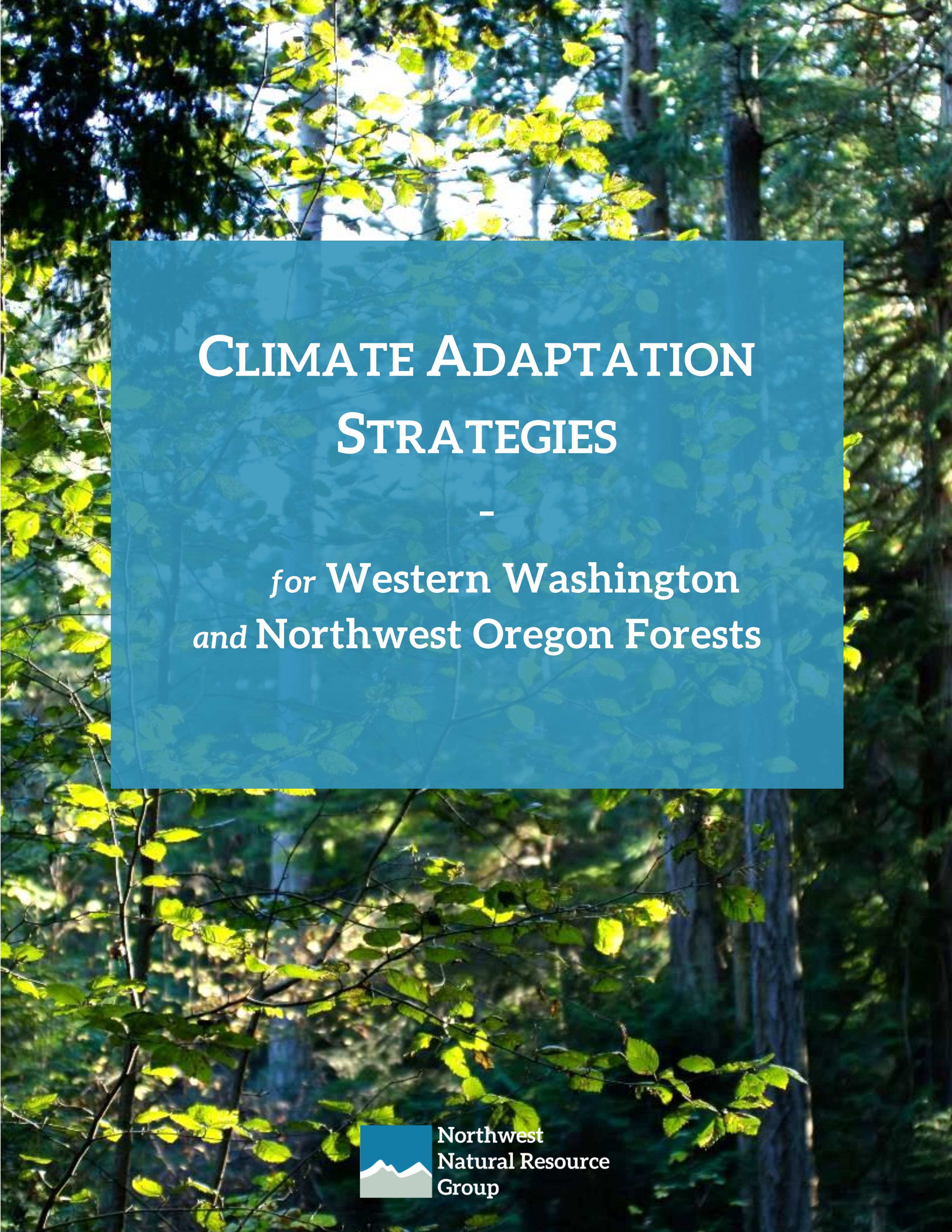

Climate Adaptation Strategies

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for Western Washington *and* Northwest Oregon Forests

Northwest Natural Resource Group

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CONTENTS

INTRODUCTION

This paper aims to help readers understand climate change projections for western Oregon and Washington, the likely effects on forest ecosystems at lower elevations, and forest management strategies and tools they can use to help Pacific Northwest forests adapt to changing climate conditions. The content is tailored to the particular experience and needs of natural resource professionals and forest owners from the Willamette Valley north to the Canadian border.

Although anthropogenic climate change undercuts the basic premise of climate stability that has historically guided forest management, forest owners and land managers can take many actions to improve forest resilience to climate change-induced stressors. Understanding the ecological processes, tree traits and life history, soil types, and environmental conditions inherent to Northwest forests is an important start. This baseline knowledge about Northwest forests can then be augmented with emerging research on how the Northwest's climate is projected to change over the next century, and how species and ecosystems are likely to respond to these changes. Combining this knowledge with keen on-the-ground observations can help land managers to recognize when conditions in their forests are changing, to discern whether changes to our region's climate are having an impact, and to start implementing adaptation strategies.

By understanding the projected impacts of climate change on Northwest forests, land managers and forest owners can also make informed decisions about adapting their management practices to continue to meet their goals and sustain their forests into the future. Most management strategies and tactics that help forests adapt to and become resilient to climate change are already commonly used silvicultural practices. A changing climate makes proactive forest management that much more important and can lead forest managers to tailor management techniques they are already using to increase their forest's resilience to the changes predicted for our region.

Climate models project that the Northwest will experience drier, warmer summers and wetter, warmer winters with less snowpack than the historical average. The anticipated effects of climate change on Northwest forests primarily involve an increase in the severity of existing stressors, such as drought, insect and tree disease outbreaks, invasive species competition, wildfires, and habitat loss and fragmentation.

These stressors will be exacerbated by increasingly warm average temperatures year-round, wetter winters, and drier spring and summer seasons. Changes in temperatures may lead to mismatches between plant species and the sites on which they can grow. Both warmer temperatures and precipitation changes have an effect on evapotranspiration and thus influence effective soil moisture, which in turn can increase new seedling mortality, increase tree susceptibility to pathogen and insect mortality, increase quantity and flammability of forest fuels, increase the length of the season when forests are most vulnerable to fire, and lead to stressors during the growing seasons with direct mortality among drought-intolerant species.

This publication provides information about climate projections for the Pacific Northwest, the likely effects of climate change on forests, and recommendations to improve forest health and resilience in light of a changing climate. After summarizing the climate trends and implications for forests, this paper focuses in detail on adaptation strategies for helping maintain forest productivity and ecosystem services. These adaptation strategies include:

1) Monitoring specific forest health indicators
2) Managing tree densities below the zone of mortality
3) Retaining diverse species and age classes in stands
4) Planting and managing tree and vegetation species appropriate to the site
5) Controlling invasive plants
6) Preparing for fire risk
7) Supporting healthy hydrology through road and stream infrastructure and other actions

Information for this publication was gathered from the Oregon Climate Change Research Institute, the Climate Impacts Group at the University of Washington, researchers with the United States Forest Service, as well as other public institutions, planners, and scientists. These findings were brought to life in a series of workshops held in late 2019 in Everett and Olympia, Washington, and Salem, Oregon, where more than a dozen presenters shared their insights into climate adaptation with a combined audience of 131 participants. Northwest Natural Resource Group thanks Western SARE (Sustainable Agriculture Research and Education), a program of the USDA, for funding this endeavor.

Photo by Paul Boers, Zena Forest Products

KEY CONSIDERATIONS AND STRATEGIES

The advent of anthropogenic climate change erodes the basic assumption of continuity that the practice of forestry is built on — a shift that is particularly significant given forestry's long-term planning horizons. Forest stewards can no longer plant trees and expect them to grow just as they did during the last 50 years.

Warmer temperatures will increase evapotranspiration and reduce soil moisture. Changes in the timing of precipitation, as well as the relative balance of rain and snow, will likewise leave the soil drier during crucial times of year. This will lead to direct mortality among drought-intolerant species, increase seedling mortality, make trees more susceptible to pathogen and insect mortality, increase the quantity and flammability of forest fuels, and increase the length of the season during which forests are most vulnerable to fire. As Yogi Berra once said, "The future ain't what it used to be." The effects will likely be quite different in moisture-limited ecosystems — which are expected to experience greater stresses — than in energy-limited (high elevation) settings at higher elevations, where early snowmelt and longer growing seasons may actually reduce some of the key stressors on plant species and increase their growth rates.

Given that the climate may begin to deviate beyond the bounds of variation that forest managers had come to expect, it is time for forest managers and ecologists to adopt a mindset of resilience by focusing on restoring or managing for structure and composition that will be resilient to climate change and other stressors. In the face of new climatic drivers, the forest will transition to a new combination of species and structure states, and forest stewards can help shape that new context to support biodiversity and productivity as best they can. Maximizing productivity, however, will become increasingly challenging as the future becomes less predictable. Instead, it will be critical to manage for resilience, uncertainty, and adaptability. With those qualities comes the need to become keen observers of the forest, and to translate those observations into management actions that respond to the new realities unfolding in the forest.

These changes will be costly and damaging to some forests that we have held dear. Areas on the edges of the forest biome, which may have supported trees for centuries, are on the verge of a change in ecological state that will leave them unsuitable to grow coniferous forests, as they transition to oak woodlands or other vegetation communities. Elsewhere, the tree species that a site can support may change. For instance, western hemlock is unlikely to thrive on south-facing slopes, fast-draining, or thin soils in the Puget Trough and Willamette Valley.

At the same time, sheltered sites will emerge as refugia that sustain species which formerly had wider distribution. These are areas that offer protections from a warmer climate and the desiccating summers forecast for our region. These refugia can be expected to emerge around such features such as year-round springs, seeps, riparian corridors, or cool drainages on north-facing slopes. Forest stewards would do well to be attuned to these sites, and to give them special consideration them in the course of their management practices.

The next section describes the expected changes in climate parameters that will challenge Northwest forests and is followed by a section examining the strategies that land managers can use in order to adapt to those new conditions. A summary table of those conditions appears on the following page.

Photo by Paul Boers, Zena Forest Products

LIST OF KEY ADAPTATION STRATEGIES

1. **Monitor and observe forest conditions**
   - Know how the conditions of your site are likely to be affected by climate change
   - Know your soils and what their properties imply for moisture retention and tree growth (for example, clay layers are often associated with shallow root systems)
2. **Practice density management**
   - Maintain stands below zone of mortality – thin to lower densities than you might have otherwise
   - Use timber harvest methods that reduce soil disturbance to help reduce drought stress
   - Use thinning and variable retention to create space to facilitate establishment of more drought-tolerant native species and maintain soil functions (root connections, some shade to mitigate higher ground temperatures/moisture loss)
3. **Manage for retaining diverse species and age classes in stands & across ownership and landscapes**
4. **Employ adaptive planting strategies**
   - Plant at lower densities over multiple years, or plant densely but save time and budget for young stand thinning
   - When planning for climate shifts, don't aim too far out, or seedlings may succumb to frost damage
   - Pamper seedlings (e.g. provide protection from browse and mulch where soils are poor)
   - Observe and use microsites; plant trees that need more moisture or shade within these features
   - If planting seedlings from different seed zones, source from hotter and drier zones on harsher sites
   - Create small openings during harvests that provide some shade and plant in these areas
   - Select drought-tolerant native species - including broadleaf species
   - Consider assisted migration of native species from other parts of their range. Use seed zone transfer - NOT species from outside the region
   - For inland Douglas-fir, seed source zone change is far more important than coastal Douglas-fir
   - Bear in mind that moisture determines the species that can grow on a site, while temperature regime determines the best adapted population or seed stock
   - Reframe disturbance as an opportunity to adapt
5. **Control invasive species**
   - Use early detection rapid response methods
   - Be aware of new invasives or others becoming more competitive
   - Report new sightings to state invasive species control boards
6. **Mitigate the fire hazard on the site**
   - Identify the site's fire regime
   - If in a frequent, mixed-severity fire regime, reduce ladder fuels and maintain defensible space
   - If in an infrequent, high-severity fire regime, landscape-level vegetation management is unlikely to affect fire behavior. However, firewise treatments around homes and roadside fuel breaks can make it easier to extinguish fires before they grow beyond controllable dimensions
7. **Hydrological considerations**
   - Invest in maintaining roads and properly sizing culverts; plan future culvert and bridge installations to sustain larger peak flow events more often
   - Maintain riparian buffers to protect ecosystem functions and moderate water temperatures
   - Use harvest systems that sustain or increase streamflows – e.g., gaps that promote snow retention

CLIMATE TRENDS AND PROJECTIONS

The entire Pacific Northwest has already experienced some climatic shifts in the past century. Oregon and Washington have warmed about 2°F since 1900 (Mote et al. 2019). Temperatures have warmed, snowpack has declined, and snowpack begins melting earlier in the spring.

In Oregon and Washington, temperatures have generally been above the long-term average for the last 25 years. The three years from 2016 through 2018 were all warmer than the 1971-2000 average. To date, 2015 stands as Oregon and Washington's warmest year on record, and the precipitation patterns and temperatures experienced that year are expected to be that of an average year in the 2070s, a half-century into the future.

Total annual precipitation in recent years has been fairly close to average, with no long-term trend towards more or less overall precipitation (Mote et al. 2019). However, due to warmer temperatures since the mid-20th century, the Pacific Northwest has shown declines in average snowpack, particularly at elevations below 4,000 feet. In most basins, declines in snowpack and increased rates of snowmelt and runoff have altered streamflows, resulting in reduced summertime flow rates and increases in wintertime flows (Mote et al. 2014).

CLIMATE MODEL PROJECTIONS

The climate projections and scenarios that are informing federal, state, and regional planning efforts are a result of climate change models. Scientists have developed numerous global climate change models over the last few decades to understand future climate trends using various greenhouse gas emissions scenarios (low and high future emissions). To understand regional trends, such as those for the Pacific Northwest, researchers have spatially downscaled the global models so that the broad projections can be described at finer resolutions that are more useful for understanding the resulting changes to local climate patterns, and implications for streamflows, plant growth, fire, and corresponding risks to infrastructure and human health.[1]

While all models have uncertainty due to the simplification of complex processes and assumptions, models can be helpful for understanding trends, and therefore for making decisions about the future. In general, researchers are more certain about the short-term projections (present to 2040) and less certain about the longer-term projections (2040-2100).

A note about the data:

The data shared in this publication are synthesized from numerous studies prepared for the national forests, national parks, and regional planning agencies in Oregon and Washington.

Regional climate and precipitation data in this report come from the Northwest Climate Toolbox and refer to broad geographic ranges — they are not site-specific or relevant to specific microclimates.

The general trends presented here are the best-known information at this time. To access data for a more specific geographic region use the Climate Toolbox, a project of the Applied Climate Science Lab at the University of Idaho.

[1] Further background information on how climate models are developed can be found in Peterson et al 2014: *Climate change effects on vegetation in the Pacific Northwest: a review and synthesis of the scientific literature and simulation model projections.*

TEMPERATURE PROJECTIONS

Compared to the observed historical temperatures from 1971-2000, all climate models project increases in average yearly temperatures in the Pacific Northwest, with warming occurring in all months of the year. Temperatures are expected to increase by 3 to 10°F over the next 80 years (Mote et al. 2014, Littell et al. 2009). Seasonally, winters will have higher low temperatures and summers will have higher high temperatures.

Models suggest the largest increases in temperature will occur in the summer months. Average temperatures may be 10 to 12°F warmer from June through August by the last three decades of this century, with more days warmer than 86°F.

- The Puget Sound region and Southwest Washington may experience 21 to 46 days a year with highs warmer than 86°F compared with 5 to 6 days of those temperatures historically.
- In the Willamette Valley, models predict 40 to 64 days a year that exceed 86°F, compared with 12 to 13 days historically (1990).
- The Central Oregon Coast Range may see 10 to 35 days a year with highs warmer than 86°F, compared with 5 days a year historically.
- Historically the Washington Coast has experienced less than 2 days per year warmer than 86°F, whereas projections suggest 7 to 17 days above 86°F per year by the end of the century.

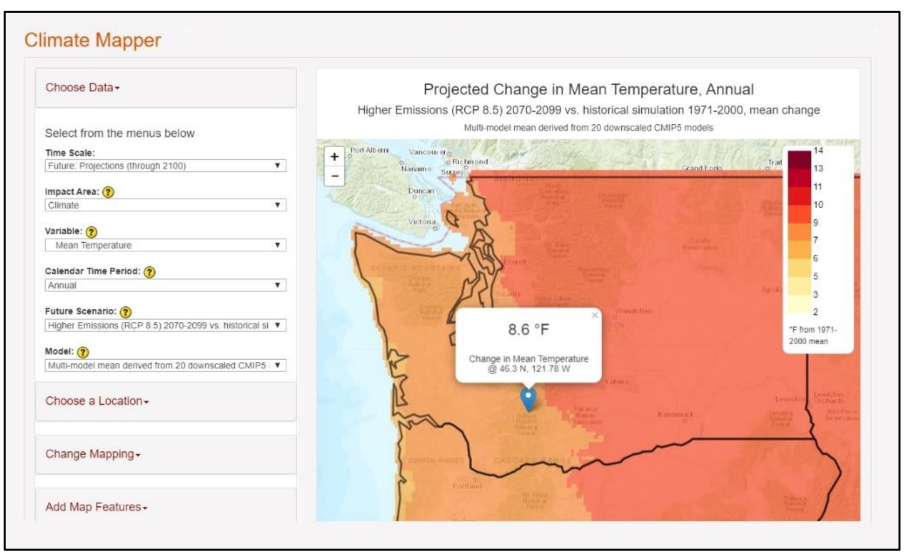
Average winter temperatures may increase 1 to 2°F by 2040 and 3 to 6°F by 2080. Warmer winter temperatures will increase the number of freeze-free days (days warmer than 32°F) across the region from a range of 288 to 328 days historically to upwards of 327 to 350 days by the end of the century. The greatest increase in freeze-free days is likely to occur in the Willamette Valley and Southwest Washington. Changes in the number of freeze-free days will be correlated with a decrease in the number of chilling hours trees experience, resulting in a shift in the timing of budbreak and the start of annual growth for Douglas-fir and several other tree species. Across Oregon and Washington, budbreak in Douglas-fir may shift by 40 to 80 days (Harrington and Gould 2015).

Illustration © Jon Wagner 2019

Average annual temperature projections for regions of Oregon and Washington

Region	Time Frame	**Change in Average Annual Temperature** *Low Emissions to High Emissions*
Puget Sound – Nisqually Region	Baseline: 1971-2000 2010-2039 2040-2069 2070-2099	-- Increase 2.0-2.4°F Increase 3.8-5.1°F Increase 4.8-8.2°F
Southwest Washington	Baseline: 1971-2000 2010-2039 2040-2069 2070-2099	-- Increase 2.0-2.4°F Increase 3.8-5.0°F Increase 4.8-8.1°F
Willamette Basin	Baseline: 1971-2000 2010-2039 2040-2069 2070-2099	-- Increase 1.9-2.3°F Increase 3.7-4.9°F Increase 4.7-8.0°F
Central Oregon Coast Range	Baseline: 1971-2000 2010-2039 2040-2069 2070-2099	-- Increase 1.8-2.1°F Increase 3.4-4.5°F Increase 4.3-7.4°F
Washington Coast	Baseline: 1971-2000 2010-2039 2040-2069 2070-2099	-- Increase 1.8-2.1°F Increase 3.5-4.7°F Increase 4.5-7.7°F

Table 1.These projections were collected from Climate Mapper, available at Climatetoolbox.org. Hegewisch, K.C., Abatzoglou, J.T., Chedwiggen, O., and Nijssen, B., 'Climate Mapper' web tool. NW Climate Toolbox accessed on July 22, 2019.



Climate Mapper Web Tool

A screenshot of the Climate Mapper Web Tool publicly accessible at climatetoolbox.org. Try it for yourself!

Precipitation and Snowpack Projections

Model projections for annual average precipitation in the Northwest are more variable than projections for temperatures, ranging from a decrease of 11 percent to increases of up to 18 percent by the end of the century. Projections generated through the Northwest Climate Toolbox generally suggest slight increases in precipitation across the region.

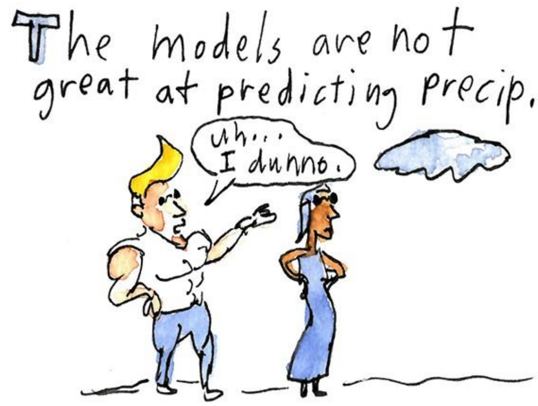
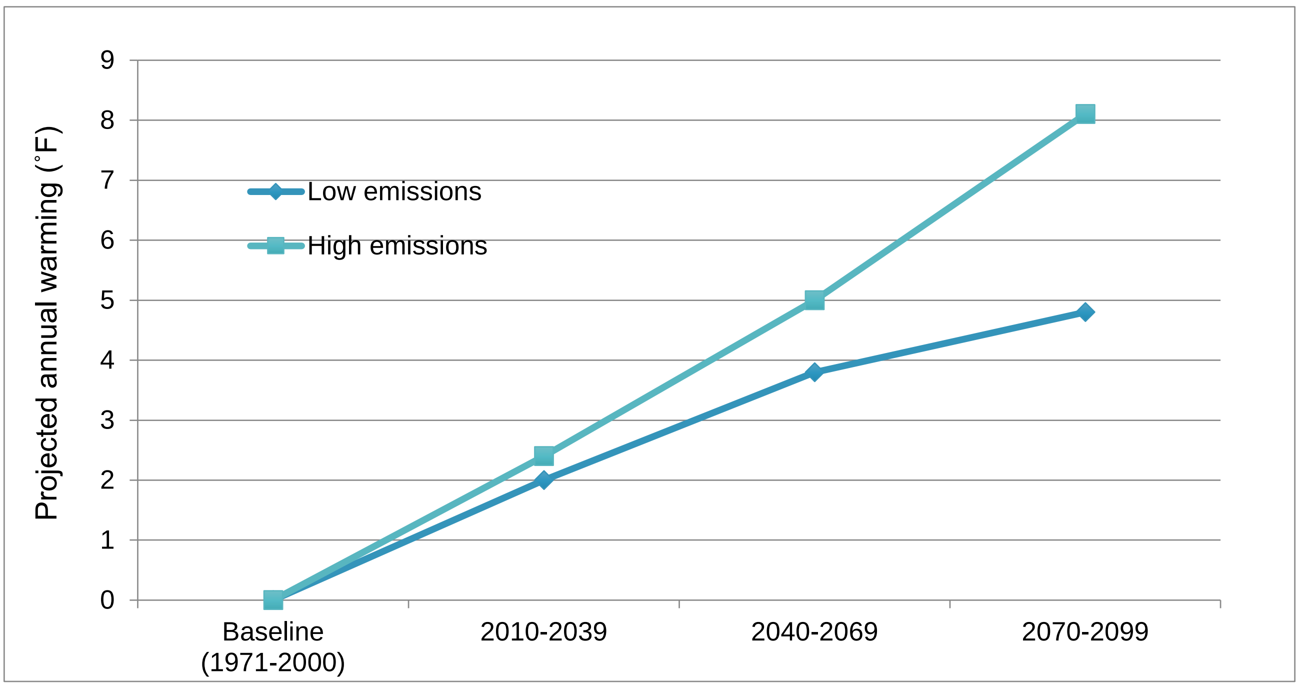


Illustration © Jon Wagner 2019

Timing of precipitation

From the standpoint of forests, however, the timing of precipitation matters more than its total annual quantity, since trees experience their greatest moisture stress during the summer. Under both low and high greenhouse gas emissions scenarios, climate models consistently predict seasonal shifts in precipitation. Climate models project that the Northwest will experience drier, warmer summers and wetter, warmer winters with less snowpack than the historical average.



Not only is the seasonal distribution of rainfall expected to change, but the variation from year to year is also forecast to increase, with climate models projecting wider swings from dry years to wet. Some years would be marked by extreme rainfall events triggered by atmospheric rivers, while others would be distinguished by especially low precipitation, potentially in consecutive years of drought (Kossin et al. 2017, Rupp et al. 2017). Heavy rain events and increases in rainfall in the spring and fall will not be in sync with the warmer, drier summer months when trees most need the water.

Declining snowpack

The Pacific Northwest has experienced declines in average snowpack, particularly in elevations below 4,000 feet. Future shifts in precipitation and overall increasing temperatures will further reduce snowpack, in both volume and coverage (Mote et al. 2014). By the middle of the 21st century, snowmelt is forecast to occur three to four weeks earlier than it did on average during the 1900s. As snow melts earlier in the spring, streamflows will peak earlier but at lower levels than typical flows in recent years, although there will be some variability depending on the geology of the particular stream reach. Consequently, summer flows are likely to be significantly lower than the 20th century average.

Regional Precipitation Changes

The tables in Appendix I include summaries of regional precipitation for the Puget Sound Basin, Southwest Washington (Greater Chehalis and Cowlitz Basins), Willamette Basin, Washington Coast near Quinault, and Central Oregon Coast Range.

Photo by Skeeze via Pixabay

FOREST VULNERABILITIES

All the changes in temperature and precipitation patterns just described will affect the future species distribution, composition, and structure of Pacific Northwest forests. Over time, the ranges of tree species, including western hemlock and western redcedar, are predicted to shift upwards in elevation. Drought-tolerant species will be better able to persist within their current range, while less drought-tolerant species may be limited to microsites of suitability and other refugia at the lower and middle ends of their current range.

The greatest risk to western Oregon and Washington forest ecosystems and individual species is the potential for climate change to exacerbate existing stressors.

The greatest risk to western Oregon and Washington forest ecosystems and individual species is the potential for climate change to exacerbate existing stressors, such as drought, insect and tree disease outbreaks, invasive species competition, wildfires, and habitat loss and fragmentation.

Many of these impacts will be driven by water deficits, as greater frequency and intensity of drought conditions increases tree stress and mortality, tree vulnerability to insects, and fuel flammability (Mote et al. 2014). The primary limiting resource for forest productivity will be available soil moisture during the growing season. Reductions in summer water availability can have negative consequences on stand density, drought-sensitive species, seedling establishment and survival, and potential for invasive species to spread further.

Vulnerability is the degree to which an ecosystem or individual is susceptible to, and unable to cope with, adverse effects of climate change. Vulnerability for Northwest tree species has been evaluated broadly at the ecoregional level. Factors that contribute to forests having less vulnerability to climate change include: diversity in species and genetics, species with wider ecological range tolerances, species adapted to disturbances (e.g. thicker fire-resistant bark, seed cones that benefit from fire), species' juvenile and adult lifespans, and forests found in larger contiguous blocks. Forest communities that are more vulnerable to climate change tend to be low in species and genetic diversity, are comprised of species with limited ecological tolerances, are comprised of species not well-adapted to disturbances (thin bark), are already comprised of rare, threatened, or endangered species, and are highly fragmented.


Photo by Paul Boers, Zena Forest Products

SPECIES SHIFTS

Researchers and forest owners across the Pacific Northwest are increasingly observing tree mortality, much of it thought to be drought-related. The frequency and extent of some drought-related impacts has likely increased due to a combination of recent climatic warming, as well as high stand densities, tree species selection (e.g. planting on marginal sites for a given tree species), and conditions during the stand establishment phase (e.g. excessive brush competition, planting late in the spring prior to summer drought). Anecdotally, forest owners and managers have observed an increase in the die-off of western hemlock, western redcedar on wet sites, loss of entire stands of young Douglas-fir on south-facing slopes with fast-draining soils, and increased mortality rates of planted seedlings in larger harvest units.

In the Puget Trough and Willamette Valley, the most significant anticipated change from current conditions is the transition of western hemlock and Douglas-fir dominated forests to stands that include more drought-tolerant species, including pines (ponderosa, western white, and lodgepole) and broadleaf species such as Oregon white oak, madrone, and bigleaf maple. The vegetation and associated wildlife communities within these forests will shift over the course of decades or centuries to adjust to changes in growing conditions. Maintaining connectivity of intact forests and waterways will help some terrestrial wildlife and plants to shift to more suitable conditions.

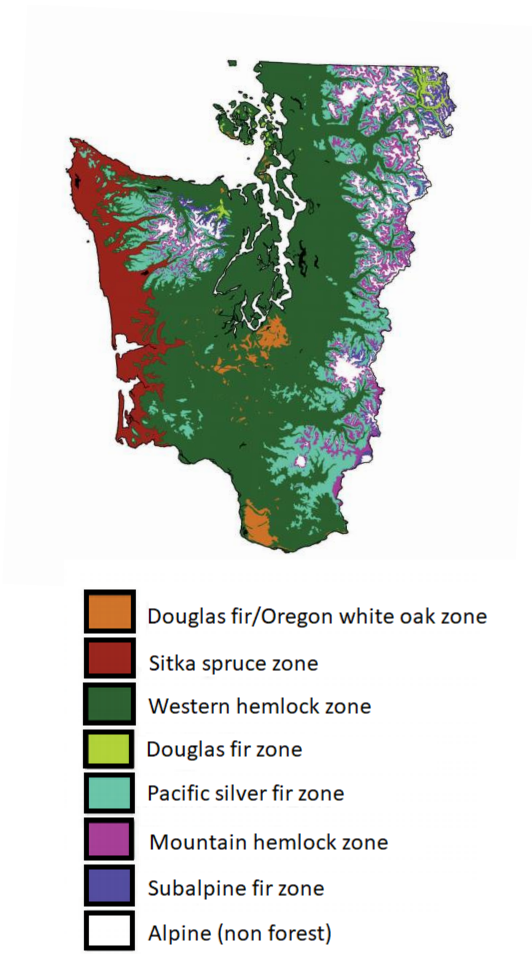
Often land managers and forest owners are working at smaller stand-level and individual-tree scales. Within such stands, some species will exhibit greater vulnerabilities than others to climate-change-induced stressors. For instance, western hemlock is noted regionally as less vulnerable than other species (high-elevation pines and true firs). But in the Puget Lowlands and Willamette Valley, many forest owners and foresters are currently observing significant die-off of young to mature hemlocks. This drought-intolerant species is widely distributed but may no longer do well on low-elevation sites in rain shadows, on droughty glacial outwash soils or shallow clay layers, and in highly stocked stands where there is a high degree of competition for late summer soil moisture. However, given the abundance of hemlock across the region there are still plenty of acceptable sites where they can thrive. For instance, if a low-elevation forested tract has springs, hollows and small depressions, or slopes with northeast aspects, these areas may continue to support hemlocks and serve as important biological refugia.

On a landscape level, foresters divide western Washington and Oregon into several vegetation zones based on the dominant plant species and the associations in which they occur. Shaped by climate, soils, and elevation, these forest zones reflect the main tree species and forest communities that can be expected to thrive in each subregion. The nomenclature for these regions varies somewhat between Washington and Oregon, but the zones exhibit continuity across the Columbia River dividing the two.

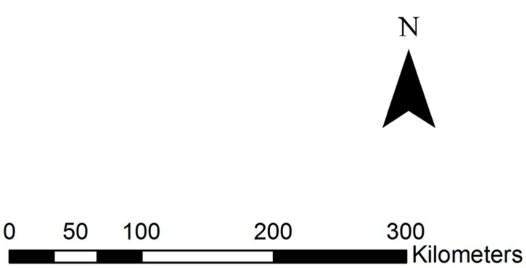
Along the coast, the wettest and most temperate forests are found in the Sitka spruce zone (known in Oregon as spruce-hemlock). Moving inland, at low elevations, this is followed by the western hemlock zone, and then further inland on warmer and drier sites by the Douglas-fir zone — sometimes divided into Douglas-fir and Douglas-fir/Oregon white oak subzones. At higher elevations in the Olympic Mountains and the Cascade Range, the silver fir zone lies above the western hemlock zone. Higher still can be found the mountain hemlock zone and then the subalpine, extending all the way up to tree line.

Mapping these zones is an imprecise exercise; it is based on an appraisal of the site's capacities, rather than the forest which happens to be growing there at the moment. The right-hand accompanying map depicts what ecologists (Reilly and Spies 2015) call the "potential natural vegetation" in western Oregon and Washington — an approximation of the type of plant community that would develop in the absence of disturbance. This map likely overstates the extent of the Douglas-fir zone in western Washington and understates its prevalence on the west side of the Willamette Valley, on the rainshadowed eastern slopes of the Coast Range. In contrast, another map, produced by Washington's Department of Natural Resources, offers a counterpoint, showing a much smaller area in the Douglas-fir and Douglas-fir/Oregon white oak zones (Van Pelt 2007). Because of their biological and timber productivity, the Douglas-fir zone and western hemlock zones deserve particular focus.

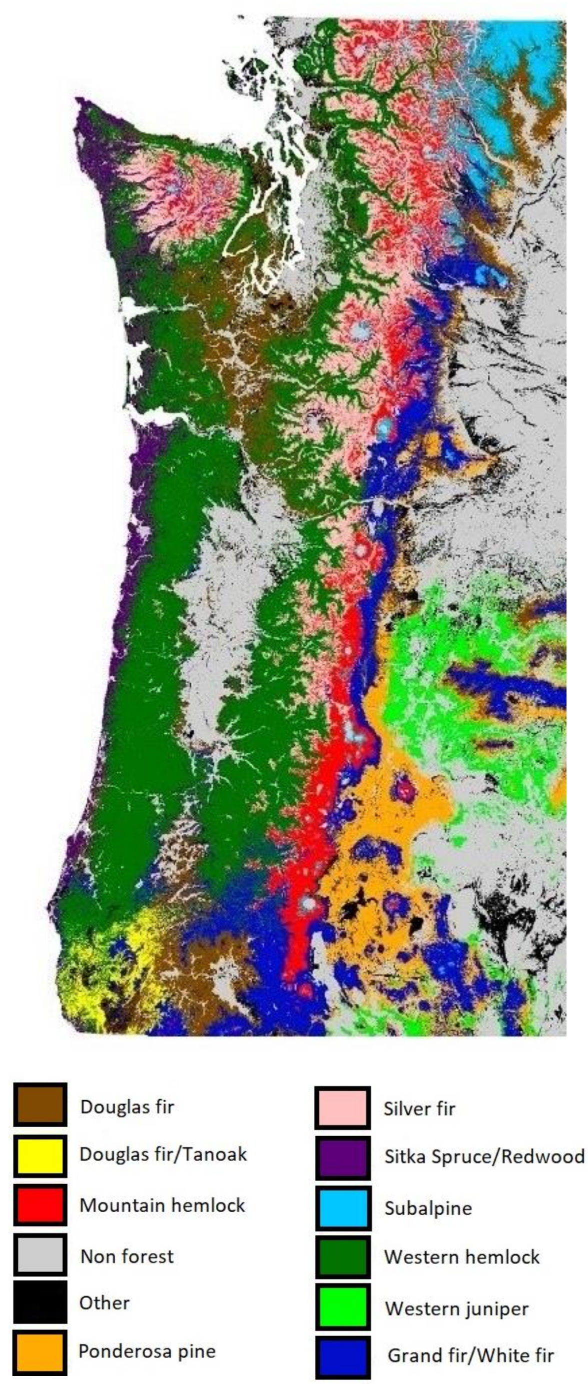
Western Washington & Western Oregon Vegetation Zones



Source: Van Pelt 2007



Two approaches to delineating the forest zones of Washington (left) or Washington and Oregon (right). Note the very different extent of the Douglas-fir zone in the two maps.



Source: Reilly & Spies 2015

PROJECTED CHANGES IN THE DOUGLAS-FIR ZONE

The Douglas-fir zone is an extensive vegetation community in the Puget Trough and Willamette Valley extending from the valley floor to just over 4,000 feet. It includes the rain shadow of the Olympic Mountains and Puget Trough through the Willamette Valley and the Columbia River Gorge. The dominant overstory species is Douglas-fir. Western hemlock, western white pine, lodgepole pine, and western redcedar also occur in association. Oregon white oak, valley ponderosa pine, and madrone occur more frequently on south-facing slopes. Incense cedar extends as far north as the mid-Willamette Valley. Climate models project the Douglas-fir zone to gradually expand in size more than other vegetation zones (Hudec et al. 2019).

Photo by Jarmila via Pixabay

Across the Douglas-fir zone, increased fire disturbance over time may reduce the proportion of area occupied by large-diameter, multi-story structural stage forests. With increased likelihood of fires, there is a greater probability of any single acre burning, and since west side forests have high levels of biomass per acre, there's a greater likelihood of stand replacement. The literature does not predict an uptick in the frequency of “synoptic wind events” in which dry east winds increase fire severity and enable wildfire to spread rapidly across the landscape. However, summertime drought stress means that vegetation will be drier, making it more likely that a synoptic wind event will encounter a small fire and turn it into a major event. Mixed fire conditions and riparian areas like the fires that have burned through the Columbia River Gorge in the last 100+ years suggest there will still be larger diameter trees retained, but even some of the giants succumb to fire.

However, on portions of the current Douglas-fir zone at lower elevations, on south-facing aspects, and on well drained, glacial outwash soils, it is anticipated that some stands will gradually shift to grass, forb (flowering plant) communities that include oak savanna and camas prairies, and potentially ponderosa pine.

At these locations, low soil moisture is common due to thin organic horizons, coarse soils, and temperature fluctuations. South-facing sites with little canopy shade experience higher soil temperatures during summer (Hudec et al. 2019).

Models suggest that the climate will remain suitable for Oregon white oak, and therefore its range may expand to upslope in the western Cascade foothills and eastern flanks of the Coast Range and Willapa Hills (Michalak et al. 2013). Warmer, drier summer conditions leading to increased summer drought may actually benefit the relatively drought-tolerant native prairie and savanna species over the less drought-tolerant tree and other forest species, possibly resulting in prairie/savanna expansion (Bachelet et al. 2011).

PROJECTED CHANGES IN THE WESTERN HEMLOCK ZONE

The western hemlock zone covers a large portion of western Washington, most of the Coast Range, and the western Cascade foothills surrounding the Willamette Valley. It is the primary forest type below 3,000 feet in all major river drainages west of the Cascade Crest. Douglas-fir is typically the primary overstory species in these forests, as it dominates regeneration after fires, while western hemlock is the main understory and midstory species. If fire does not occur for 400 to 500 years, the overstory Douglas-fir can die off, allowing western hemlock to dominate. Expansive wildfires in the early 20th century, followed by extensive timber management and reforestation, have resulted in forests within the western hemlock zone being dominated by various age classes of second-growth and third-growth Douglas-fir (Hudec et al. 2019).

Although the overall area encompassed by the zone is not expected to change much, the distribution of plant species is expected to shift over time (Hudec et al. 2019) as western hemlock may move up in elevation, thereby displacing the current lower extent of the Pacific silver fir zone. In turn, a warmer climate with drier summers could favor a gradual transition of a portion of the western hemlock zone to the Douglas-fir zone. However, the western hemlock zone is expected to remain continuous for genetic mobility and migration (the ability of plant species to move through the zone).

Forests in the western hemlock zone will continue to be dominated by Douglas-fir and other early seral plant associates as temperature and natural disturbance rates increase, preventing the forests from reaching the later seral stages during which western hemlock predominates — a rare occurrence in any case. Shrubs could compete with tree seedlings in areas that experience multiple high-severity fire disturbances, particularly on drier sites where vine maple, giant chinquapin, or snowbrush are present prior to disturbance (Hudec et al. 2019).

CHANGES IN HIGHER-ELEVATION FOREST TYPES

Above the western hemlock zone, predicted changes in climate will have the overall effect of pushing forest types upward, to higher elevations. For example, the lower portions of the silver fir zone are apt to be encroached upon by western hemlock (Hudac et al. 2019), while in turn, its high-elevation edge will expand into the mountain hemlock zone above it.

In general, impacts on higher-elevation forest types will be governed by the balance between three factors: increases in the growing season that favor energy-limited systems where light, temperature, and snow-free days constrain plants' ability to grow; decreases in productivity due to moisture stress as a result of prolonged summer dry spells; and increased pressure from insects, whose life cycles are favored by warmer winters (Hudac et al. 2019).

In addition, warmer, drier summers are apt to increase the chances of fire. In the mountain hemlock zone, higher-severity, infrequent fires can lead to the predominance of lodgepole pine, while lower-intensity, more frequent fires favor the establishment and maintenance of mountain hemlock overstory.

HYDROLOGICAL CHANGES AND STREAMFLOWS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The overall trends of warmer temperatures, decreased precipitation in summer months, increased precipitation in winter months and increased frequency of extreme rain events associated with atmospheric rivers will have an impact on streamflows. In general, hydrological models project streams will experience greater flashiness, higher runoff and more flooding in fall, winter and spring. In the summer, higher temperatures and lower soil moisture will increase evaporation rates, resulting in decreasing streamflows and warmer water temperatures. These changes to streamflows and increase in extreme events are forms of hydrologic intensification that may increase the likelihood for culvert washouts, road damage, erosion and sedimentation as well as impacts to fish habitat.

Winter storm intensity is projected to increase, with rainfall and snowmelt concentrated into shorter time periods, leading the region to experience patterns of higher runoff and more flooding. In the words of an early assessment of the consequences of climate change for the Willamette Valley,

> Greater sediment input, debris flow, and landslide risks are likely, especially in areas with road networks, extensive timber harvesting, and other intense land uses. While periodic floods are necessary for maintaining stream health because they create and maintain deep pools, clean spawning gravels, and recruit large wood to the stream, floods that are too frequent or intense can cause shortages of woody debris, dislodge salmonid redds and egg masses of other species, and further compromise stream structure and function (Climate Leadership Initiative 2009).

Warming will also have an impact on summertime streamflows. Warmer air temperatures in summer will boost evaporation from streams and lakes and reduce soil moisture through evapotranspiration. Thus, even if total annual precipitation remains the same, summer flows will decline, with cascading effects on the aquatic environment. Lower summer flows, and a longer season of low flows, will cause water temperatures to increase, likely leading to blooms of blue-green algae (cyanobacteria) and a decrease in dissolved oxygen.

This degradation of water quality will harm fish and amphibians, as they tend to be more vulnerable to disease at warmer temperatures; in some cases, water temperatures may exceed their range of biophysical tolerance. These impacts are associated with extreme maximum temperatures, and with increases in nighttime thermal minima, which appear to have more impact than a change in mean temperature (Climate Leadership Initiative 2009). Lower flows also decrease the volume of pools, reducing streams' carrying capacity for juvenile salmonids.

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The underground water storage of spring-fed streams and riparian areas may somewhat buffer shifts in flow and temperature. These sources of cooler water will be important refugia for fish and other aquatic organisms and should be buffered to provide continued protection.

Overall, forests are essential to the water quality of the streams that run through them, moderating temperature, controlling sedimentation, and providing inputs of leaf litter and woody debris. To the extent that a warming climate decreases forest cover, it may negatively impact stream nutrient levels, sediment loads, and temperature (Sun and Lockaby 2012). Streamflows are also affected by forest cover and stand ages.

Researchers with the U.S. Environmental Protection Agency worked in the Nisqually River watershed in Washington to use the analytical tool VELMA (Visualizing Ecosystem Land Management Assessments) to model hydrological and biogeochemical processes specifically to predict stream flows as they correspond to stand ages and harvest patterns. VELMA simulates how hydrological, soil and vegetation processes interact across spatial and temporal scales, from plots to watersheds and from days to centuries. The results of a study in the Mashel watershed – a sub-basin of the Nisqually – suggest that older forests have lower rates of transpiration and can maintain higher soil moisture which can substantially increase summer low flows. Younger stands (trees less than 40 years old) have higher transpiration rates, drawing up water from the system at a faster rate and thereby contributing to lower soil moisture and stream flows. By the time a stand reaches 40 years of age, its effect on stream flows is approximately neutral.

VELMA modeling shows a positive streamflow impact from maintaining and managing for older forests and longer harvest intervals (McKane et al. 2018). Consequently, the more frequent disturbance regime that is likely to result from climate change is apt to lead to overall younger stand ages, which can aggravate the summertime low-flow issues facing sensitive aquatic species.

INSECTS

Some insect species will be favored by climate change, but it is not yet known exactly which ones, because many biotic and abiotic factors play into the response of forest insects, their host trees and community associates. Warmer, drier summers and winters with fewer freezes are expected to increase the frequency and extent of insect outbreaks in forests. Summer conditions may exacerbate moisture stress, making more trees more susceptible to insects. Warmer winter temperatures may further assist many insect species, such as pine beetles and spruce budworm, to overwinter and increase overall reproduction that can lead to larger outbreaks.

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Insect outbreaks are typically observed the year of drought and the following year. Insect-caused mortality tends to be species specific, so large outbreaks can significantly alter vegetation structure and forest composition. These outbreaks can open growing space that could be colonized by vegetation and trees in the understory as well as new vegetation (Peterson et al. 2014).

Predicted insect outbreaks could prompt forest managers to take adaptive action on sites where outbreaks are more probable. For instance, if a bark beetle infestation is considered likely in a particular stand, forest managers could prioritize thinning to reduce tree density and planting to increase stand diversity, which will increase overall stand resiliency and reduce the forest's vulnerability to an outbreak of any one insect.

PATHOGENS

A diverse spectrum of pathogens — from fungi, bacteria, and viruses to parasitic plants, nematodes and other microorganisms — can all cause tree diseases, making it hard to generalize about the impact of climate change on forest pathogens. Thus, trends for forest pathogens in a changing climate are difficult to predict (Dukes et al. 2009).

Overall, the environmental factors reviewed above — particularly those related to moisture availability and heat waves — reduce trees' resistance to disease. Since insects serve as vectors promoting the introduction of disease-causing microorganisms, the factors that increase susceptibility to insect outbreaks will also tend to increase tree infection (Raffa et al. 2008).

Specific effects of climate change on tree pathology include:

- Root and canker diseases that are favored by warmer, drier summers, such as *Armillaria* root disease and *Cytospora* canker (Kliejunas 2011). "Decline disease" also falls in this category (Allen et al. 2010) and often stems from the cumulative effect of drought, insects, and pathogens on stressed hosts (Manion 1991).
- Foliar and rust diseases favored by warmer and wetter winters, such as sudden oak death and Phytophthora root rot, are projected to increase (Kliejunas 2011). Swiss needle cast (*Phaeocryptopus gaeumannii*) was historically present at low levels, but in the last 20 years, it has had a significant impact on Douglas-fir plantations in Oregon's coastal fog belt (Kliejunas et al. 2009). Swiss needle cast thrives where winter and spring temperatures are mild, particularly if there is ample moisture (Kliejunas et al. 2009); those conditions are apt to be accentuated in Oregon's changing climate. Although Swiss needle cast usually doesn't kill its host, it can cause serious reductions in growth and productivity where rates of infection are high. (Magurie et al. 2002).

Naturally, because many pathogens are most virulent toward one species or life stage, a diversity of species and age classes will help buffer a forest stand against a potentially catastrophic impact of a single species-specific pathogen (Miller et al. 2007).

FIRE

Historically fire has been a natural, though relatively infrequent, process in western Oregon and Washington forests in the Douglas-fir, western hemlock, and Sitka spruce zones. These forests experience fire every 200 to 400 years and were historically burned by moderate to high severity large fires in the late summer or fall that spread rapidly across hundreds of thousands of acres. Dry east winds, combined with large amounts of biomass, cause these fires to burn hot with flames tall enough to kill most of the trees (Gedalof et al. 2005). After a fire resets these Westside landscapes, a new forest generally develops for centuries without fire. Westside forests are not dependent on frequent fire to maintain them. The Douglas-fir zone and drier parts of the western hemlock zone had more frequent fires (every 50 to 200 years) that typically burned in a less intense, patchier manner, known as a mixed-severity fire regime.

Longer fire seasons, increased human ignitions, and increased fuel loads of dead and dying trees will gradually contribute to increased fire risk in western Oregon and Washington. The Pacific Northwest fire season runs roughly from late July to mid-September, though it can start earlier and end later — as has been observed in recent years. Warmer, drier conditions in the summer may shift the start of the fire season earlier in the year and extend the duration of the season, thus increasing the probability of ignitions and the likelihood that any given wildfire will spread beyond a few acres.

Human ignitions and lightning strikes start fires every year in western Oregon and Washington forests; however, these ignitions rarely intersect with strong east winds and dry fuel conditions. Even though the climate is getting warmer and drier, the probability of fire at any one location is still less than 0.1% per year in western Oregon and Washington (Ager et al. 2013), according to recent Forest Service modeling. With climate change, area burned in west-side Douglas-fir regions is projected to increase about threefold by the 2040s, but will still remain a relatively small portion of landscape (Littell et al. 2010). Without high winds, fires spread slowly, burn fewer acres and kill a smaller portion of the trees. In the lowlands and foothills that have gentle slopes and lots of roads, they are generally easy to put out quickly.

Climate change-induced mortality among drought-intolerant trees combined with increased mortality within overstocked and/or under-managed forests may lead to an increase in the volume of dead wood that serves as fuel during a forest fire. The growth of shrubs and other understory vegetation may increase due to heavier spring rains, creating more biomass that is susceptible to drying out during prolonged summer droughts.

Dry understory vegetation can serve as a "ladder fuel" that carries ground fires up into the forest canopy. Dry understory vegetation is particularly susceptible to fire where it is adjacent to public roads and urban development. The largest increases in the frequency of extreme fire risk in Oregon include the Willamette Valley (Mote et al. 2019).

Although the increase in moderate severity fire is well established, the impact on more intense fires is harder to project. The extensive high-severity fires that lead to stand replacement across hundreds of thousands of acres are linked to synoptic dry east wind conditions, whose frequency is not necessarily expected to increase with climate change. As a result, there is no clear signal from climate models suggesting that the largest, most significant events will become more frequent (Halofsky et al. 2018).

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STORM EVENTS

While data on precipitation patterns is uncertain, warmer oceans and more available moisture in the atmosphere are expected to increase the frequency and intensity of storm events, including heavy precipitation and windstorms. Heavy rainfall associated with atmospheric rivers is anticipated to occur more often (Kossin et al. 2017, Rupp et al. 2017). These storms also bring with them episodes of high wind, which is a primary natural disturbance agent in western Oregon and Washington. Wind can cause significant tree mortality, particularly in late fall and winter, when windstorms occur in conjunction with heavy rains or wet snow, saturated soils, and ice storms. Although most wind disturbances involve individual trees or small groups of trees, large blow-down events also occur periodically (such as the Great Coastal Gale of 2007, the Olympic Blowdown of 1921, and the Columbus Day Storm of 1962).

An indirect effect of storm events that cause blowdown is heightened vulnerability to Douglas-fir beetles (*Dendroctonus pseudotsugae)* outbreak. Historical analysis reveals that landscape-scale factors such as prolonged drought and windstorm events were important predictors of local outbreaks of Douglas-fir beetles that occurred in the western Cascades of Oregon as recently as the early 1990s (Powers et al. 1999). Douglas-fir beetle epidemics occurred more frequently in areas with a greater abundance of mature and old-growth conifer vegetation. Beetle densities were sufficient to overcome the resistance associated with individual tree and stand vigor.

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INVASIVE SPECIES

The disruption of existing ecosystems that can be expected from climate change may also lead to increased pressure from invasive species. In the short to medium term, more severe summer droughts and heat waves can be expected to kill some trees and shrubs that make up various layers of the forest canopy, leaving sites that are only partially occupied by vegetation and creating an opening into which invasive species may intrude.

Many exotic and weedy species are already present in the region and are better colonizers of disturbed sites than native species. Similarly, the bare mineral soil in the pit and mound microtopography created by windthrown trees also provides fertile ground for early colonizer species. With the increase in windstorms described in the previous section, more niches may open up that can be captured by invasives, many of which are early colonizer species. Finally, another possible category of bare ground for invasives to occupy is harvested openings that have been planted unsuccessfully. Warmer, drier summers leave conifer plantations at risk for reforestation failure, particularly if forest managers do not take the changing climate into account in selecting their planting stock. The more time goes by without the establishment of a new generation of conifers, the greater the chance that the site will be taken over by other species, including non-natives such as pampas grass, holly, and English ivy.

As temperature and precipitation patterns change, new invasive species may come into the region, bringing threats that are unfamiliar to forest managers. The warmer climate will also allow existing invasives to expand their range into higher elevations, entering into contention for sites that may have hitherto been safe from those non-native species. This displacement is likely to decrease biodiversity, reduce the resources available to native pollinators, and further reduce the vigor and population of vulnerable native species.

A point that may seem philosophical but will actually require careful discernment is the decision about whether to treat a newly arrived species as an invasive to be controlled or as a climate change refugee to be conserved (a species forced to disperse from another locale due to climate change). Forest stewards will have to discern between the two on a case-by-case basis, relying on such markers as the distance from its original native range, its threat to existing ecological relationships in its new terrain, and the length of time since this species or a similar one was last present on the site.

FOREST ADAPTATION STRATEGIES

Conserving forest landscapes and keeping forests resilient and productive is essential to mitigating the effects of climate change. Most of the management strategies and tactics to help forests adapt to and become resilient to climate change are already commonly used practices and familiar silvicultural techniques. A changing climate just makes active forest management that much more important.

The strategies recommended here fall into several categories. First, forest managers must redouble their efforts to monitor and observe forest conditions. In an epoch of stable climate, it was easier to fit one's casual observations into a preconceived framework of the phenomena one expected to see. But in a period of potentially dramatic change, it is essential to keep the senses finely attuned to what is actually unfolding on the ground, since it might easily confound one's expectations. In addition, careful observation can help avoid attribution error, in which a phenomenon (cedar die-off, for instance) is noted and automatically ascribed to climate change. How many cedars? On what aspect? Restricted to areas of wet soils, or impacting all cedars? Is this rate of die-off out of the ordinary compared to what was observed five, 10, or 20 years before?

Second, the increased stresses of climate change mean that the climatic, topographic, and edaphic (soils) qualities of each site are especially important, particularly for species near the edge of their range. That means understanding the distribution of soil types and depths across the management unit, and matching those sites with the species and seedling provenances that are most likely to succeed there.

Third, as John Muir said, "The first principle of intelligent tinkering is to keep all the pieces." Although climate change is not the result of deliberate tinkering, the same guideline applies: it is crucial to maintain a full complement of "pieces" (e.g., species and age classes) so that forests can emerge which are better adapted to climate change than the forest that developed in the pre-anthropogenic climate.

Finally, consider the direct impacts of climate change, and prepare the existing forest to withstand the impacts of warming to the greatest extent possible. For instance, thinning the forest to spread the available soil moisture among fewer trees; creating small openings at mid-elevations to maximize the amount of ground-level snow accumulation; and installing culverts and other drainage structures that are sized for the larger storm events anticipated in a changed climate.

The following pages explore these strategies in greater detail.

MONITOR THE FOREST & BE READY TO RESPOND

Climate knowledge combined with keen observations will help forest owners and land managers recognize changes they are seeing in the woods and consider options to respond to these changes. Regular forest monitoring can help managers to respond more promptly to trees or other vegetation affected by climate stressors, and to improve resiliency at various stages.

Questions specific to climate adaptation monitoring include:

- Is natural seedling regeneration occurring on expected sites?
- Which species are regenerating on their own? Are these seedlings surviving, or dying after they reach a certain age or size?
- Do some trees appear stressed?
    - What is their species, size, age, soil type, slope, aspect?
- Which trees show signs of good vigor?
    - What is their species, size, age, soil type, slope, and aspect?
- Are trees dying in the forest? If so, what species and where?
- When do the first blossoms emerge in the forest, and when does bud-break occur for each species?
    - How has that changed over time?
- Are invasive species appearing? Where and in what abundance?
- How do culverts and roads fare after large storm events?

It's important to be aware of specific risks for the forest and to be observant of forest conditions and how they are changing. This knowledge can inform decisions about tree species to plant, where to plant them, what stocking density to maintain, and how to plan and prioritize culvert and road work.

TAKE ADVANTAGE OF REFUGIA

The natural features that contribute to high biodiversity, provide habitat for rare species, and support species most susceptible to warmer temperatures and drier growing seasons are important areas to recognize and protect. These special features and sites are referred to as *climate change refugia* and often result from some sort of spatial variability in topography that decouples climatic processes at a smaller scale from broader, regional conditions. Examples include northeast-facing slopes, wetlands, riparian zones, talus slopes, and topographic features that facilitate cold-air pooling, where concentrated cold, dense air flows downslope into valleys or basins.

These climate change refugia are “areas that remain relatively buffered from contemporary climate change over time and enable persistence of valued physical, ecological, and sociocultural resources,” according to a definition from the Refugia Research Coalition, a collaborative program of the Northwest and Northeast Climate Adaptation Science Centers. A key element of these refugia is their relative persistence, despite changes in the climate of the surrounding landscape (Morelli et al. 2016). These sites often play an important role in protecting water quality and quantity and supporting other ecosystem functions. Refugia, be they microsites or larger features, contribute to and sustain biodiversity over long periods of time (e.g. the Alaska yellow-cedar (*Cupressus nootkatensis*) population in the northeastern slopes of the Aldrich Mountains of eastern Oregon).

The Nature Conservancy conducted a geospatial analysis to identify resilient terrestrial landscapes in the Pacific Northwest with the goal of assessing and mapping regional sites that are most likely to constitute climate change refugia. The report and resources are available to download here: Climate Change Resilience in the Pacific Northwest

Microsites are important for individual landowners to consider when planning and executing management activities. For example, while planting post-harvest or during a restoration project, managers can favor western hemlock in the damper depressions or on the north sides of rocks, stumps, large woody debris, or shrub features.


Photos via Pixabay

MANAGE FOR LOWER STAND DENSITY

Managing to reduce stand density — typically by thinning — is one of the most useful tools for forest managers to use in adapting to a warmer climate. In managed stands, denser forests are more prone to drought stress due to competition between individual trees for available soil moisture. Thinning forests reduces competition for water and nutrients, and thus the remaining trees have more resources to withstand drought, insects, and root rot. Thinning can also benefit wildlife habitat by increasing the diversity and abundance of other plants, and may prevent broad-scale vegetation die-back. The stresses that can be relieved by thinning are well matched to those that will be exacerbated by warming trends in the climate.

> *"Density management to avoid excessive inter-tree competition may be one of the most useful means for increasing tree and stand vigor, and therefore forest resistance and resilience to climate-related stresses."*
>
> *Anderson & Palick 2011*

Managers would do well to thin dense stands and maintain them at moderate densities to sustain tree vigor and reduce soil moisture composition. When underplanting an existing stand, plant at a wider spacing to avoid competition. If natural tree regeneration becomes dense, proactively thin to reduce competition. By using variable density thinning techniques, managers can increase stocking heterogeneity, and avoid placing all of their chips on a single estimate of optimal density.

In the past, stewards of the region's Douglas-fir forests have been guided by clearly delineated relationships between stand density, growth, and site quality. Thinning guidelines commonly recommend reducing density to 35% of maximum density or 35 relative density (RD) (Curtis 1982). Basal area or trees per acre targets for thinning are derived from this 35 RD target. A warming climate will likely shift the effective carrying capacity or maximum stand density index of most forests in the region. Thus, thinning to a lower relative density will provide a greater buffer against drier conditions (Anderson and Palick 2011). There are currently no specific projections for changes in maximum stand density across

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the region. At this time, thinning to 20-30 RD of current maximum stand density is recommended. Specific targets can be derived for stands with different average tree sizes.

Mean Diameter (inches)	Post-thinning density at RD=35, in trees/acre	Post-thinning density at RD=25, in trees/acre	Post-thinning density at RD=20, in trees/acre
6	461	329	263
8	290	207	166
10	203	145	116
12	151	108	87
14	118	84	68
16	95	68	55
18	79	56	45
20	67	48	38

Table 2. A revised thinning schedule for westside Douglas-fir, to accommodate a shift from a light-limited system to a moisture-limited regime. The relative density (RD) is the percentage of the maximum stand density index, considered to be approximately 580 for Douglas-fir in western Washington.

The stands of highest priority for thinning are young, dense stands, which currently lack resilience to fire and drought, and which are common on private property being intensively managed for timber. Thinning projects can also include the creation of small gaps, which can then be planted to diversify the age classes in the stand. While thinning, it is important to safeguard soil productivity through careful harvest practices, such as distributing logging slash throughout the harvest unit, retaining large non-merchantable log sections, and minimizing compaction by heavy equipment.

RETAIN DIVERSE SPECIES AND AGE CLASSES IN STANDS

Strategies to increase resiliency include creating multi-aged stands and favoring more drought- and fire-tolerant trees in existing stands. Given that droughty summer conditions can impact some species and age-classes more severely than others, maintaining a diverse array of ages and tree species in the forest is a way for forest managers to hedge their bets against the climatic extremes that will characterize the region's changing climate (Anderson and Palick 2011). One thing that is certain is that forests' response to climate change will surprise us.

Older trees and stands are thought to have a greater chance of enduring the rigors of the climate of the future. Among other factors, bigger trees have thicker bark, which makes them more fire-resistant, making it more likely that they would survive wildfire, particularly of low to moderate intensity — a key advantage in a warmed climate, where wildfires are expected to be more frequent. However, large and old trees can have a harder time adjusting their foliage and root systems to drier conditions. Thus in some cases, younger trees survive droughts while the larger trees die off.

As forests age, they also become more complex, making them less vulnerable to high mortality in a natural disturbance event. For instance, trees of a certain age may be particularly vulnerable to an insect infestation, so having a mixture of ages and sizes of trees is likely to promote the health of the stand and its resilience to disturbance due to diversity of age class.

ADJUST PLANTING STRATEGIES

TAILOR PLANTING SITES TO SOIL TYPES

Knowing the soils and hydrologic conditions of a forest stand is important for understanding the most suitable sites for less drought-tolerant species such as western hemlock, Sitka spruce, black cottonwood, and red alder. These species should not be outright removed from the planting palette. Instead, in areas seeing impacts from changing conditions, they should be conserved or planted in local microsites (e.g. wet depressions, riparian areas, or north-facing side of a legacy old-growth stump) that best support their ecological preferences. Knowing the site's soil type and its soil moisture capacity will help indicate if this adjusted planting strategy is necessary, and if so, which species to plant.

Northwest Natural Resource Group

BROADLEAF TREES

Species	Shade tolerance	Drought tolerance	Soil moisture tolerance	Seedling establishment	Average max age	Vulnerable locations
Bigleaf maple *Acer macrophyllum*	Medium	Low to medium	Moderately tolerant of dry soils	Seedling mortality may result from competition, moisture stress, low light, and herbivory.	250	Dry, southern regions & eastern slopes of the Cascades. High elevations
Red alder *Alnus rubra*	Low	Low	Intolerant of dry soils	Seedlings tolerate shade for several years; full sunlight required for normal development. Seedlings are very sensitive to drought.	100	High-elevation sites with dry, south-facing slopes
Black cottonwood *Populus balsamifer ssp. Trichocarpa*	Low	Low	Intolerant of dry soils	Seedlings intolerant of drought. Intolerant of dry soils for first month after germination.	200	Dry, south-facing slopes
Oregon white oak (Garry oak) *Quercus garryana*	Low to Medium	High	Very tolerant of dry soils	Seedlings form a vigorous taproot after germination, which enables survival on dry sites and where vegetative competition is severe.	500	Fire-suppressed areas with encroaching conifers
Oregon ash *Fraxinus latifolia*	Low to Medium	Low	Intolerant of dry soils	Seedlings tolerant of drought and moderately shade -tolerant. Seedlings prefer rich soils.	250	Historically moist regions increasingly susceptible to periods of drought
Pacific madrone *Arbutus menziesii*	Low to Medium	High	Tolerant of dry soils	Seedlings tolerant of shade, preferring well-draining mineral soils and mild winter temperatures.	250	Dry sites in southern and central Oregon

Table 3. Traits, site preferences, and vulnerabilities of common Pacific Northwest broadleaf trees. Sources: Oregon Forest Resources Institute, Trees of Oregon's Forests; Oregon State University Extension Service, Selecting and Buying Quality Tree Seedlings, Trees to Know in Oregon; USDA Forest Service, Fire Effects Information System Species Reviews; Oregon Historical Society, The Oregon Encyclopedia; USDA Forest Service, Climate Change and Forest Biodiversity: A Vulnerability Assessment and Action Plan for National Forests in Western Washington; USDA Natural Resources Conservation Service, PLANTS Database; The ForeCASTS Project, Forecasts of Climate-Associated Shifts in Tree Species.

CONIFERS

Species	Shade tolerance	Drought tolerance	Soil moisture tolerance	Seedling establishment	Average max age	Vulnerable locations
Douglas-fir *Pseudotsuga menziesii*	Medium	High	Tolerant of very dry soils	Grows on a wide range of sites, at all slopes and aspects. Seedlings prefer bare mineral soil and moist soils.	500+	Lower elevations of the Willamette Valley. Dry, south-facing slopes in southern Oregon.
Grand fir *Abies grandis*	Medium	Medium	Tolerant of relatively dry soils	Seedlings vulnerable to summer droughts. On exposed or dry sites seedlings form deep taproots.	250-300	Dry, high elevation sites outside of the Cascades.
Lodgepole (Shore) pine *Pinus contorta var. latifolia*	Low	High	Tolerant of very dry to very wet soils	Seedlings are vulnerable to drought and dry soils.	150-200	Lower elevations
Ponderosa pine *Pinus ponderosa*	Low	High	Moderately tolerant of very dry soils	Seedlings are vulnerable to moisture stress and competing vegetation. Highly vulnerable to frost damage.	300-600	This species' range is projected to expand in a warming climate.
Sitka spruce *Picea sitchensis*	High	Low	Intolerant of dry soils.	Seedlings establish best in open areas with well-draining soil.	200-250	Dry, exposed, inland sites.
Western hemlock *Tsuga heterophylla*	High	Low	Intolerant of dry soils	Seedlings are very shade tolerant. And prefer moderate soil moisture.	400-500	South-facing, exposed slopes
Western redcedar *Thuja plicata*	High	Medium	Moderately tolerant of dry soils	Seedlings in exposed areas are less tolerant of high soil temperatures, drought, and frost.	500+	Dry, exposed slopes
Western white pine *Pinus monticola*	Medium	Medium	Moderately tolerant of dry soils	On harsh sites, partial shade increases seedling establishment. Once established, growth is best in full sunlight.	200-250	Exposed, south-facing slopes with fast-draining soils.

Table 4. Traits, site preferences, and vulnerabilities of common Pacific Northwest conifers. Sources: Oregon Forest Resources Institute, Trees of Oregon's Forests; Oregon State University Extension Service, Selecting and Buying Quality Tree Seedlings, Trees to Know in Oregon; USDA Forest Service, Fire Effects Information System Species Reviews; Oregon Historical Society, The Oregon Encyclopedia; USDA Forest Service, Climate Change and Forest Biodiversity: A Vulnerability Assessment and Action Plan for National Forests in Western Washington; USDA Natural Resources Conservation Service, PLANTS Database; The ForeCASTS Project, Forecasts of Climate-Associated Shifts in Tree Species.

SELECT DROUGHT-TOLERANT NATIVE SPECIES

The plants in forest ecosystems have a tremendous capacity to adapt to changing conditions in their local environment. Over time, plant populations can adapt to changing climate by altering their genetic makeup through reproduction and natural selection, improving their ability to grow and persist at a particular location (Peterson et al. 2014). In the shorter term, individual plants can respond to persistent changes in their environment through phenotypic plasticity (the ability to alter their physical structure).

Understanding a species' ecological suitability for future climatic conditions is a key consideration when selecting trees to plant for climate adaptation. Higher temperatures and generally lower soil moisture conditions combined with such factors as pathogens, insects, invasive species, and disturbances will have an impact on tree species vulnerability. A greater diversity of tree species representing a range of environmental adaptations will decrease the likelihood of widespread loss of productive forest ecosystems.

In general, managing forests to include a mix of conifer and broadleaf species will increase resilience to climate-change-induced stressors such as drought, wind, insects and fire. A critical climate adaptation strategy is to include a significant component (upwards of 20 percent) of suitable broadleaf trees species (e.g. bigleaf maple, madrone, Oregon white oak, Oregon ash, red alder, willow species, black cottonwood). Broadleaf species tend to have a higher moisture content in their wood and less resinous content, making them less prone to fire.

Planting drought-tolerant tree species is an important component of this strategy. Douglas fir, western white pine, lodgepole pine, Pacific madrone, and bigleaf maple are some of the more drought-tolerant species. On the driest of sites, Oregon white oak and ponderosa pine are appropriate, and in the southern half of the Willamette Valley incense cedar is also appropriate. These trees would be more apt to survive the predicted summer water deficits in a warmer climate. At this point in time, replacing native species with non-native species is not recommended, although (as described below), selecting seed stock of a native species from a drier seed zone may be helpful. Familiarity with the traits of an individual site is critically important when deciding what to plant. These strategies can be applied not only in clearcuts or burn restoration sites, but also where smaller gaps are created in the aftermath of windthrow or the harvest of root rot pockets.

In summary, to improve tree survival:

- Protect existing trees that exhibit adaptation to water stress or growing well within a dry microsite
- Plant drought-tolerant native species
- Plant genetically-adapted species from appropriate seed zones
- Plant a diversity of tree species, including both broadleaf species and conifers

NURTURE NEW SEEDLINGS

Seedling establishment is the most stressful life stage for trees due to the young trees' limited root systems. Their capacity to collect moisture is especially prone to be overtaxed in the face of summer droughts during the first year of growth, high ground temperatures in clearcuts or large gaps, and competition from surrounding vegetation.

In order to help seedlings cope with these challenges, managers would do well to plant robust seedlings, such as "1-1" planting stock which has spent a year in the seedbed and a year in a transplant bed, that are capable of tolerating difficult growing conditions. Planting in the late fall or early spring helps seedlings by giving them a chance to root before the high evapotranspiration of late spring and summer arrives. Retaining debris on the forest floor helps by providing a mulching effect that conserves soil moisture. Finally, reducing competition for moisture from understory species such as shrubs and grasses, be they invasive or native, is crucial to giving the seedlings a chance to become established.

Tips for seedling establishment

- Use 1-1 planting stock with well-developed root systems
- Plant in late fall or early spring
- Use stock grown to have active root tips
- Retain debris on the forest floor
- Minimize soil disturbance to reduce germination of invasive species
- Reduce competition for soil moisture during the first summers from surrounding vegetation (e.g. shrubs, groundcovers, grasses)

SELECT SEED STOCK FOR FUTURE CLIMATES

Assisted migration can refer either to the translocation of species from other areas, or simply the propagation of a locally native species using seed stock from other regions, whose historic climate is believed to mirror the future climate conditions of the receiving site. This section refers only to the second (within-species) form of assisted migration.

The practice of assisted migration is based on the theory that populations of native tree species are adapted to local climates within their range, and moving seed sources from warmer to cooler climates is one option for adapting forests to a future climate. This approach is supported by common garden experiments in which seed sources from different populations are planted at several sites with different climates and evaluated for survival and performance.

Some species, such as Douglas-fir, have a wide diversity of genetic traits even within each local population. Thus, on-site trees may provide the right genes in some fraction of their seeds to thrive in a warming climate. By encouraging natural regeneration, the seeds manifesting that hardier constitution will have a chance to occupy the site over time.

Selecting seed source locations requires specific information about the current and projected future climate of the site to be planted. While seedlings from a different climate may struggle early on, they may be better adapted to future climates and may contribute genetic material to help future stands be more resistant. Matching the prospective climate of 2100 may require planting seedlings grown from seed collected 1500 to 2000 feet lower in elevation, or 1.8 to 2.5 degrees further south in latitude, or some combination of the two (Anderson and Palick 2011).

Including seed stock from drier or warmer regions alongside seedlings grown from local seed may be especially beneficial on droughty soils, on steep southwest exposures, or if there have been past problems with seedling establishment. Time scale is important, too. For forests intended to be raised for a short industrial rotation (35 to 50 years), climate change may be slow enough that seed stock shifting is unnecessary or only small shifts in zones are needed. For stands planted for extended rotations or to grow old growth, it will be more necessary and bigger shifts will be needed.

Different species show different levels of local adaptation to climate, however. “Whereas Douglas-fir demonstrates a relatively high degree of localized population adaptation, other widely distributed species such as western white pine are broadly adapted and show little localized adaptive population structuring,” according to Anderson and Palick (2011). Western redcedar, like western white pine, shows little genetic diversity between regional populations.

FIND THE RIGHT SEED STOCK: SEEDLOT SELECTION TOOL

The Seedlot Selection Tool (SST) is a web-based mapping application designed to help natural resource managers and forest owners match seedlots (where seedlings are grown) with planting sites based on climatic information. It can be used to find seed sources for a planting site or to find planting sites for a specific seed source, under both current and future climates: https://seedlotselectiontool.org/sst/

Users specify the species, a climate warming scenario, a time frame for which to optimize, and a measure of climatic stress such as mean highest temperature, and the model will suggest the regions from which seed should be collected in order to best match the future climate.

The impact of these seedlot migration strategies will likely reveal itself only over a period of decades, making it particularly important to keep good records of what seed stock was used and the location of local and imported seed stock on the site, so as to facilitate future learning about the success of this strategy.

Photo by NNRG

CONTROL INVASIVE SPECIES

Invasive species will likely become increasingly competitive with native species as warmer temperatures and changes in precipitation patterns cause drought stress and increased mortality of native trees and shrubs. Many invasive species are annuals and thus able to more rapidly adapt to changing conditions. Implementing an early detection monitoring program followed by rapid response management can reduce the spread of non-natives and competition stress. See the box for specific management suggestions, none of which are specific to climate adaptation, but instead are reflections of good forest stewardship.

Monitor and control invasive species:

- Learn which invasive species are present in your area and practice early detection and rapid response eradication
- Regularly monitor the forest to detect new species and populations
- Remove and destroy invasive plants found on your property. Make sure to dispose of plants appropriately so that seeds are not dispersed in the process.
- Maintain closed forest canopies that provide sufficient shade to suppress shade-intolerant invasive plants (e.g. scotch broom, Himalayan blackberry).
- Prevent non-native plant introductions during harvest projects, road, and culvert work that bring in heavy equipment.
- Plan to do additional monitoring of disturbed ground after harvest activities.
- Plan to do additional control on invasive species in the first few years after harvest activities.

REDUCE FIRE RISK

Wildfires in western Oregon and Washington are characterized primarily as stand-replacing disturbance events. Large-scale thinning and prescribed fire treatments aimed at reducing the likelihood or size of large fires are not effective and do not fit the ecology of westside forests. Wind-driven fires often burn right through such treatments. In drier forest types where the spread and severity of fire is limited by fuel availability, wildfire intensity can be mitigated by fuel treatments. But that's impractical in most westside forests, where fuel is abundant and would regrow quickly following treatment (Halofsky et al. 2018). Thinning has other ecological benefits in western Oregon and Washington forests, but fire risk reduction is not one of them. "Large fires are like earthquakes in that they are rare, can cause great damage, and cannot be stopped through human actions," writes forest ecologist Derek Churchill (Churchill 2019).

Land managers and forest owners can reduce the impacts of some forest fires, however. Disaster planning can better prepare property owners and residents to respond to these events and reduce losses. Property and homeowners can research and adopt Firewise principles such as building with fire-resistant materials, removing flammable vegetation close to the home (creating "defensible space"), maintaining road access and turnarounds, as well as incorporating other design features that significantly reduce the risk of losing homes to wildfire. These practices are especially effective when wind speeds are relatively low, which leads to slower rates of spread and lower flame heights.

SUPPORT FOREST HYDROLOGY

FOREST ROADS & DRAINAGE SYSTEMS

Climate change is projected to result in larger storms that increase landslide risks and contribute to higher peak flows. For many Pacific Northwest rivers and streams, this means increased flooding following heavy downpours, prolonged rains, and rapid melting of snowpack that can cause increased road damage at stream crossings and compromise safety during extreme events. Damage to culverts and road networks can be a significant cost and pose significant safety risks. Under these conditions, current Best Management Practices (BMPs) may prove insufficient for safe design of roads, bridges, and culverts.

These predicted increases in peak flows will lead to increases in stream width, which is a key input in the design of stream crossings such as culverts and bridges. Designing for climate change therefore means installing larger culverts to reduce the risk of culvert failure and damage to anadromous fish habitat.

Most culverts are designed to last 50 to 100 years. When they come due for replacement — either because of damage or deterioration — land managers should take the opportunity to consider future stream width in project planning. Modifications of current management practices to address greater precipitation variability might include wider riparian buffers, larger culverts at road crossings, and more efficient and stable road design.

The University of Washington Climate Impacts Group and Washington State Department of Fish and Wildlife developed a model to understand the probability of culvert failures based on projected changes to the seasonality and intensity of precipitation and other hydrologic factors. The report, Climate Robust Culvert Design (Mauger et al 2018), and corresponding tool are intended to help engineers and land managers evaluate the implications of climate change for culvert design. The Culvert Design tool can be found here: https://cig.uw.edu/our-work/decision-support/culvert-phase-2/.

Increase resilience of forest roads and drainage systems:

- Conduct annual maintenance on ditches, cross drains, water bars and other drainage systems to ensure storm water efficiently moves off the forest road and onto the forest floor
- Create an inventory of all culverts and stream crossings to aid in monitoring and future replacement decisions
- Replace culverts with higher capacity culverts or other appropriate drainage in high-risk locations.
- Decommission high-risk roads and road systems

MAINTAIN FORESTED RIPARIAN BUFFERS

In the face of a warming climate, aquatic and riparian ecosystems will gain crucial benefits from the microclimatic buffering provided by forested riparian corridors. Climate models suggest that Pacific Northwest streams will experience extreme water flow conditions more often. In the fall, winter, and spring, more precipitation and storm events will result in greater runoff, more flooding, and higher peak flows. In the summer, higher temperatures and lower soil moisture will increase evaporation rates, thereby decreasing streamflows and increasing water temperatures.

Maintaining and enhancing forested riparian buffers is a critical strategy for moderating the effects of drought by shading streams and keeping water temperatures low. Riparian buffers also help moderate flooding by reducing sedimentation during larger storm events. Large trees and large woody debris in streams help to slow the flow of water and creates stream channel features used by fish. Riparian buffers also provide food, cover, and connectivity for terrestrial and aquatic organisms, and moderate near-stream temperatures for sensitive amphibians. All of these functions will gain heightened importance in the face of the stressors created by climate change.

As a result, forest managers would be well advised to manage riparian buffers to retain ample stream shading and contribute large woody debris to streams; to protect springs, seeps, and other perennial sources of cold water; to encourage beaver populations, where feasible, to help with water storage and filtration; and to retain a diverse mixture of tree and understory species to ensure that these riparian forest corridors continue thrive as the climate shifts.

ACCUMULATING AND CONSERVING AVAILABLE SNOW

At the middle elevations (2000 to 4000 feet), a continuous forest canopy is actually not the optimal configuration to capture incident snowfall and store it for slow release in the spring and summer, when snowmelt is an important contributor to both soil moisture and streamflow. Snow that accumulates on tree crowns is exposed to sun and wind, leading to more rapid melting or evaporation than if it were to fall on open ground. Research in the Pacific Northwest has shown that snow accumulates in the open to twice or three times the depth, and lasts 2 to 4 weeks longer, than it does under forest cover (Dickerson-Lange et al. 2017). While adaptive forest management would not suggest removing the forest cover entirely, research is underway to determine the optimal size of gaps that promote snow accumulation and storage. At the right size for the aspect and elevation, the gap would be large enough to allow snow to accumulate on the ground, while also providing protection from wind and direct sunlight to delay evaporation and melting.

CONCLUSION

The Pacific Northwest's climate is already beginning to change as a result of anthropogenic global warming. It would behoove forest managers — as stewards of long-lived ecosystems — to prepare for the altered circumstances that the region's forests will face as they grow through the 21st century and beyond.

This white paper represents a 2020-vintage understanding of how climate change will affect the region's forests, and how forest managers can best respond to put their forests on the most resilient footing possible. As greenhouse gases accumulate in the atmosphere, climate will remain a moving target, making monitoring of the state of the forest and communication among forest managers even more valuable than before. Through ongoing information-sharing, forest stewards can continue to adapt our management practices to best suit the emerging climate parameters that shape what is possible in this green corner of the world.

Illustration © Jon Wagner 2019

RESOURCES FOR FORESTRY PROFESSIONALS

The following are helpful sources of information for addressing the effects of climate change on Pacific Northwest forests:

- **Adaptation Partners** – http://adaptationpartners.org/ – Researchers and resource managers provide scientific information on climate change effects and adaptation for specific regions in the Northwest and Intermountain West.
- **Adaptation Workbook**– https://adaptationworkbook.org/
- **AdaptWest** – https://adaptwest.databasin.org/ – AdaptWest is a spatial database designed to help land management agencies and other organizations implement strategies that promote resilience, protect biodiversity, and conserve and enhance the adaptation potential of natural systems in the face of a changing climate.
- **Climate Change Resource Center (CCRC)** – https://www.fs.usda.gov/ccrc/ – US Forest Service collection of resources and tools.
- **Climate Impact Groups at UW (CIG)** – https://cig.uw.edu/ – Leading researchers and providers of primary science and decision making tools.
- **Climate Impact Research Consortium at OSU (CIRC)** – https://pnwcirc.org/ – A climate science-to-action team providing research, decision making tools for communities, and developer of analytic tools resource managers and land use planners.
- **Conservation Gateway from The Nature Conservancy** – https://www.conservationgateway.org/conservationbygeography/northamerica/unitedstates/oregon/science/pages/resilient-landscapes.aspx – A report to assess and map sites of climate change refugia.
- **NW Climate Hub** – https://www.climatehubs.oce.usda.gov/hubs/northwest – USDA portal for science-based Northwest-specific information and technologies to assist with climate-informed decision making.
- **NW Climate Toolbox** – https://climatetoolbox.org/ – Suite of online tools to put a variety of climate data and information in reach of organizations and people for site specific locations, including: historical climate variability, temperature and precipitation normal, streamflow projections, climate projections, and data for Tribal Lands.
- **Seedlot Selection Tool** – https://seedlotselectiontool.org/sst/ – Web-based mapping application that can be used to map current or future climates based on different climate change scenarios to inform the selection of seedlings for tree planting as part of reforestation and restoration efforts.
- **U.S. Climate Resilience Toolkit** – https://toolkit.climate.gov/ – Portal for general information about change for many audiences.

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APPENDIX: PROJECTED PRECIPITATION CHANGES

Puget Sound - Nisqually Region

Time frame	**Annual precipitation**	**Precipitation in winter (October-March)**	**Precipitation in summer (April-September)**
Historical baseline: 1971-2000	42.7 inches	32.0 inches	10.7 inches
2010-2039	*Low emissions:* 43.6 inches 0.9 inch increase *High emissions:* 43.1 inches 0.4 inch increase	*Low emissions:* 33.0 inches 1.0 inch increase *High emissions:* 32.7 inches 0.7 inch increase	*Low emissions:* 10.6 inches 0.1 inch decrease *High emissions:* 10.3 inches 0.4 inch decrease
2040-2069	*Low emissions:* 44.2 inches 1.5 inch increase *High emissions:* 44.4 inches 1.7 inch increase	*Low emissions:* 34.0 inches 2.0 inch increase *High emissions:* 34.0 inches 2.0 inch increase	*Low emissions:* 10.3 inches 0.4 inch decrease *High emissions:* 10.3 inches 0.4 inch decrease
2070-2099	*Low emissions:* 44.6 inches 1.9 inch increase *High emissions:* 45.7 inches 3.0 inch increase	*Low emissions:* 34.5 inches 2.5 inch increase *High emissions:* 35.7 inches 3.7 inch increase	*Low emissions:* 10.1 inches 0.6 inch decrease *High emissions:* 10.0 inches 0.8 inch decrease

Southwest Washington

Time frame	Annual precipitation	Precipitation in winter (October-March)	Precipitation in summer (April-September)
Historical baseline: 1971-2000	80.0 inches	60.9 inches	19.1 inches
2010-2039	*Low emissions:* 81.4 inches 1.4 inch increase *High emissions:* 80.3 inches 0.2 inch increase	*Low emissions:* 62.6 inches 1.6 inch increase *High emissions:* 61.9 inches 0.9 inch increase	*Low emissions:* 18.8 inches 0.3 inch decrease *High emissions:* 18.4 inches 0.7 inch decrease
2040-2069	*Low emissions:* 81.9 inches 1.9 inch increase *High emissions:* 82.3 inches 2.3 inch increase	*Low emissions:* 63.8 inches 2.9 inch increase *High emissions:* 63.9 inches 3.0 inch increase	*Low emissions:* 18.2 inches 0.9 inch decrease *High emissions:* 18.3 inches 0.8 inch decrease
2070-2099	*Low emissions:* 82.4 inches 2.4 inch increase *High emissions:* 84.4 inches 4.4 inch increase	*Low emissions:* 64.5 inches 3.5 inch increase *High emissions:* 66.9 inches 5.9 inch increase	*Low emissions:* 17.9 inches 1.2 inch decrease *High emissions:* 17.6 inches 1.5 inch decrease

Willamette Basin

Time frame	Annual precipitation	Precipitation in winter (October-March)	Precipitation in summer (April-September)
Historical baseline: 1971-2000	64.1 inches	48.4 inches	15.6 inches
2010-2039	*Low emissions:* 64.9 inches 0.9 inch increase *High emissions:* 63.9 inches 0.2 inch decrease	*Low emissions:* 49.5 inches 1.1 inch increase *High emissions:* 49.0 inches 0.5 inch increase	*Low emissions:* 15.3 inches 0.3 inch decrease *High emissions:* 15.0 inches 0.6 inch decrease
2040-2069	*Low emissions:* 64.8 inches 0.7 inch increase *High emissions:* 65.1 inches 1.0 inch increase	*Low emissions:* 50.0 inches 1.6 inch increase *High emissions:* 50.1 inches 1.7 inch increase	*Low emissions:* 14.9 inches 0.8 inch decrease *High emissions:* 14.9 inches 0.8 inch decrease
2070-2099	*Low emissions:* 64.9 inches 0.9 inch increase *High emissions:* 66.6 inches 2.6 inch increase	*Low emissions:* 50.2 inches 1.8 inch increase *High emissions:* 52.3 inches 3.9 inch increase	*Low emissions:* 14.7 inches 1.0 inch decrease *High emissions:* 14.3 inches 1.3 inch decrease

Washington Coast

Time frame	**Annual precipitation**	**Precipitation in winter (October-March)**	**Precipitation in summer (April-September)**
Historical baseline: 1971-2000	112.6 inches	86.2 inches	26.4 inches
2010-2039	*Low emissions:* 115.1 inches 2.5 inch increase *High emissions:* 113.9 inches 1.3 inch decrease	*Low emissions:* 88.8 inches 2.6 inch increase *High emissions:* 49.0 inches 0.5 inch increase	*Low emissions:* 26.1 inches 0.3 inch decrease *High emissions:* 25.6 inches 0.8 inch decrease
2040-2069	*Low emissions:* 117.0 inches 4.5 inch increase *High emissions:* 117.5 inches 4.9 inch increase	*Low emissions:* 50.0 inches 1.6 inch increase *High emissions:* 50.1 inches 1.7 inch increase	*Low emissions:* 25.4 inches 1.0 inch decrease *High emissions:* 25.5 inches 0.8 inch decrease
2070-2099	*Low emissions:* 118.6 inches 6.0 inch increase *High emissions:* 121.1 inches 8.5 inch increase	*Low emissions:* 50.2 inches 1.8 inch increase *High emissions:* 52.3 inches 3.9 inch increase	*Low emissions:* 24.8 inches 1.5 inch decrease *High emissions:* 24.5 inches 1.9 inch decrease

Central Oregon Coast Range

Time frame	Annual precipitation	Precipitation in winter (October-March)	Precipitation in summer (April-September)
Historical baseline: 1971-2000	91.2 inches	72.1 inches	19.1 inches
2010-2039	*Low emissions:* 92.4 inches 1.1inch increase *High emissions:* 91.1 inches 0.1 inch decrease	*Low emissions:* 73.5 inches 1.4 inch increase *High emissions:* 72.9 inches 0.8 inch increase	*Low emissions:* 18.7 inches 0.3 inch decrease *High emissions:* 18.2 inches 0.8 inch decrease
2040-2069	*Low emissions:* 92.6 inches 1.4 inch increase *High emissions:* 92.9 inches 1.7 inch increase	*Low emissions:* 74.6 inches 2.5 inch increase *High emissions:* 74.7 inches 2.6 inch increase	*Low emissions:* 18.1 inches 1.0 inch decrease *High emissions:* 18.0 inches 1.1 inch decrease
2070-2099	*Low emissions:* 92.9 inches 1.6 inch increase *High emissions:* 95.4 inches 4.1 inch increase	*Low emissions:* 75.1 inches 3.0 inch increase *High emissions:* 78.1 inches 6.0 inch increase	*Low emissions:* 17.6 inches 1.4 inch decrease *High emissions:* 17.2 inches 1.8 inch decrease

To access data for specific geographic regions, use the Climate Toolbox Future Climate Mapper tool to look at projections for a particular area. The tool is available here: https://climatetoolbox.org/tool/Future-Climate-Dashboard

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