J. Stanford, P. Kiffney, N. Mantua. 2012. Restoring Salmon Habitat for a Changing Climate. *River Research and Applications*. DOI: 10.1002/rra.2590.
50. Franklin, J. F., F. J. Swanson, M. E. Harmon, D. A. Perry, T. A. Spies, V.H. Dale, A. McKee, W. K. Ferrell, J. E. Means, S. V. Gregory, J. D. Lattin, T. D. Schowalter, and D. Larsen. 1991. Effects of global climatic change on forests in northwestern North America. *Northwest Environmental Journal* 7:233–254.
51. Farnum, P. 1992. Forest adaptation to global climate change through silvicultural treatments and genetic improvement. In *Implications of climate change for Pacific Northwest forest management*. G. Wall (editor). Department of Geography, University of Waterloo, Waterloo, Ont. Occasional Paper No. 15, pp. 81–84.
52. Hurteau MD, Stoddard MT, and Fulé PZ. 2010. The carbon costs of mitigating high-severity wildfire in southwestern ponderosa pine. *Glob Change Biol*; doi:10.1111/j.1365-2486.2010.02295.x.
53. 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.
54. Mitchell SR, Harmon ME, and O'Connell KEB. 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. *Ecol Appl* 19: 643–55.
55. Olson et al. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou Ecoregion. *Nature Areas Journal* 31: 65–74.
56. J. M. Sunday, A. E. Bates, M. R. Kearney, R. K. Colwell, N. K. Dulvy, J. T. Longino, R. B. Huey. 2014. Thermal-safety margins and the necessity of thermoregulatory behavior across latitude and elevation. *Proc. Natl. Acad. Sci. U.S.A.* 111, 5610–5615.
57. R. A. Long, R. T. Bowyer, W. P. Porter, P. Mathewson, K. L. Monteith, J. G. Kie. 2014. Behavior and nutritional condition buffer a large-bodied endotherm against direct and indirect effects of climate. *Ecol. Monogr.* 84, 513–532.
58. B. R. Scheffers, R. M. Brunner, S. D. Ramirez, L. P. Shoo, A. Diesmos, S. E. Williams. 2013. Thermal buffering of microhabitats is a critical factor mediating warming vulnerability of frogs in the Philippine biodiversity hotspot. *Biotropica* 45, 628–635.
59. Morelli TL, Daly C, Dobrowski SZ, Dulen DM, Ebersole JL, Jackson ST, et al. 2016. Managing Climate Change Refugia for Climate Adaptation. *PLoS ONE* 11(8): e0159909. doi:10.1371/journal.pone.0159909
60. Camp AE, Oliver C, Hessburg P, Everett R. 1997. Predicting late-successional fire refugia pre-dating European settlement in the Wenatchee Mountains. *For Ecol Manage.* 95:63–77.
61. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science*. 313(5789):940–3. doi: 10.1126/science.1128834 PMID:16825536
62. Dobrowski, Soloman Z. 2011. A climatic basis for microrefugia: the influence of terrain on climate. *Global Change Biology* 17: 1022–1035. doi: 10.1111/j.1365-2486.2010.02263.x
63. 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.
64. Meigs GW, Law BE, Donato DC, et al. 2009. Influence of mixed severity wildfires on pyrogenic carbon transfers, postfire

carbon balance, and regeneration trajectories in the eastern Cascades, Oregon. *Ecosystems* 12: 1246–67.

65. Scherrer D, Körner C. 2010. Infra-red thermometry of alpine landscapes challenges climatic warming projections. *Glob Change Biol* 16(9):2602–2613.

66. Dobrowski SZ, Abatzoglou J, Greenberg JA, Schladow G. 2009. How much influence does landscape-scale physiography have on air temperature in a mountain environment? *Agricultural and Forest Meteorology*, 149, 1751–1758.

67. Alexander, E., Coleman, R., Keeler-Wolf, T. & Harrison, S. 2006. *Serpentine Geocology of Western North America*. Oxford University Press, New York, NY.

68. Chen, J.S., S.C. Saunders, T.R. Crow, R.J. Naiman, K.D. Brosofske, G.D. Mroz, B.L. Brookshire, and J.F. Franklin. 1999. Microclimate in forest ecosystems and landscape ecology. *Bio-Science* 49:288–297.

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

70. Coleman, R.G. & Kruckeberg, A.R. 1999. Geology and plant life of the Klamath-Siskiyou mountain region. *Natural Areas Journal*, 19, 320–340.

71. Anacker, Brian L. and Susan P. Harrison. 2012. Climate and the evolution of serpentine endemism in California. *Evol. Ecol.* 26: 1011–1023.

72. Colinvaux, P. 1978. *Why big fierce animals are rare: an ecologist's perspective*. Princeton University Press, Princeton, New Jersey.

73. Lloret F, Escudero A, Iriondo JM, Nezvialta JM, Valladares F. 2012. Extreme climatic events and vegetation: the role of stabilizing processes. *Global Change Biol.* 18:797–805.

74. Carroll, C., J.R. Dunk, and A. Moilanen. 2010. Optimizing resiliency of reserve networks to climate change: multispecies conservation planning in the Pacific Northwest. *Global Change Biology* 16:891–904.

75. Bogan MT, Boersma KS, Lytle DA. 2015. Resistance and resilience of invertebrate communities to seasonal and suprasedasonal drought in arid-land headwater streams. *Freshwat Biol.* 60(12):2547–58.

76. Dobrowski, S.Z. 2010. A climatic basis for microrefugia: the influence of terrain on climate. *Global Change Biology*: (doi:10.1111/j.1365-2486.2010.02263.x).

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

78. Walker, B. H., C. S. Holling, S. C. Carpenter, and A. P. Kinzig. 2004. Resilience, adaptability, and transformability. *Ecology and Society* 9(2):5. [online] URL: <http://www.ecologyandsociety.org/vol9/iss2/art5/>

79. Holling CS. 1973. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* 4:1–23

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

81. Carpenter, S. R., E. M. Bennett, and G. D. Peterson. 2006. Scenarios for ecosystem services: an overview. *Ecology and Society* 11(1):29. [online] URL: <http://www.ecologyandsociety.org/vol11/iss1/art29/>

82. Walker, B. 1992. Biological diversity and ecological redundancy. *Conservation Biology* 6:18–23.

83. Walker, B. 1995. Conserving biological diversity through ecosystem resilience. *Conservation Biology* 9:747–752.

84. Luck, G. W., G. C. Daily, and P. R. Ehrlich. 2003. Population diversity and ecosystem services. *Trends in ecology and evolution* 18(7):331–336.

85. Tilman D, Wedin D, Knops J. 1996. Productivity and sustainability influenced by biodiversity in grasslands ecosystems. *Nature* 379:718–20.

86. Naiman RJ, Pinay G, Johnston CA, Pastor J. 1994. Beaver influences on the long-term biogeochemical characteristics of boreal forest drainage networks. *Ecology* 75:905–21.

87. Diemer JE. 1986. The ecology and management of the gopher tortoise in the southeastern United States. *Herpetologica* 42:125–33.

88. Estes JA, Duggins DO. 1995. Sea otters and kelp forests in Alaska: generality and variation in a community ecological paradigm. *Ecol Monogr* 65:75–100.

89. Terborgh J. 1986. Keystone plant resources in the tropical forest. In: Soulé ME, editor. *Conservation biology: the science of scarcity and diversity*. Sunderland (UK): Sinauer. p 330–44.

90. Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C. S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology and Systematics* 35:557–581.

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

92. Whitford, W. G., D. J. Rapport, and A. G. DeSoyza. 1999. Using resistance and resilience measurements for “fitness” tests in ecosystem health. *Journal of Environmental Management* 57:21–29.

93. Frank DA, McNaughton SJ. 1991. Stability increases with diversity in plant communities: empirical evidence from the 1988 Yellowstone drought. *Oikos* 62:360–62.

94. Naeem S, Thompson LJ, Lawler SP, Lawton JH, Woodfin RM. 1994. Declining biodiversity can alter the performance of ecosystems. *Nature* 368:734–7.

95. Baker, W. L. 1992. Effects of settlement and fire suppression on land-scape structure. *Ecology* 73:1879–1887.

96. Agee, J.K., 1993. *Fire ecology of Pacific Northwest forests*. Island Press, Washington, DC.

97. Taylor, A.H. and C.N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. *Ecological Applications* 13(3): 704–719.

98. Huntzinger, M. 2003. Effects of fire management practices on butterfly diversity in the forested western United States. *Biological Conservation* 113:1–12.

99. 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.

100. Taylor, A. H., and C. N. Skinner. 1998. Fire history and landscape dynamics in a late successional reserve, Klamath Mountains, California, USA. *Forest Ecology and Management* 111:285–301.

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

102. Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. *Science* 313, 940–943.

103. Westerling A, Gershunov A, Brown T, et al. 2003. Climate and wildfire in the western United States. *B Am Meteorol Soc* 84: 595–604.

104. Higuera, P.E., Brubaker, L.B., Anderson, P.M., Hu, F.S. & Brown, T.A. 2009. Vegetation mediated the impacts of postglacial

- climate change on fire regimes in the south-central Brooks Range, Alaska. *Ecological Monographs*, 79, 201–219.
105. Thompson, J. R., and T. A. Spies. 2009. Vegetation and weather explain variation in crown damage within a large mixed severity wildfire. *Forest Ecology and Management* 258:1684–1694.
106. Stephens, S. L. 2001. Fire history differences in adjacent Jeffrey pine and upper montane forests in the Sierra Nevada. *International Journal of Wildland Fire* 10:161–167.
107. Halofsky, J. E. and D. E. Hibbs. 2008. Determinants of riparian fire severity in two Oregon fires, USA. *Canadian Journal of Forest Research* 38:1959–1973.
108. Bond, W. J., and B. W. van Wilgen. 1996. *Fire and plants*. Chapman and Hall, London.
109. Azuma, D.L., Donnegan, J. & Gedney, D. 2004. Southwest Oregon Biscuit Fire: An Analysis of Forest Resources and Fire Severity. Research Paper PNW-RP-560. US Department of Agriculture, Forest Service, Portland, OR.
110. Countryman, C. M. 1955. Old-growth conversion also converts fire climate. *U.S. Forest Service Fire Control Notes* 17:15–19.
111. Weatherspoon, C. P. and C. N. Skinner. 1995. An assessment of factors associated with damage to tree crowns from 1987 wildfires in northern California. *Forest Science* 41:430–451.
112. Hart, S.J., et al. 2015. Area burned in the western United States is unaffected by recent mountain pine beetle outbreaks. *PNAS Early Edition* www.pnas.org/cgi/doi/10.1073/pnas.1424037112.
113. Kulakowski, D. and T. T. Veblen. 2007. Effect of prior disturbances on the extent and severity of wildfire in Colorado subalpine forests. *Ecology* 88(3): 759–769.
114. Hart, S.J., et al. 2015. Negative feedbacks on bark beetle outbreaks: widespread and severe spruce beetle infestation restricts subsequent infestation. *PLOS ONE* | DOI:10.1371/journal.pone.0127975
115. Harvey, B.J. et al. 2013. Influence of recent bark beetle outbreak on fire severity and postfire tree regeneration in montane Douglas-fir forests. *Ecology* 94: 2475–2486.
116. Donato, D.C. 2013. Bark beetle effects on fuel profiles across a range of stand structures in Douglas-fir forests of Greater Yellowstone. *Ecol. Applications* 23:3–20.
117. Bond, M.L., et al. 2009. Influence of pre-fire tree mortality on fire severity in conifer forests of the San Bernardino Mountains, California. *The Open Forest Science Journal* 2:41–47.
118. Adapted from Black, S.H. et al. 2013. Do bark beetle outbreaks increase wildfire risks in the Central U.S. Rocky Mountains: Implications from Recent Research. *Nat. Areas J.* 33:59–65.
119. Hutto RL. 1995. Composition of bird communities following stand-replacement fires in northern Rocky Mountain (USA) conifer forests. *Conserv Biol* 9: 1041–58
120. Dixon, R.D., Saab, V.A., 2000. Black-backed woodpecker (*Picoides arcticus*). In: Poole, A., Gill, F (Eds.), *The Birds of North America*. The Birds of North America, Inc., Philadelphia, PA.
121. Donato, D. C., J. B. Fontaine, W. D. Robinson, J. B. Kauffman, and B. E. Law. 2009. Vegetation response to a short interval between high-severity wildfires in a mixed-evergreen forest. *Journal of Ecology* 97:142–154.
122. Thompson, J. R., and T. A. Spies. 2010. Factors associated with crown damage following recurring mixed-severity wildfires and post-fire management. *Landscape Ecology* 25:775–789.
123. Peters, R. L., and T. E. Lovejoy, editors. 1992. *Global warming and biological diversity*. Yale University Press, New Haven, Connecticut.
124. Coope, G. R. 1979. Late Cenozoic fossil Coleoptera: evolution, biogeography, and ecology. *Annual Review of Ecology and Systematics* 10:247–267.
125. Campbell JC, Donato DC, Azuma DA, and Law B. 2007. Pyrogenic carbon emission from a large wildfire in Oregon, United States. *J Geophys Res. Atmos* 112: G04014.
126. Schulze, E.-D., C. Wirth, and M. Heimann. 2000. Managing forests after Kyoto. *Science* 289:2058–2059.
127. Hurteau MD and North M. 2010. Carbon recovery rates following different wildfire risk mitigation treatments. *Forest Ecol Manag* 260: 930–37.
128. Finkral AJ and Evans AM. 2008. The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. *Forest Ecol Manag* 255: 2743–50.
129. North M, Hurteau M, and Innes J. 2009. Fire suppression and fuels treatment effects on mixed-conifer carbon stocks and emissions. *Ecol Appl* 19: 1385–96.
130. Stephens SL, Moghaddas JJ, Hartsough BR, et al. 2009. Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest. *Can J Forest Res* 39: 1538–47.
131. Lindenmayer, D. B., D. R. Foster, J. F. Franklin, M. L. Hunter, R. F. Noss, F. A. Schmiegelow, and D. Perry. 2004. Salvage harvesting policies after natural disturbance. *Science* 303:1303.
132. De Frenne P, et al. 2011. Interregional variation in the floristic recovery of postagricultural forests. *J Ecol* 99(2):600–609.
133. Hector, A.; Bagchi, R. 2007. Biodiversity and ecosystem multifunctionality. *Nature*, 448, 188–190.
134. Gamfeldt, L.; Snäll, T.; Bagchi, R.; Jonsson, M.; Gustafsson, L.; Kjellander, P.; Ruiz-Jaen, M.C.; Froberg, M.; Stendahl, J.; Philipson, C.D.; et al. 2013. Higher levels of multiple ecosystem services are found in forests with more tree species. *Nat. Commun.*, 4, 1340, doi:10.1038/ncomms2328.
135. Norse, E. A. 1990. *Ancient forests of the Pacific Northwest*. The Wilderness Society, Washington, D.C.
136. Franklin, J. F., and T. A. Spies. 1991. Composition, function, and structure of old-growth Douglas-fir forests. Pages 71–90 in L. F. Ruggiero, K. B. Aubry, A. B. Carey, and M. Huff, technical coordinators. *Wildlife and vegetation of unmanaged Douglas-fir forests*. General technical report PNW-GTR-85. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, Oregon.
137. Thomas, J. W. 1991. Research on wildlife in old-growth forests: setting the stage. Pages 1–4 in L. F. Ruggiero, K. B. Aubry, A. B. Carey, and M. Huff, technical coordinators. *Wildlife and vegetation of unmanaged Douglas-fir forests*. General technical report PNW-GTR-85. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, Oregon.
138. NRC (Natural Research Council). 2000. *Environmental issues in Pacific Northwest forest management*. Committee on Environmental Issues in Pacific Northwest Management, Board on Biology, NRC, Washington, D.C.
139. Lindenmayer, D. B., and J. F. Franklin. 2002. *Conserving forest biodiversity: a comprehensive multiscaled approach*. Island Press, Washington, D.C.
140. DellaSala, D. A., S. B. Reid, T. J. Frest, J. R. Strittholt, and D. M. Olson. 1999. A global perspective on the biodiversity of the Klamath-Siskiyou ecoregion. *Natural Areas Journal* 19:300–319.
141. Peterson, D. W., B. K. Kerns, and E. K. Dodson. 2014. Climate change effects on vegetation in the Pacific Northwest: A review and synthesis of the scientific literature and simulation model projections. *USDA Forest Service General Technical Report PNW-GTR-900*.

142. Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T., Curtis-McLane, S., 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evol. Appl.* 1, 95–111.
143. EcoNorthwest. 2009. “An Overview of Potential Economic Costs to Oregon of a Business-As-Usual Approach to Climate Change.” Climate Leadership Initiative. Institute for a Sustainable Environment. University of Oregon.
144. Abigail L. S. Swann, Forrest M. Hoffman, Charles D. Koven, James T. Randerson. 2016. Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity. *Proceedings of the National Academy of Sciences*; 201604581 DOI: 10.1073/pnas.1604581113
145. Willson, M. F., and K. C. Halupka. 1995. Anadromous fish as keystone species in vertebrate communities. *Conservation Biology* 9(3):489–497.
146. Merz, J. E., and P. B. Moyle. 2006. Salmon, wildlife, and wine: marine-derived nutrients in human-dominated ecosystems of central California. *Ecological Applications* 16(3):999–1009.
147. 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/>
148. Gresh, T., J. Lichatowich, and P. Schoonmaker. 2000. An estimation of historic and current levels of salmon production in the Northeast Pacific ecosystem: evidence of a nutrient deficit in the freshwater systems of the Pacific Northwest. *Fisheries* 25(1):15–21.
149. Finney, B. P., I. Gregory-Eaves, J. Sweetman, M. S. V. Douglas, and J. P. Smol. 2000. Impacts of climate change on Pacific salmon abundance over the past 300 years. *Science* 290:795–799.
150. Reimchen, T. et al. 2003. Isotopic evidence for enrichment of salmon-derived nutrients in vegetation, soil, and insects in riparian zones in coastal British Columbia. *American Fisheries Society Symposium* 34:59–69.
151. Schindler, D. E., M. D. Scheuerell, J. W. Moore, S. M. Gende, T. B. Francis, and W. J. Palen. 2003. Pacific salmon and the ecology of coastal ecosystems. *Frontiers in Ecology and the Environment* 1(1):31–37.
152. Karr JR, Rhodes JJ, Minshall GW, et al. 2004. The effects of postfire salvage logging on aquatic ecosystems in the American west. *BioScience* 54: 1029–33.
153. Oregon Department of Environmental Quality (ODEQ). 2012. Regional Focus on Water Quality. Rogue Basin Water Quality Status and Action Plan Summary 2012. Retrieved 3/8/2013 from <http://www.oregon.gov/deq/FilterDocs/BasinRogueSum.pdf>.
154. Bury, R.B., 2008. Low thermal tolerances of stream amphibians in the Pacific Northwest: implications for riparian and forest management. *Appl. Herp.* 5, 63–74.
155. 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.
156. Briles, C.E., Whitlock, C., Skinner, C.N. & Mohr, J. 2011. Holocene forest development and maintenance on different substrates in the KlamathMountains, northern California, USA. *Ecology*, 92, 590–601.
157. Fernandez-Going, B.M., Anacker, B.L. & Harrison, S. 2012. Temporal variability in California grasslands: soil type and species functional traits mediate response to precipitation. *Ecology*, doi: 10.1890/11–2003.1.
158. Harrison, S. 1997. How natural habitat patchiness affects the distribution of diversity in Californian serpentine chaparral. *Ecology*, 78, 1898–1906.
159. Harrison, S., Gornish, E. and S. Copeland, unpubl. data.
160. Damschen, E.I., Harrison, S.P. & Grace, J.B. 2010. Climate change effects on an endemic-rich edaphic flora: resurveying Robert H. Whittaker’s Siskiyou sites (Oregon, USA). *Ecology*, 91, 3609–3619.
161. Snyder, MA and LC Sloan. 2005. Transient future climate over the western United States using a regional climate model. *Earth Interact* 9: 1–21.
162. Johnstone, J.A., and T.E. Dawson. 2010. Climatic context and ecological implications of summer fog decline in the coast redwood region. *PNAS* 107:4533–4538.
163. Stavros, E. N., J. T. Abatzoglou, D. McKenzie, and N. K. Larkin. 2014. Regional projections of the likelihood of very large wildland fires under a changing climate in the contiguous Western United States. *Climatic Change* 126:455–468.
164. Pounds, J.A., M.R. Bustamante, L.A. Coloma, J.A. Consuegra, M.P.L. Fogden, P.N. Foster, E. La Marca, K.L. Masters, A. Merino-Viteri, and R. Puschendorf. 2006. Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* 439:161–167.
165. Loarie, S.R., P.B. Duffy, H. Hamilton, G.P. Asner, C.B. Field, and D.D. Ackerly. 2009. The velocity of climate change. *Nature* 462:1052–1055.
166. Burkett, V.R., D.A. Wilcox, R. Stottlemeyer, W. Barrow, D. Fagre, J. Baron, J. Price, J.L. Nielsen, C.D. Allen, and D.L. Peterson. 2005. Nonlinear dynamics in ecosystem response to climatic change: case studies and policy implications. *Ecological Complexity* 2:357–394.
167. 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
168. 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
169. Root, T.L. and S.H. Schneider. 1993. Can large-scale climatic models be linked with multiscale ecological studies? *Conservation Biol* 7: 256–270.
170. Brandt, P.; Abson, D.J.; DellaSala, D.A.; Feller, R.; von Wehrden, H. 2014. Multifunctionality and biodiversity: Ecosystem services in temperate rainforests of the Pacific Northwest, USA. *Biol. Conserv.*: 169, 362–371.

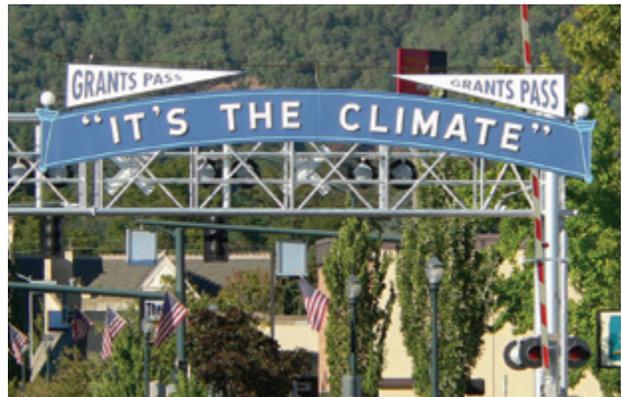


PHOTO: DARREN CAMPBELL



PHOTO: SISKIYOU REGIONAL EDUCATION PROJECT

“ We stand now where two roads diverge. But unlike the roads in Robert Frost’s familiar poem, they are not equally fair. The road we have long been traveling is deceptively easy, a smooth superhighway on which we progress with great speed, but at its end lies disaster. The other fork of the road—the one ‘less traveled by’—offers our last, our only chance to reach a destination that assures the preservation of the earth. ”

RACHEL CARSON

