# Port-Orford-Cedar (*Chamaecyparis lawsoniana*)
## *Northern California Climate Change Vulnerability Assessment Synthesis*

***An Important Note About this Document:*** *This document represents an initial evaluation of vulnerability for Port-Orford-cedar in northern California based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by regional experts, relevant references from the scientific literature, and peer-review comments and revisions (see end of document for a glossary of terms and brief overview of study methods). The aim of this document is to expand understanding of habitat vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.*

*Peer reviewers for this document included Everett Hansen (Oregon State University), Richard Sniezko (U.S. Forest Service), and Donald Zobel (Oregon State University). Vulnerability scores were provided by Eureka workshop participants.*

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## Species Description

Port-Orford-cedar (*Chamaecyparis lawsoniana*) is a shade-tolerant evergreen conifer endemic to northwestern California and southwestern Oregon, where it is distributed at elevations from sea level to 1,950 m (0–6,400 ft; Zobel et al. 1985; Jimerson et al. 2003). Port-Orford-cedar primarily occurs in coastal forests from the Mad River in Humboldt County north to Coos County, Oregon and inland along the drainages of the northern Coast Range and western Klamath and Siskiyou Mountains (Griffin & Critchfield 1972; Zobel et al. 1985). However, isolated inland populations also occur along the upper reaches of the Trinity and Sacramento River systems (Zobel et al. 1985). Across its range, this species is found on sites where soil moisture remains high year round, such as in riparian areas (Zobel & Hawk 1980; Zobel et al. 1985; Sawyer 2007). In California, which comprises the warmest, driest portion of its range, it is often restricted to the area along active stream channels and around seeps (Zobel & Hawk 1980; Zobel et al. 1985; Sawyer 2007). Port-Orford-cedar can reach at least 600 years of age, and mature trees typically grow to heights of 60 m (200 ft) and can reach 1.2–1.8 m (4–6 ft) in diameter (Uchytil 1990).

It reaches its highest density and is frequently the dominant species on ultramafic substrates (e.g., serpentinite, peridotite) where competition from other species is reduced (Hawk 1977; Zobel et al. 1985). At lower elevations, particularly in California, it is often restricted to these nutrient-poor soils (Hawk 1977; Zobel et al. 1985). On more productive sites, it occurs as a smaller portion of the stand within the redwood, mixed evergreen, and true fir vegetation zones in California (Griffin & Critchfield 1972; Franklin & Dyrness 1973; Uchytil 1990). Commonly associated tree species include Douglas-fir (*Pseudotsuga menziesii*), tanoak (*Notholithocarpus densiflorus*), white fir (*Abies concolor*), western hemlock (*Tsuga heterophylla*), sugar pine (*Pinus lambertiana*), golden chinquapin (*Chrysolepis chrysophylla*), Pacific yew (*Taxus brevifolia*), California bay (*Umbellularia californica*), Pacific madrone (*Arbutus menziesii*), western white pine (*P. monticola*), canyon live oak (*Quercus chrysolepis*), bigleaf maple (*Acer macrophyllum*), incense cedar (*Calocedrus decurrens*), red alder (*Alnus rubra*), Pacific dogwood (*Cornus nuttallii*), Jeffrey pine (*P. jeffreyi*), and Shasta red fir (*A. magnifica var. shastensis*), among others (Hawk 1977; Jimerson & Daniel 1994; Jimerson et al. 1995, 1996, 2003). As a shade-tolerant species demonstrates shade-tolerance, it is able to reproduce in the shade of old-growth forests, as well as following disturbances such as fire or clear-cutting (Hawk 1977; Zobel & Hawk 1980).

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## Executive Summary

The relative vulnerability of Port-Orford-cedar in northern California was evaluated as moderate-high by regional experts due to moderate-high sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and low-moderate adaptive capacity.

| Port-Orford-Cedar | Rank | Confidence |
|---|---|---|
| Sensitivity | Moderate-High | High |
| Future Exposure | Moderate-High | Moderate |
| Adaptive Capacity | Low-Moderate | High |
| **Vulnerability** | **Moderate-High** | **High** |

| Sensitivity & Exposure Summary | *Climate and climate-driven factors*:<br>• Precipitation amount, soil moisture, drought<br>*Disturbance regimes*:<br>• Disease, wildfire<br>*Non-climate stressors*:<br>• Roads/highways/trails, fire suppression, timber harvest and forest product gathering, residential and commercial development, agriculture |
|---|---|

Port-Orford-cedar is sensitive to climate stressors that reduce water availability through changes in precipitation patterns and increased drought. Greater moisture stress is likely to reduce establishment and growth, potentially limiting species distribution. Changes in precipitation may also alter patterns of disease related to the *Phytophthora lateralis* fungus that causes Port-Orford-cedar root rot and depends on wet conditions for survival and long-distance dispersal. The spread of *P. lateralis* has contributed to population declines across most of the species' range, causing particularly high rates of mortality in large trees along active stream courses. Heavy fuel loads on infected sites can also enhance the risk of large and/or intense wildfires, further increasing tree mortality rates. Non-climate stressors such as the presence and use of roads/highways/trails, timber harvest, and fire suppression activities impact Port-Orford-cedar by spreading soil containing *P. lateralis* spores from infected to uninfected sites. These stressors, along with land use conversion to residential/commercial development and agriculture, have resulted in the loss of mature Port-Orford-cedar trees and shifts in stand structure and composition.

| Adaptive Capacity Summary | *Factors that enhance adaptive capacity*:<br>+ High genetic and phenotypic diversity, with some trees exhibiting disease-resistant traits<br>+ Valued by the public, increasing potential for societal support of conservation<br>+ Breeding program has identified disease-resistant families in most breeding zones and is producing seed for restoration/reforestation purposes<br>*Factors that undermine adaptive capacity*:<br>– Patchily distributed, due to dependence on year-round water supply for seedling establishment and edaphic factors that limit competition<br>– Short dispersal distances and association with edaphic controls on distribution make natural migration unlikely |
|---|---|

Although Port-Orford-cedar occurs across a wide range of environmental conditions, it is patchily distributed within a relatively narrow geographic range that reaches its southern limit in California. Roughly nine percent of Port-Orford-cedar on Forest Service and BLM lands in California is infested with *P. lateralis* root rot that exacerbates declining population health and already-limited connectivity in the region. Genetic and phenotypic diversity in Port-Orford-cedar are generally very high, particularly in California. However, high rates of disease-related mortality may reduce genetic diversity and the potential for adaptation. Port-Orford-cedar wood is highly valued by northern California tribes, as well as by wood products industries for lumber and ornamental purposes. Management of this species will likely focus on limiting the spread of disease to uninfected sites and propagating/planting disease-resistant trees both within the species' current range and on new sites expected to become more climatically suitable in the future.

## Sensitivity and Exposure

Port-Orford-cedar was evaluated by regional experts as having moderate-high overall sensitivity (high confidence in evaluation) and moderate-high overall future exposure (moderate confidence) to climate and climate-driven factors, changes in disturbance regimes, and non-climate stressors.

Available models suggest that climatically suitable habitat for Port-Orford-cedar will shift northward along the coast, with significant losses (up to 98%) occurring by the end of the century (McKenney et al. 2007; Crookston et al. 2010). However, the distribution of this species is primarily controlled by edaphic rather than climatic factors (Zobel 2016, 2018), limiting the usefulness of modeling efforts that do not include soil/geology and biotic interactions (Zobel 2010).

Seedling establishment in Port-Orford-cedar appears to be constrained, at least in part, by cold temperatures at high elevations (Zobel 1990). Thus, warmer spring temperatures may allow expansion into areas currently above the species' range, such as around Preston Peak, in the upper Sacramento drainage, and above the Cedar Valley site where the species currently reaches its highest elevation (Vuln. Assessment Reviewer, pers. comm., 2019). However, lack of population connectivity and short seed dispersal distances are likely to limit natural migration (Vuln. Assessment Reviewer, pers. comm., 2019). Refugia may include seeps that are protected by local topography from water-borne and soil-borne pathogens (Hansen et al. 2000).

### Sensitivity and future exposure to climate and climate-driven factors

Regional experts evaluated Port-Orford-cedar as having high sensitivity to climate and climate-driven factors (high confidence in evaluation), with an overall moderate-high future exposure to these factors within the study region (low confidence). Key climatic factors that affect Port-Orford-cedar include precipitation amount, soil moisture, and drought.[1]

<u>Precipitation amount, soil moisture, and drought</u>
Port-Orford-cedar requires year-round soil moisture for establishment and growth (Zobel et al. 1985; Carroll & Jules 2005), and precipitation primarily impacts this species by mediating levels of soil moisture (Vuln. Assessment Reviewer, pers. comm., 2019). Most stands in northern California historically received at least 150 cm (59 in) of precipitation annually, though disjunct inland stands receive less (a minimum of 126 cm [49 in] annually; Zobel & Hawk 1980). The presence of summer fog allows the persistence of Port-Orford-cedar on sites that would otherwise be too dry to support the species (Zobel & Hawk 1980), suggesting that coastal fog

[1] All climate and climate-driven factors presented were ranked as having a moderate or higher impact on this species.

may ameliorate drought stress as it does for other trees (Vuln. Assessment Reviewer, pers. comm., 2019). Radial growth in Port-Orford-cedar is positively correlated with above-average precipitation and abundant soil moisture throughout the year, but these factors appear to be most important in the late spring and summer (Carroll & Jules 2005). By contrast, severe drought can be associated with extreme reductions in growth (Carroll & Jules 2005), though mortality of adult trees is relatively rare (Vuln. Assessment Reviewer, pers. comm., 2019).

Although the direction and amount of change in future projections for precipitation in California are highly uncertain, reduced soil moisture and drier overall conditions are likely even in areas where precipitation may increase, due to enhanced evaporative demand associated with warmer temperatures (Sherwood & Fu 2014; Thorne et al. 2015; Dobrowski et al. 2015). Drier overall conditions would negatively impact habitat suitability for Port-Orford-cedar by reducing the area where soil moisture is high enough during the dry season to support germination and seedling survival (Vuln. Assessment Workshop, pers. comm., 2017). However, coastal stands at the southern edge of the species' California range, which experience high rainfall and frequent coastal fog, are unlikely to survive significant and prolonged reductions in precipitation or fog (Vuln. Assessment Reviewer, pers. comm., 2019). Drier conditions are also likely to increase wildfire risk in riparian areas by reducing fuel moisture (Skinner 2003; Pettit & Naiman 2007).

Changes in precipitation are also likely to alter patterns of disease related to the *Phytophthora lateralis* pathogen that causes Port-Orford-cedar root rot (Hansen et al. 2000). *P. lateralis* requires wet conditions for spore survival and long-distance movement in running water, and reduced precipitation could result in lower rates of *P. lateralis* transport to uninfected sites (Hansen et al. 2000). By contrast, increases in winter rainfall could facilitate the survival of resting spores through multiple seasons (Hansen & Hamm 1996) and increase the rate of spread to downstream trees during winter floods, including those in currently uninfected areas (Hansen & Hamm 1996; Hansen et al. 2000; Jules et al. 2002).

| **Regional Precipitation, Soil Moisture, & Drought Trends**[2] | |
|---|---|
| *Historical & current trends:*<br>• 7.2–9.4 cm (2.8–3.7 in) increase in mean annual precipitation between 1900 and 2009 for the Northwestern California and Southern Cascade ecoregions (Rapacciuolo et al. 2014) | *Projected future trends:*<br>• 20% decrease to 28% increase in mean annual precipitation by 2100 (compared to 1951–1980) for the North Coast, Northern Coast Range, Klamath Mountain, and Southern |

[2] Trends in climate factors and natural disturbance regimes presented in this and subsequent summary tables are not species-specific; rather, they represent broad trends and future projections for the study region. The precipitation, temperature, climatic water deficit, and snowpack projections for this project are derived from the Basin Characterization Model, which uses modified Jepson ecoregions (Flint et al. 2013; Flint & Flint 2014). Projections for all other factors are based on a review of relevant studies in the scientific literature. For this project, exposure was evaluated by calculating the magnitude and direction of projected change within the modified Jepson ecoregions that include habitat distribution within the study geography.

| Regional Precipitation, Soil Moisture, & Drought Trends[2] | |
|---|---|
| • No trends available for soil moisture<br>• Drought years have occurred twice as often over the last two decades compared to the previous century (Diffenbaugh et al. 2015)<br>• 2012–2014 drought set records for lowest precipitation, highest temperatures, and most extreme drought indicators on record (Griffin & Anchukaitis 2014; Diffenbaugh et al. 2015) | Cascade ecoregions (Flint et al. 2013; Flint & Flint 2014)[3]<br>• Seasonal changes are projected to be more significant as the wet season becomes wetter and shorter (i.e., later onset of fall rains and earlier onset of summer drought) and the dry season becomes drier and longer (Pierce et al. 2018; Swain et al. 2018)<br>• Overall, interannual variability is expected to increase (Pierce et al. 2018; Swain et al. 2018)<br>• Decreased top-level soil moisture is likely even if precipitation increases due to temperature-related changes in evaporative demand (Pierce et al. 2018)<br>• Drought years are twice as likely to occur over the next several decades due to increased co-occurrence of dry years with very warm years (Cook et al. 2015)<br>• 80% chance of multi-decadal drought by 2100 under a high-emissions scenario (Cook et al. 2015)<br>• Severe droughts that now occur once every 20 years will occur once every 10 years by 2100 and once-in-a-century drought will occur once every 20 years (Pierce et al. 2018) |
| **Summary of Potential Impacts on Species** *(see text for citations)* | |
| • Decreased growth under drier conditions<br>• Reduced habitat suitability due to loss of sites with abundant soil moisture year-round<br>• Reduced fuel moisture, resulting in greater wildfire risk in riparian areas<br>• Changes in patterns of disease that impact infection risk and spread of Port-Orford-cedar root rot | |

### Sensitivity and future exposure to changes in natural disturbance regimes

Regional experts evaluated Port-Orford-cedar as having moderate-high sensitivity to changes in natural disturbance regimes (high confidence in evaluation), with an overall high future exposure to these stressors within the study region (moderate confidence). Key natural disturbance regimes that affect Port-Orford-cedar include disease and wildfire.[4]

[3] Projections for changes in annual and seasonal precipitation by ecoregion can be found in the full climate impacts table (https://bit.ly/2LHgZaG).
[4] All disturbance regimes presented were ranked as having a moderate or higher impact on this species.

Disease

Historically, few pathogens affected Port-Orford-cedar due to its high volatile oil content, and none were known to cause mortality (Zobel et al. 1985). However, a non-native root pathogen, *Phytophthora lateralis*, was introduced into the Pacific Northwest in the 1920s (Zobel et al. 1985) and was first discovered within the species' native range in 1952 (Roth et al. 1957). Roughly nine percent of the mapped Forest Service and BLM lands supporting this species is infested with the disease, particularly on riparian sites and in roaded areas (Casavan et al. 2003). Though infested sites are widely scattered across the species' range, these areas appear to be more concentrated in the northern portion of Six Rivers National Forest, while disjunct inland populations within Shasta-Trinity National Forest are less impacted (Casavan et al. 2003).

*P. lateralis* causes very high mortality rates in Port-Orford-cedar (Hansen et al. 2000; Jules et al. 2002, 2015; Casavan et al. 2003), with most trees dying within the first 10 years following site exposure (Kauffman & Jules 2006; Jules et al. 2015). Following initial infection, *P. lateralis* colonizes the roots and lower trunks of host trees, eventually cutting off the tree's supply of water and nutrients (Cannon et al. 2016). Mature trees typically die 2–4 years following initial infection, but seedlings can die within a much shorter timespan (Cannon et al. 2016). Inoculation trials have found that seedlings from susceptible parent trees usually take a little over three months to reach 100% mortality (Sniezko et al. 2019), though this could be accelerated if there is flooding  (Vuln. Assessment Reviewer, pers. comm., 2019). However, some families exhibit genetic resistance to the disease that increases survival rates (Sniezko et al. 2012a, 2012b, 2019).

In dense stands, the disease can also spread directly from the roots of one tree to the next (Zobel et al. 1985; Jules et al. 2002; Cannon et al. 2016). *P. lateralis* spores are transmitted through both water and soil (Cannon et al. 2016), with most new infections beginning after soil containing chlamydospores (i.e., resting spores) from an infected area is carried on vehicle tires and falls off near a stream crossing (Jules et al. 2002; Cannon et al. 2016). After infecting the roots of Port-Orford-cedars nearby, the pathogen produces zoospores that are transported downstream or overland in floodwaters (Jules et al. 2002, 2015; Cannon et al. 2016). Disease transmission is also frequently facilitated by humans through accidental introduction of spore-containing mud along roads, in logging and construction sites, and commercial movement of nursery stock (Zobel et al. 1985; Jules et al. 2002; Cannon et al. 2016). In lowland areas, disease spread between watersheds can occur through movement of livestock and native ungulates (Cannon et al. 2016). Left to itself, this disease can remain somewhat restricted to certain microtopographical features within infected areas, generally following drainage lines (Vuln. Assessment Reviewer, pers. comm., 2019). Thus, infection risk varies depending on proximity to streams and roads (Kauffman & Jules 2006; Jules et al. 2015). Larger trees also have a higher risk of infection (Kauffman & Jules 2006; Jules et al. 2015), likely due to their more extensive root system (Kauffman & Jules 2006). In many areas, stand structure has been dramatically altered towards smaller size classes, and the loss of old trees can impact stream ecology and the functioning of riparian forests (Hansen et al. 2000).

*P. lateralis* can survive on a site for 7 years in the absence of living host trees (Hansen & Hamm 1996), and potentially longer depending on site conditions (Vuln. Assessment Reviewer, pers. comm., 2019). This pathogen is sensitive to warm, dry conditions, and opportunities for spread of the disease are limited by temperature in the summer months (Hansen & Hamm 1996). Thus, warmer, drier future conditions could limit spread of the disease (Vuln. Assessment Workshop, pers. comm., 2017). However, more intense storms and flooding events may enhance spread, albeit in fewer years and/or over shorter time periods (Vuln. Assessment Reviewer, pers. comm., 2019). In many areas, restoration with disease-resistant seedlings may help re-establish and maintain Port-Orford-cedar (Harrington et al. 2012; Sniezko et al. 2019), though it is currently unknown whether warmer temperatures, periodic flooding, and other climate changes will reduce the efficacy of resistance (Vuln. Assessment Reviewer, pers. comm., 2019).

Port-Orford-cedar is also susceptible to Stigmina foliage blight (caused by *Stigmina thujina*), particularly within the southern portion of the species' range (e.g., California) and at higher elevations (Martin 2008). Vulnerability to infection varies greatly by seed source, as susceptibility to the disease appears to be heritable (Martin 2008). This suggests the potential for issues if seed from susceptible families are planted in other locations (Vuln. Assessment Reviewer, pers. comm., 2019). It is currently unknown whether climate change will impact this and other pathogens that affect Port-Orford-cedar, such as additional *Phytophthera* species (Vuln. Assessment Reviewer, pers. comm., 2019).

| **Regional Disease Trends** | |
|---|---|
| *Historical & current trends:*<br>• Spread of *P. lateralis* throughout the species' range since 1952 (Jules et al. 2015)<br>• Initial rapid rate of spread appears to have slowed since 2000 (Jules et al. 2015) | *Projected future trends:*<br>• Continued spread to infected watersheds likely (Jules et al. 2015) |
| **Summary of Potential Impacts on Species** *(see text for citations)* | |
| • High rates of tree mortality, particularly among large trees and those in close proximity to streams<br>• Shifts in stand structure towards smaller size classes | |

<u>Wildfire</u>

Prior to Euro-American settlement, riparian forests dominated by Port-Orford-cedar on federal lands had a mean fire return interval of 30 years (range 10-160 years; Van de Water & Safford 2011), typically burning less frequently and at more variable intervals compared to surrounding upland forests (Skinner 2003; Olson & Agee 2005; Bendix & Commons 2017).[5] Although young Port-Orford-cedar trees are easily killed by fire, older trees have thick, fire-resistant bark that allows them to survive low- to moderate-intensity surface fires (Zobel et al. 1985; Uchytil 1990; Skinner et al. 2018). Surviving trees provide seed sources for post-fire seedling establishment, and as long as a seed source is present rapid regeneration typically occurs on disturbed mineral

[5] Refer to the section on non-climate stressors for a more complete discussion of the impacts of fire suppression on Port-Orford-cedar.

soil (Uchytil 1990). On productive sites, seedlings are often outcompeted by faster-growing conifers such as Douglas-fir (Uchytil 1990), though Port-Orford-cedar can sometimes remain within the lower canopy of the stand (Vuln. Assessment Reviewer, pers. comm., 2019). However, on ultramafic substrates, Port-Orford-cedar typically remains dominant (Vuln. Assessment Reviewer, pers. comm., 2019). Overall, fire plays an important role in maintaining Port-Orford-cedar by limiting more fire-sensitive species, and in some cases (e.g., in the presence of western hemlock and white fir) can even allow increases in this species following repeated fires (Zobel et al. 1985; Vuln. Assessment Reviewer, pers. comm., 2019). However, the species may be unable to persist where too-frequent fires eliminate regenerating trees before they develop more fire-resistant bark (Uchytil 1990).

High-intensity fires can cause extensive mortality, reducing seed sources (Skinner et al. 2018). Because Port-Orford-cedar is decay resistant, heavy fuel loading can occur on productive sites during long fire-free periods (Skinner et al. 2018), as well as on infected sites with large numbers of dead trees (Vuln. Assessment Workshop, pers. comm., 2017). These increases in fuel availability can result in greater risk of extensive and/or high-intensity fires during dry years that cause high rates of tree mortality (Skinner et al. 2018).

| **Regional Wildfire Trends** | |
|---|---|
| *Historical & current trends:*<br>• 85% of U.S. Forest Service lands in northern California are burning less frequently compared to pre-1850 fire return intervals, largely due to fire suppression (Safford & Van de Water 2014)<br>• Fire size and total area burned increased on U.S. Forest Service lands in northwestern California between 1910-2008, with the highest values occurring after 2000 (Miller et al. 2012)<br>• Changes in large fires (over 400 ha) in the inland northern California/Sierra Nevada region since the 1970s (Westerling 2016):<br>  ○ 184–274% increase in frequency<br>  ○ 270–492% increase in total area burned<br>  ○ 215% increase in length of the fire season<br>• Changes in fire size, area burned, and fire frequency over the past several decades remain well below historical tribally-influenced frequency and extent of burning in California (Stephens et al. 2007)<br>• No significant trends in the average areal proportion of high-severity fire were documented in northwestern CA from 1984–2008 (Miller et al. 2012; Parks et al. 2015; Law | *Projected future trends:*<br>• State-wide, up to 77% increase in mean annual area burned and 50% increase in the frequency of extremely large fires (>10,000 ha) by 2100 (Westerling 2018)<br>  ○ Greatest increases in burned area (up to 400%) occur in montane forested areas in northern California (Westerling et al. 2011; Westerling 2018)<br>  ○ Less significant increases or possible decrease along the North Coast (Westerling et al. 2011)<br>• Little projected change in fire severity in northwestern California by 2050 in models based solely on historical fire-climate relationships (Parks et al. 2016)<br>  ○ However, human activity and fuel buildup from decades of fire suppression have altered historical fire-climate relationships (Taylor et al. 2016; Syphard et al. 2017; Wahl et al. 2019), and projections that incorporate these factors suggest that more significant increases in fire severity and size may occur (Mann et al. 2016; Wahl et al. 2019)<br>• The majority of impacts to natural and human |

<table>
<tr><th colspan="2">Regional Wildfire Trends</th></tr>
<tr><td>& Waring 2015; Keyser & Westerling 2017)<br>○ The relatively short period of record for fire severity data may obscure long-term trends<br>○ To date, there are no peer-reviewed studies on trends in northern California fire severity that include data from the last ten years</td><td>ecosystems come from extreme fire events (i.e., fires that have a low probability of occurring in any given place and time), which are likely to increase over the coming century (Westerling 2018)<br>○ Generally, these patterns are not well-represented in studies that evaluate indices of mean fire size, intensity/severity, etc.</td></tr>
<tr><th colspan="2">Summary of Potential Impacts on Species (see text for citations)</th></tr>
<tr><td colspan="2">• Tree mortality during intense fires, particularly during dry years and/or where heavy fuel loads have accumulated<br>• Reduced recruitment where more frequent fires kill regenerating trees</td></tr>
</table>

### Dependency on habitat and/or other species

Regional experts evaluated Port-Orford-cedar as having high dependency on sensitive habitats (high confidence in evaluation). In general, Port-Orford-cedar was evaluated as having a moderate-high degree of specialization (high confidence).

Port-Orford-cedar is dependent on microsites with abundant moisture, including riparian areas, wetlands, seeps (Zobel et al. 1985), and moist west- and northwest-facing slopes (Vuln. Assessment Reviewer, pers. comm., 2019). This dependence may be due to higher temperature requirements that result in seed germination later in the season, exposing seedlings to the summer dry period at a younger age compared to most other conifers (Zobel 1990). It is unknown how warmer spring temperatures and changing patterns of precipitation and soil moisture will interact to affect seedling recruitment (Vuln. Assessment Reviewer, pers. comm., 2019). For instance, warmer spring temperatures could result in earlier germination, potentially allowing establishment on drier microsites; however, drier spring conditions could counteract the effect of earlier germination (Vuln. Assessment Reviewer, pers. comm., 2019).

Despite high dependence on moist microsites, Port-Orford-cedar grows across a broad range of temperatures and soil types compared to associated tree species (Zobel et al. 1985), reaching its greatest densities on ultramafic substrates where competition from other species is reduced (Hawk 1977; Zobel et al. 1985; Zobel 2016, 2018). Because the growth of this species is less restricted by nutrient-poor substrates (e.g., serpentine soils) than Douglas-fir and other associates (Whittaker 1960; Hawk 1977; Vuln. Assessment Reviewer, pers. comm., 2019), the presence of ultramafics maintains the presence of this species on lower-elevation sites and near the warmer, drier edges of its range (Zobel 2010).

### Sensitivity and current exposure to non-climate stressors

Regional experts evaluated Port-Orford-cedar as having moderate-high sensitivity to non-climate stressors (moderate confidence in evaluation), with an overall moderate-high current exposure to these stressors within the study region (moderate confidence). Key non-climate stressors that affect Port-Orford-cedar include roads/highways/trails, fire suppression, timber harvest and forest product gathering, residential and commercial development, and agriculture.[6]

Roads, highways, and trails

Roads, highways, and trails are the primary vector of disease transmission for *P. lateralis*, which occurs when infected soil is carried into uninfected microsites and/or spread to new areas by foot and on vehicle tires (Hansen et al. 2000; Jules et al. 2002). Infection risk is strongly associated with tree abundance alongside roads and the amount of traffic at stream crossings (Jules et al. 2002). To a lesser degree, foot traffic on roads and trails can transport spores into previously uninfected watersheds, although this occurs over shorter distances (Hansen et al. 2000; Jules et al. 2002). Off-trail foot traffic, such as by people collecting florists' greens, can also spread the disease by spreading infected soil within and between stands (Vuln. Assessment Reviewer, pers. comm., 2019).

Fire suppression

Fire suppression activities (e.g., back burning, construction of fire lines) have the potential to transport root rot to uninfected sites (Vuln. Assessment Workshop, pers. comm., 2017) through the movement of mud on heavy machinery or spraying of water from ponds or streams infested by pathogen spores (Vuln. Assessment Reviewer, pers. comm., 2019). Additionally, activities undertaken during fire suppression activities can directly injure or kill mature trees that might not have otherwise burned (Lake 2013). Long fire-free periods in riparian forests associated with fire suppression practices, which were widely introduced in the early 1900s (Skinner 2003; Safford & Van de Water 2014), have also resulted in heavy fuel loading that can increase the risk of high-intensity fires (Skinner et al. 2018).

Timber harvest and forest product gathering

The wood of Port-Orford-cedar is strong, light, and resistant to decay, making it a valued timber resource (Zobel et al. 1985; Zobel 1986). It also has the ability to machine finely and takes finishes well, adding to its high value (Zobel 1986). Commercial export of this species began in 1854, and it was in high demand within the U.S. until the 1950s (Zobel 1986). This species remains very popular in Japan due to its aesthetic value and similarity to a culturally-important wood from the congeneric Japenese species hinoki (*C. obtusa*; Zobel et al. 1985; Zobel 1986). Thus, intensive timber harvest over the past 165 years has significantly reduced the abundance of mature Port-Orford-cedar trees (Zobel et al. 1985; Zobel 1986, 2016). Timber harvest of Port-Orford cedar has now declined due to disease, changes in management activities, and reduced availability of high-quality wood for export as logging of old-growth forests was slowed following the implementation of the Northwest Forest Plan (Vuln. Assessment Reviewer, pers. comm., 2019).

[6] All non-climate stressors presented were ranked as having a moderate or higher impact on this species.

The spread of *P. lateralis* is accelerated by the long-distance vehicle travel related to timber harvest and the commercial and recreational gathering of forest products such as mushrooms (Hansen et al. 2000) and florists' greens (Vuln. Assessment Reviewer, pers. comm., 2019). As a result, a large proportion (over 60%) of coastal Port-Orford-cedar trees that regenerated following cutting between 1880 and 1930 experienced mortality due to *P. lateralis* (Zobel et al. 1985). Declines in timber harvest over recent decades may have contributed to observed reductions in the spread of Port-Orford-cedar root rot on public lands (Jules et al. 2015).

Residential/commercial development and agriculture

Development and agricultural activities (including cannabis [*Cannabis sativa, C. indica*] cultivation and livestock grazing) contribute to the spread of *P. lateralis* across the landscape (Zobel et al. 1985; Vuln. Assessment Workshop, pers. comm., 2017). Land-use conversion to agriculture has also been associated with range reductions in privately-owned lowland areas (Vuln. Assessment Reviewer, pers. comm., 2019).

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## Adaptive Capacity

Port-Orford-cedar was evaluated by regional experts as having low-moderate overall adaptive capacity (high confidence in evaluation).

### Species extent, status, connectivity, and dispersal ability

Regional experts evaluated Port-Orford-cedar as having a low geographic extent (high confidence in evaluation), declining population status (moderate confidence), and a low-moderate degree of connectivity between populations (high confidence).

Regional experts evaluated Port-Orford-cedar as having a low dispersal ability (high confidence in evaluation). Barriers to dispersal were evaluated as having a high impact on the species (high confidence). Disease, geologic features, and the absence of perennial water networks were identified as the primary barriers to dispersal.[7]

Port-Orford-cedar is restricted to a 350-km (220-mi) range from north to south (Uchytil 1990). In California, this species is patchily distributed across the landscape due to its association with riparian areas and serpentine soils (Zobel et al. 1985). Some patchiness may be due to extirpation of populations where climate conditions became less suitable in recent geologic history (Sawyer 2007; Zobel 2010). The small, wind-dispersed seeds of Port-Orford-cedar only travel for short distances (Zobel et al. 1985; Uchytil 1990), although their dispersal distance may be increased where they float on running water (Zobel et al. 1985). These short seed dispersal distances may have contributed to a lack of recolonization in areas that currently appear suitable for establishment (Sawyer, pers. comm., 2009 cited in Zobel 2010). This suggests that, in the absence of management assistance, migration of Port-Orford-cedar over the coming century is unlikely (Zobel 2010). Both disease and historical timber harvest have contributed to increased patchiness and declining population health (Hansen et al. 2000; Casavan et al. 2003;

[7] All barriers presented were ranked as having a moderate or higher impact on this species.

Jules et al. 2015), although the rate of decline has likely decreased in recent decades (Vuln. Assessment Reviewer, pers. comm., 2019).

Despite its overall patchy distribution, Port-Orford-cedar stands are generally connected to some degree by their association with streams (Vuln. Assessment Reviewer, pers. comm., 2019). In the context of *P. lateralis* root rot, however, this connectivity means that all Port-Orford-cedar populations downstream of infected stands are vulnerable to disease (Vuln. Assessment Reviewer, pers. comm., 2019). By contrast, the lack of connectivity between adjacent stands that lie across watershed boundaries limits spread between drainages in the absence of human or animal vectors (Vuln. Assessment Reviewer, pers. comm., 2019). Wider deployment of disease-resistant populations may also reduce the importance of existing connectivity over the coming decades (Vuln. Assessment Reviewer, pers. comm., 2019).

### Intraspecific/life history diversity

Regional experts evaluated Port-Orford-cedar as having low life history diversity (high confidence in evaluation), moderate-high genetic diversity (high confidence), and moderate-high phenotypic plasticity (moderate confidence).

Genetic and phenotypic diversity in Port-Orford-cedar are generally very high (Zobel et al. 1985, 2001, 2002; Millar & Marshall 1991; Sharpe 2002; Kitzmiller 2008), leading to variable form and growth rates that have allowed the development of over 200 cultivated varieties (Zobel et al. 1985). Strong natural selection of contrasting climates between northern coastal and southern inland populations have also resulted in significant genetic and phenotypic variation among populations (Kitzmiller 2008). Within California, inland populations appear to be genetically distinct from both coastal populations and from each other, though genetic diversity within populations is higher on the coast than in inland areas (Millar & Marshall 1991). Adaptive differences in survival, height, health (i.e., the absence of injury or defect), phenology, physiology, and root properties have been associated with geography and elevation (Zobel et al. 2001, 2002; Sharpe 2002; Kitzmiller 2008). However, high rates of disease-related mortality have the potential to reduce genetic diversity and the potential for adaptation (Kitzmiller 2008; Potter et al. 2019). Inbreeding depression may also be occurring in some isolated areas (Kitzmiller 2008).

### Resistance and recovery

Regional experts evaluated Port-Orford-cedar as having low resistance to climate stressors and natural disturbance regimes (high confidence in evaluation). Population recovery potential (i.e., recruitment rate) was evaluated as moderate (low confidence).

Port-Orford-cedar is resistant to low to moderate-intensity surface fires, especially at larger sizes (Zobel et al. 1985; Skinner et al. 2018). Additionally, natural genetic resistance to *P. lateralis* has been identified in trees across the species' range, though fewer resistant families have been identified within California breeding zones compared to zones in the northern part of the range (Sniezko et al. 2012b, 2012a, 2019).

Port-Orford-cedar typically begin reproducing via seed between 5 and 9 years of age, and produce heavy seed crops every 4 or 5 years throughout the remainder of their life (Zobel et al. 1985). Although seed production varies from year to year, it is often abundant and total crop failure is rare (Zobel et al. 1985). This relatively consistent seed production compared to many other conifers gives Port-Orford-cedar an advantage by allowing establishment following disturbances that may occur in a year when seed production is not particularly high (Vuln. Assessment Reviewer, pers. comm., 2019). Reproductive buds set in the fall and are pollinated the following spring, then the seeds ripen within small cones in September and October (Zobel et al. 1985; Uchytil 1990). The small, winged seeds fall from the cones throughout the following winter and spring and are dispersed by wind or by floating on water (Zobel et al. 1985; Uchytil 1990). Most seeds germinate the first spring following dispersal, and seed viability can be relatively low (Zobel et al. 1985; Uchytil 1990).

The loss of mature seed-producing trees in stands affected by *P. lateralis* may reduce seedling establishment in diseased areas (Vuln. Assessment Workshop, pers. comm., 2017). Regeneration is also limited by the dependence of this species on high soil moisture throughout the year (Vuln. Assessment Workshop, pers. comm., 2017).

### Management potential

*Public and societal value*

Regional experts evaluated Port-Orford-cedar as having moderate public and societal value (high confidence in evaluation).

Port-Orford-cedar is highly valued by northern California tribes, including the Karuk and Hoopa tribes, and the wood is used to build houses, canoes, utensils, and ceremonial structures (e.g., sweathouses; Schenck & Gifford 1952; Zobel et al. 1985). This species is also commercially valued for lumber and ornamental purposes (Zobel et al. 1985; Zobel 1986), commanding the highest stumpage price of any conifer species in the United States (Nunamaker et al. 2007). Riparian Port-Orford-cedar communities are also appreciated by the public for recreation and their aesthetic beauty (Vuln. Assessment Workshop, pers. comm., 2017).

Because of its limited distribution and current threats (e.g., disease), Port-Orford-cedar has received a ‘Near Threatened’ status on the International Union for Conservation of Nature and Natural Resources (IUCN) Red List (Farjon 2013). The loss of this species has caused significant economic and ecological impacts in the region (Hansen et al. 2000), as well as impacting the use of Port-Orford-cedar for tribal ceremonial use (Long et al. 2018). Management and policy recommendations intended to help limit the spread of disease (e.g., seasonal road closures) may help conserve the species (Hansen et al. 2000; Jules et al. 2002, 2015; Betlejewski et al. 2003). However, road closures intended to increase forest sustainability can also affect tribe members’ ability to access forest resources (Long et al. 2018).

*Management capacity and ability to alleviate impacts*[8]
Regional experts evaluated the potential for reducing climate impacts on Port-Orford-cedar through management as moderate (high confidence in evaluation).

Management of Port-Orford-cedar depends, in large part, on the availability of disease-resistant genotypes that can be used for restoration and reforestation in populations that have been reduced through harvesting or disease-related mortality (Sniezko et al. 2012a, 2019; Potter et al. 2019). In 1997, the U.S. Forest Service and Bureau of Land Management established a program to screen for genetic resistance within 13 breeding zones, as well as to oversee the production of resistant seed (Sniezko et al. 2012b, 2012a, 2017, 2019). Outplanting resistant trees could help preserve genetic diversity, increasing the potential for future adaptation to changing climate conditions and other stressors (Harrington et al. 2012; Sniezko et al. 2012a, 2017, 2019; Potter et al. 2019). Because natural migration of this species is unlikely, planting can occur in areas that may remain or become climatically suitable for Port-Orford-cedar. In California, areas at higher elevations relative to its current range may become suitable, such as around Preston Peak in the Siskiyou Mountains (Vuln. Assessment Reviewer, pers. comm. 2019). Because planted seedlings are less sensitive to year-round water availability than newly-germinated seedlings, they likely can survive in drier areas that may expand the availability of suitable habitat (Zobel 2016, 2018; Vuln. Assessment Reviewer, pers. comm., 2019). Ideally, planting sites should also minimize the risk of disease spread by maintaining relatively low proportions of Port-Orford-cedar within a given stand (up to 25%), and thinning trees where needed to reduce ease of root rot disease transmission (Betlejewski et al. 2011; Zobel 2016).

Many management strategies also focus on reducing the risk of new infections by limiting human activity that might transport spores over long distances (Hansen et al. 2000; Jules et al. 2015). Examples of strategies currently used to minimize the spread of disease include seasonal road closures, road decommissioning, scheduling timber harvest during the dry season, washing vehicles and equipment to remove soil, and thinning to reduce disease transmission (Goheen et al. 2003, 2012; Jules et al. 2015). However, the capacity to protect populations at larger scales (e.g., watershed, landscape) is limited (Vuln. Assessment Workshop, pers. comm., 2017).

*Ecosystem services*
Port-Orford-cedar provides a variety of ecosystem services, including:

- Provisioning of wood and ornamental resources;
- Regulation of air quality, climate/microenvironments (e.g., shade), erosion control (i.e., through streambank stabilization), and natural hazard regulation;
- Support of primary production, oxygen production, soil formation/retention, nutrient cycling, and water cycling; and

[8] Further information on climate adaptation strategies and actions for northern California can be found on the project page (https://bit.ly/31AUGs5).

- Cultural/tribal uses for spiritual/religious purposes, knowledge systems, educational values, aesthetic values, social relations, sense of place, cultural heritage, inspiration, and recreation (Vuln. Assessment Workshop, pers. comm., 2017).

In addition to being valued for aesthetic and cultural purposes, Port-Orford-cedar acts as a foundation species in riparian forests by stabilizing soil along streambanks and increasing calcium availability on nutrient-poor soils (Zobel et al. 1985; Hansen et al. 2000). It also provides large, slowly rotting wood that increases aquatic productivity in streams (Vuln. Assessment Reviewer, pers. comm., 2019).

According to local fur trappers, American martens (*Martes americana*) have a particular affinity for cedar swamps along the Oregon coast, many of which are dominated by Port-Orford-cedar (Maser 1981). Port Orford cedar is also commonly a component of Humboldt marten (*Martes caurina humboldtensis*) habitat (Slauson et al. 2019) and is utilized for denning by Pacific fishers (*Pekania pennanti*; Matthews et al. 2019).

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## Recommended Citation

Hilberg LE, Reynier WA, Kershner JM. 2019. Port-Orford-Cedar (*Chamaecyparis lawsoniana*): Northern California Climate Change Vulnerability Assessment Synthesis. Version 1.0. EcoAdapt, Bainbridge Island, WA.

Further information on the Northern California Climate Adaptation Project is available on the project website (https://tinyurl.com/NorCalAdaptation).

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# *Northern California Climate Adaptation Project:*

## Vulnerability Assessment Methods and Application

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## Defining Terms

**Exposure:** A measure of how much of a change in climate or climate-driven factors a resource is likely to experience (Glick et al. 2011).

**Sensitivity:** A measure of whether and how a resource is likely to be affected by a given change in climate or factors driven by climate (Glick et al. 2011).

**Adaptive Capacity:** The ability of a resource to accommodate or cope with climate change impacts with minimal disruption (Glick et al. 2011).

**Vulnerability:** A function of the sensitivity of a particular resource to climate changes, its exposure to those changes, and its capacity to adapt to those changes (IPCC 2007).

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## Vulnerability Assessment Model

The vulnerability assessment model applied in this process was developed by EcoAdapt (EcoAdapt 2014a; EcoAdapt 2014b; Kershner 2014; Hutto et al. 2015; Gregg 2018),[9] and includes evaluations of relative vulnerability by local and regional stakeholders who have detailed knowledge about and/or expertise in the ecology, management, and threats to focal habitats, species groups, individual species, and the ecosystem services that these resources provide. Stakeholders evaluated vulnerability for each resource by discussing and answering a series of questions for sensitivity and adaptive capacity. Exposure was evaluated by EcoAdapt using projected future climate changes from the scientific literature. Each vulnerability component (i.e., sensitivity, adaptive capacity, and exposure) was divided into specific elements. For example, habitats included three elements for assessing sensitivity and six elements for adaptive capacity. Elements for each vulnerability component are described in more detail below.

In-person workshops were held in Eureka, Redding, and Upper Lake between May and October 2017. Participants self-selected habitat and species group/species breakout groups and evaluated the vulnerability of each resource. Participants were first asked to describe the habitat and/or to list the species to be considered in the evaluation of an overarching species group. Due to limitations in workshop time and participant expertise, multiple resources were not assessed during these engagements. Evaluations for remaining habitats, species groups, and species were completed by contacting resource experts.[10]

[9] Sensitivity and adaptive capacity elements were informed by Lawler 2010, Glick et al. 2011, and Manomet Center for Conservation Sciences 2012.

[10] Resources evaluated by experts included: coastal bluff/scrub habitats, coastal conifer hardwood forest, true fir forest, lakes/ponds, freshwater marshes, vernal pools, seeps/springs, native insect pollinators, native ungulates, salamanders, frogs, native mussels, marbled murrelet, and northwestern pond turtle.

Stakeholders assigned one of five rankings (High, Moderate-High, Moderate, Low-Moderate, or Low) for sensitivity and adaptive capacity. EcoAdapt assigned rankings for projected future climate exposure. Rankings for each component were then converted into scores (High-5, Moderate-High-4, Moderate-3, Low-Moderate-2, or Low-1), and the scores were averaged (mean) to generate an overall score. For example, scores for each element of habitat sensitivity were averaged to generate an overall habitat sensitivity score. Scores for exposure were weighted less than scores for sensitivity and adaptive capacity because the uncertainty about the magnitude and rate of future change is greater. Sensitivity, adaptive capacity, and exposure scores were combined into an overall vulnerability score calculated as:

**Vulnerability = [(Climate Exposure*0.5) x Sensitivity] - Adaptive Capacity**

Elements for each component of vulnerability were also assigned one of three confidence rankings (High, Moderate, or Low). Confidence rankings were converted into scores (High-3, Moderate-2, or Low-1) and the scores averaged (mean) to generate an overall confidence score. These approximate confidence levels were based on the Manomet Center for Conservation Sciences (2012) 3-category scale, which collapsed the 5-category scale developed by Moss and Schneider (2000) for the IPCC Third Assessment Report. The vulnerability assessment model applied here assesses the confidence associated with individual element rankings and, from these rankings, estimates the overall level of confidence for each component of vulnerability and then for overall vulnerability.

Stakeholders and decision-makers can consider the rankings and scores presented as measures of relative vulnerability and confidence to compare the level of vulnerability among the focal resources evaluated in this project. Elements that received lower confidence rankings indicate knowledge gaps that applied scientific research could help address.

### Vulnerability Assessment Model Elements

*Sensitivity & Exposure (Applies to Habitats, Species Groups, Species)*

- **Climate and Climate-Driven Factors:** e.g., air temperature, precipitation, freshwater temperature, soil moisture, snowpack, extreme events: drought, altered streamflows, etc.
- **Disturbance Regimes:** e.g., wildfire, flooding, drought, insect and disease outbreaks, wind
- **Future Climate Exposure:** e.g., consideration of projected future climate changes (e.g., temperature and precipitation) as well as climate-driven changes (e.g., altered fire regimes, altered water flow regimes, shifts in vegetation types)
- **Stressors Not Related to Climate:** e.g., tectonic and volcanic events; residential or commercial development; agriculture and/or aquaculture; roads, highways, trails; dams and water diversions; invasive and other problematic species; livestock grazing; fire suppression; timber harvest; mining; etc.

*Sensitivity & Exposure (Applies to Species Groups and Species)*

- **Dependencies:** e.g., dependencies on sensitive habitats, specific prey or forage species, and the timing of the appearance of these prey and forage species (concern for mismatch)

*Sensitivity & Exposure (Applies to Species ONLY)*

- **Life History:** e.g., species reproductive strategy, average length of time to reproductive maturity

*Adaptive Capacity (Applies to Habitats, Species Groups, Species)*

- **Extent, Integrity, and Continuity/Connectivity:** e.g., resources that are widespread vs. limited, structural and functional integrity (e.g., degraded or pristine) of a habitat or health and functional integrity of species (e.g., endangered), isolated vs. continuous distribution
- **Landscape Permeability:** e.g., barriers to dispersal and/or continuity (e.g., land-use conversion, energy production, roads, timber harvest, etc.)
- **Resistance and Recovery:** e.g., *resistance* refers to the stasis of a resource in the face of change, *recovery* refers to the ability to "bounce back" more quickly from the impact of stressors once they occur
- **Management Potential:** e.g., ability to alter the adaptive capacity and resilience of a resource to climatic and non-climate stressors (societal value, ability to alleviate impacts, capacity to cope with impacts)
- **Ecosystem Services:** e.g., provisioning, regulating, supporting, and/or cultural services that a resource produces for human well-being

*Adaptive Capacity (Applies to Habitats ONLY)*

- **Habitat Diversity:** e.g., diversity of physical/topographical characteristics, component native species and functional groups

*Adaptive Capacity (Applies to Species Groups, Species)*

- **Dispersal Ability**: i.e., ability of a species to shift its distribution across the landscape as the climate changes
- **Intraspecific/Life History Diversity:** e.g., life history diversity, genetic diversity, phenotypic and behavioral plasticity

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