WASHINGTON NATURAL HERITAGE PROGRAM

# Conservation Status of Whitebark Pine in Washington

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US Fish and Wildlife Service

Prepared by

Walter Fertig & Jake Kleinknecht

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WASHINGTON STATE DEPARTMENT OF NATURAL RESOURCES

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**ON THE COVER:** Whitebark pine (*Pinus albicaulis*) from Baldy Pass, Okanogan County, Washington.

Photographs by: Walter Fertig

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# Introduction

Whitebark pine (*Pinus albicaulis*) is a five-needled conifer with purple cones that disintegrate at maturity to release its large, edible, wingless seeds. It occurs at alpine treeline and in subalpine and upper montane forests in mountain ranges from northern British Columbia and northern Alberta to central California, northern Nevada, central Idaho, western Montana, and northwestern Wyoming (Ellenwood et al 2015, Kral 1993) (Figure 1). At treeline, whitebark pine often has a short, stunted, "krummholz" growth form due to exposure to strong winds. It is considered a keystone species because of its out-sized ecological significance (Tomback et al. 2001). Whitebark pine helps slow runoff from melting snow, retains soil, and provides cover and shelter for wildlife. Its nut-like seeds are rich in protein and a critical food source for grizzly bears (*Ursus arctos horribilis*) and Clark's nutcrackers (*Nucifraga columbiana*) (Nicholas 2018, Tomback et al. 2001).

In the past two decades, whitebark pine has declined by more than 50% across its range (Goeking and Izlar 2018). Mortality has occurred primarily due to the non-native fungal pathogen white pine blister rust (*Cronartium ribicola*) and infestations of mountain pine beetle (*Dendroctonus ponderosae*). White pine blister rust grows within the phloem tissue below the bark and can kill a tree by interrupting the flow of nutrients between needles and roots. Mountain pine beetle outbreaks are natural phenomena that are becoming more frequent as average winter temperatures have increased (Nicholas 2018). Holes drilled into bark by the beetles can serve as a point of entry for blister rust spores. Dead whitebark pine trees make stands more vulnerable to catastrophic wildfire (US Fish and Wildlife Service 2020). On-going climate change and fire suppression may also make the high elevation habitat of whitebark pine more suitable for lower elevation tree species, resulting in a shift in community composition (Arno and Hammerly 1984). Modeling of recent mortality and environmental stressors suggest that whitebark pine populations in western national parks are likely to decline an additional 25% in the next 100 years (Jules et al. 2020). The continued loss of whitebark pine populations will likely have negative impacts on rare and declining wildlife species, such as grizzly bears and Clark's nutcrackers (US Fish and Wildlife Service 2020). All of these stressors are likely to increase in severity in the future (Nicholas 2018).

Based on its pronounced downward trend and high threats, whitebark pine was petitioned for listing as Threatened or Endangered under the US Endangered Species Act in 2008 by the Natural Resources Defense Council. In 2011, the US Fish and Wildlife Service (USFWS) issued a finding that listing was "warranted but precluded" by higher conservation priorities, but that whitebark pine would become an official Candidate for listing (US Fish and Wildlife Service 2011). In December 2020, the Service published a notice that whitebark pine was being officially proposed for Threatened status and was accepting public comments on the action for 60 days. A final listing rule has not been published as of 18 August 2021, but is anticipated later this year or in early 2022.

In 2018, USFWS contracted with the Washington Natural Heritage Program (WNHP) to assign a conservation status rank for whitebark pine in Washington consistent with ranking and mapping procedures used in other states and provinces within the range of the species. Consistent methodology is important for multiple agencies (USFWS, US Forest Service [USFS], Bureau of

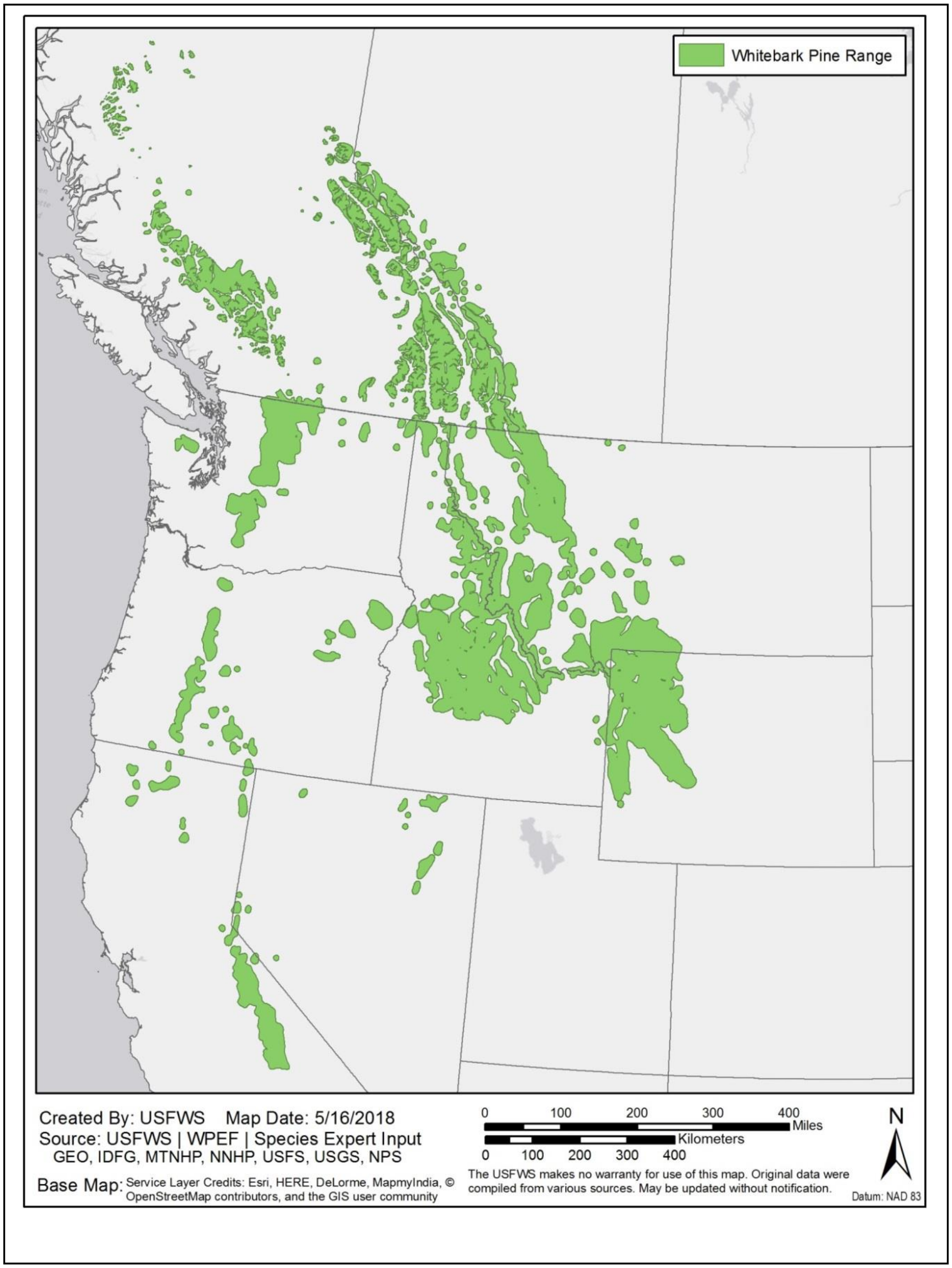


**Figure 1. Distribution of Whitebark pine in Washington and Northwestern North America.** From Nicholas (2018).

Land Management [BLM], National Park Service [NPS]) and programs (e.g., Sustainable Forestry Initiative certification) involved in whitebark pine management and conservation. In order to assign a conservation status rank for whitebark pine, we compiled information on its distribution, area of occupied habitat, number of biological populations ("element occurrences"), abundance, trends, and threats in the state. The following report summarizes the results of this project, including a method to model the potential distribution and occupied area of whitebark pine (Appendix A).

## Methods

Developing Consistent Element Occurrence and State Ranking Criteria

Each state or provincial program within the NatureServe network assigns Subnational Conservation Status ranks following similar criteria (NatureServe 2020a, 2020b), but differences frequently occur in how programs record locality data (as element occurrences, modeled distribution, or observation reports) or differentiate populations. Neither NatureServe nor WNHP have authority over other Natural Heritage network programs and how they manage and report data. NatureServe also does not currently have specific criteria for recognizing element occurrences in whitebark pine (Tomaino 2018). In the interest of identifying and applying consistent ranking methods, we sent a questionnaire to heritage botanists and ecologists in eight western states and provinces to better understand how they were ranking whitebark pine and storing locality data. The questions included:

1. Does your program maintain whitebark pine locality data as traditional element occurrences (EOs) or observations?
2. If your program uses EOs, are you using the default NatureServe element occurrence specifications?
3. Has your program modeled the potential distribution of whitebark pine?
4. Are your state conservation status ranks based on the NatureServe ranking calculator?

We used the results of this survey to define distance criteria to differentiate EOs in Washington and for guidance in assigning scores using the ranking calculator so that our state results would be comparable to those from across most of the heritage network.

Identifying Potential Element Occurrences in Washington

To identify potential element occurrences of whitebark pine in Washington, we first assembled georeferenced vegetation plot data from the US Forest Service (Smith 2002), Washington Department of Natural Resources (DNR) Forest Resource Inventory System (FRIS), and the National Park Service North Coast and Cascade Network (NCCN) Inventory and Monitoring Program (Table 1). Additional datasets were available from the Consortium of Pacific Northwest Herbaria (https://www.pnwherbaria.org/index.php), SEINet (https://swbiodiversity.org/seinet/) and iNaturalist (https://www.inaturalist.org/) websites, but we chose to exclude these due to

**Table 1. Ranking Factors and Sources for Deriving the State Conservation Rank (S Rank) of Whitebark Pine in Washington.**

| Ranking Factor | Information Sources | Comments |
|---|---|---|
| Range Extent | USFS *National Individual Tree Species Atlas* (Ellenwood et al. 2015); Nicholas (2018); Consortium of Pacific Northwest Herbaria (pnwherbaria.org) | Location data plotted in the Geospatial Conservation Assessment Tool (GeoCat) developed by Kew Gardens (geocat.kew.org) to calculate area of minimum-sized polygon capturing all location points. |
| Area of Occupancy | USFS Forest Inventory and Analysis (FIA) data (Smith 2002); WA DNR Forest Resource Inventory System (FRIS) data; NPS North Coast and Cascades Inventory & Monitoring Network (NCCN) vegetation plot data | Presence and absence locality data were intersected in GIS with surface geology, soils, land cover, climate (precipitation and temperature), and 10m resolution elevation, slope, and aspect data to model the potential habitat and distribution of whitebark pine in Washington using Random Forest methods (Appendix A). The sum of the potential area was used to calculate the approximate number of 2 x 2 km grids occupied by the species in Washington. |
| Number of Occurrences | Potential distribution model for whitebark pine (Appendix A) intersected by presence points (cited above) | Calculated using modified element occurrence separation distance criteria in accordance with NatureServe (2020a) for wide-ranging plant species |
| Population Size | Estimated whitebark pine density and abundance data for mature trees at Mount Rainier National Park (Cottone and Ettl 2001); Estimated area of occupancy derived from habitat modeling (Appendix A) | Population size extrapolated from average density/ha in Mount Rainier NP to estimated area of range in entire state, divided by estimated mortality rate (50%) in recent years (Jules et al. 2020). |
| Percent of Area Occupied with Good Viability | Cottone and Ettl (2001); Jules et al. (2020); Rochefort et al. (2018) | Literature review |
| Environmental Specificity | Nicholas (2018); Tomback et al. (2001) | Literature review |
| Overall Threat Impact | Nicholas (2018); Tomaino (2018); Tomback et al. (2001) | Literature review |
| Short Term Trend | Cottone and Ettl (2001); Goeking and Izlar (2018); Jules et al. (2020); Nicholas (2018); Rochefort et al. (2018) | Literature review |
| Long Term Trend | Nicholas (2018) | Literature review |

problems of insufficient spatial accuracy or questions over identification. We plotted presence points from the assembled dataset to create a map depicting the distribution of whitebark pine in Washington (Figure 2).

We then used presence and absence points from our assembled dataset to model the potential habitat of whitebark pine using Random Forest methodology (Breiman 2001, Breiman et al. 1984) (see Appendix A for more complete details). Environmental predictors in the model (Table 6, Appendix A) included soil, geology, local relief, land cover (vegetation), tree canopy, and 25 precipitation and temperature variables (AdaptWest 2015). We ran 7 iterations of the model using 1, 2, 5, 10, 25, 50, or 100 distinct "trees" (separate model runs using a different set of randomly selected presence and absence points) to identify the simplest model that reduced sufficient misclassification error without over-fitting the data.

The selected model was intersected by known presence points to create a map depicting clusters of whitebark pine populations and areas of predicted habitat (Figure 2). We used a 5 km separation distance (derived from input from other state and provincial heritage programs; see Discussion section below) to then aggregate the presence points into potential element

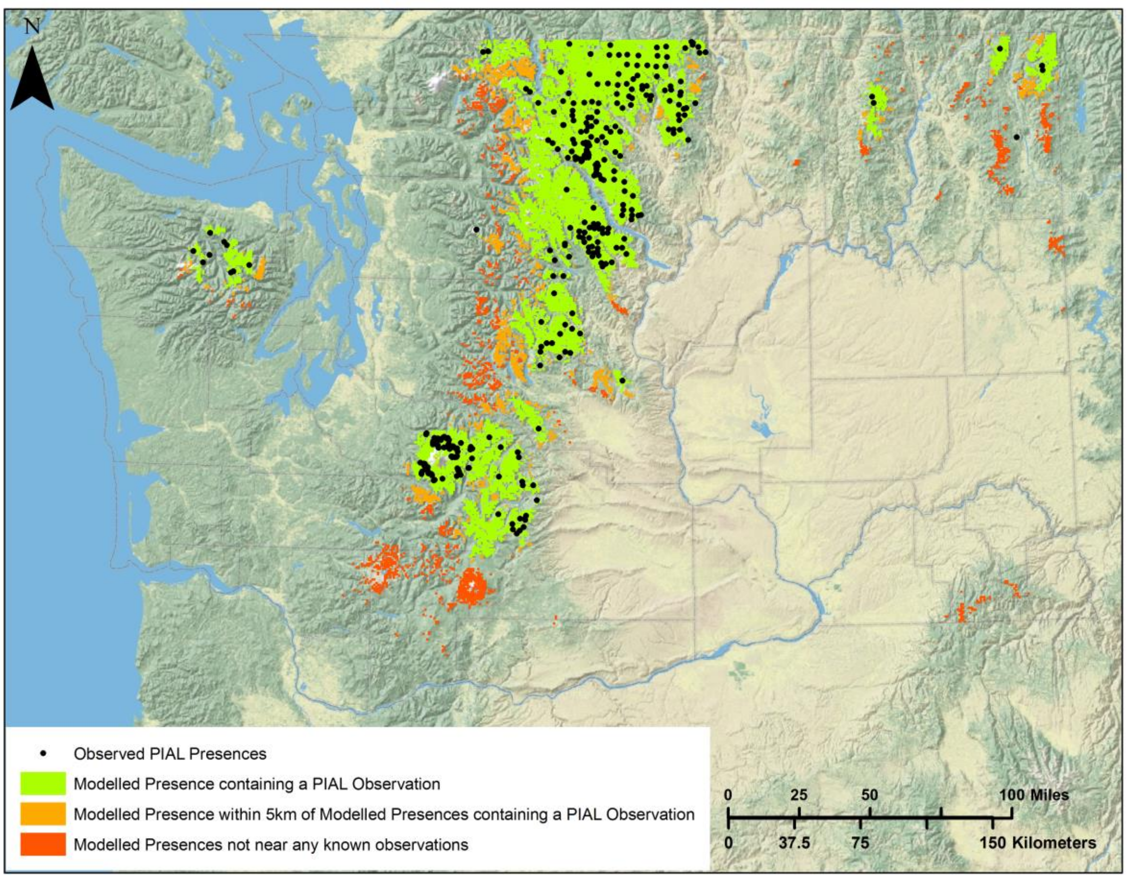


**Figure 2. Known and Modeled Distribution of Whitebark Pine in Washington.**

occurrences (Figure 3). The EOs are metapopulations consisting of 1 to 228 separate, point-based "source features" or subpopulations. Modeled areas connect these individual source features as potential (but unconfirmed) habitat and are not themselves the EO.

## Assigning State Rank

NatureServe, the umbrella network of state and provincial natural heritage programs, has specific guidance for ranking the global (G) and subnational (S) status of plant and animal species and ecological communities (Faber-Langendoen et al. 2012) on a scale of 1 (critically imperiled) to 5 (secure). Network programs utilize an excel spreadsheet-based tool (ranking calculator) to

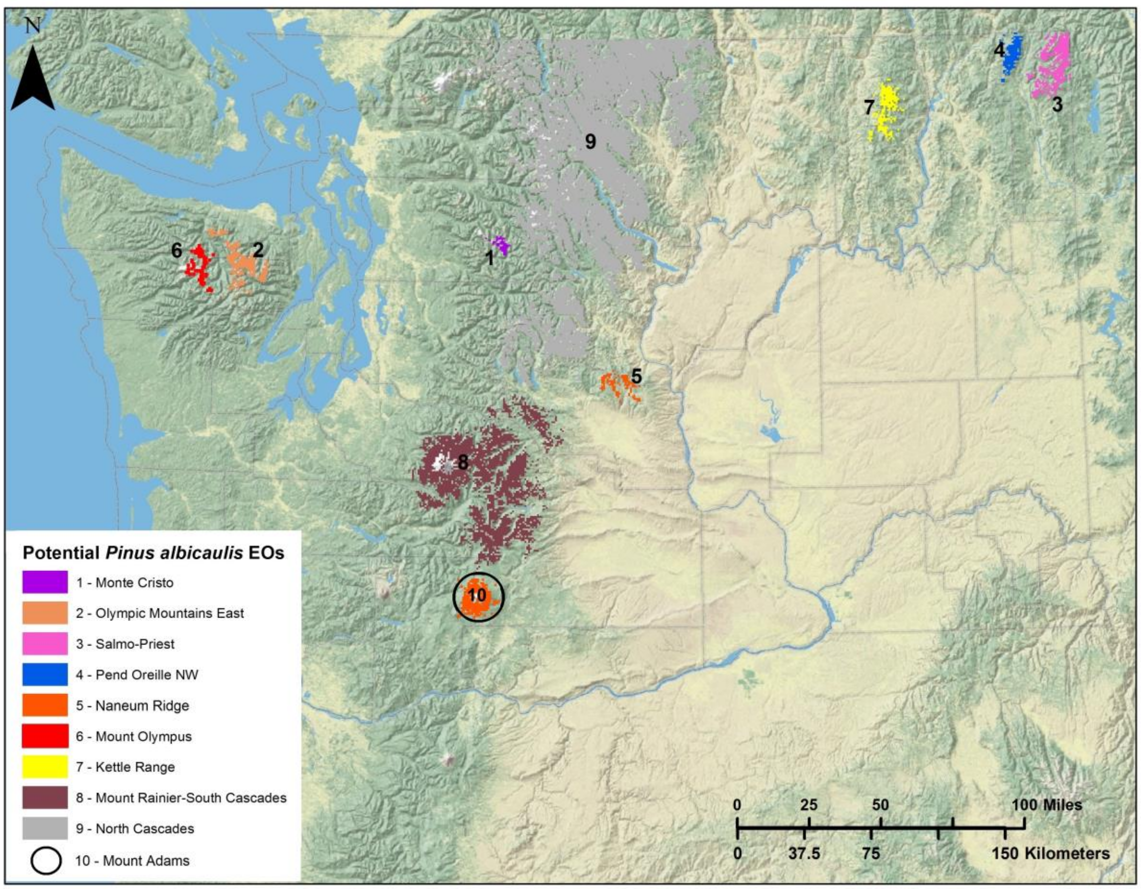


**Figure 3. Potential Element Occurrences of Whitebark Pine in Washington**. Occurrences are based on modeled distribution of known presence points (see Figure 2 and Appendix A) but excludes areas of predicted habitat that are not within 5 km of confirmed presence points. EO 10 (Mount Adams) is based on confirmed herbarium records rather than plot data.

assign G and S ranks based on range extent, area of occupancy, number of occurrences, population size, percentage of area occupied with good viability, environmental specificity, threats, and short and long-term trends. Each of these factors is scored using a picklist of qualitative to semi-quantitative values based on a review of literature or expert knowledge. A composite score is then derived based on a weighted sum of the individual scores and translated to a G or S rank (Faber-Langendoen et al. 2012).

We derived data for ranking the conservation status of whitebark pine in Washington from a variety of sources, summarized in Table 1. Scores for each ranking factor were based on standardized values derived by NatureServe (Table 2) (Faber-Langendoen et al. 2012). Range extent was calculated using locality data entered into the Geospatial Conservation Assessment Tool (GeoCat) developed by Kew Gardens (geocat.kew.org) to derive the area of the smallest polygon needed to encompass all mapped points. Area of occupancy was derived from modeling the potential habitat of whitebark pine in the state using Random Forest techniques (Appendix A). The sum of the potential area identified by the model was used to calculate the number of 2 x 2 km grids occupied by the species in Washington. Number of occurrences was similarly derived from modeled habitat intersected by known presence points and using revised NatureServe (2020a) criteria for defining separation distances. Population size of mature trees across the state was extrapolated from average density data per hectare from Mount Rainier National Park (Cottone and Ettl 2001). This estimate was then reduced by 50% to represent the documented decline of whitebark pine in recent years (Jules et al. 2020). Other factors, including area of occupied habitat with good viability, environmental specificity, threats, and trends, were scored based on a review of recent literature (Cottone and Ettl 2001, Jules et al. 2020, Nicholas 2018, Rochefort et al. 2018, Tomaino 2018, and Tomback et al. 2001).

# Results

Defining Element Occurrences in Washington and Other States and Provinces

Element occurrences (EOs) are defined by NatureServe (2002) as the "…area of land and/or water in which a species or natural community is, or was, present. An EO should have practical conservation value for the element as evidenced by potential continued (or historical) presence and/or regular recurrence at a given location. For species elements, the EO often corresponds with the local population, but when appropriate may be a portion of a population or a group of nearby populations (e.g. metapopulation)". NatureServe has general guidelines for differentiating EOs on the basis of physical barriers (canyons, mountain tops) or unsuitable habitats (including human-induced habitat fragmentation) that interfere with gene flow through pollen or seed exchange. Minimum separation distances are also used to differentiate EOs in landscapes where obvious natural or anthropogenic barriers are not readily discernable. Some plant taxa have species-specific EO specifications, but if these are not available the default separation distance is 1-2 km (NatureServe 2002). Recently, NatureServe (2020a) adopted new EO criteria for plants occurring as widely scattered individuals over large areas with few physical barriers that allow for larger separation distances to be used.

**Table 2. NatureServe Rank Calculator Scores.** From Faber-Langendoen et al. (2012).

| Ranking Factor | Score | Score Value |
|---|---|---|
| Range Extent | Z | Zero (no occurrences believed extant |
| | A | <100 sq km (< ca 40 sq miles) |
| | B | 100-250 sq km (ca 40-100 sq miles) |
| | C | 250-1,000 sq km (ca 100-400 sq miles) |
| | D | 1,000-5,000 sq km (ca 400-2,000 sq miles) |
| | E | 5,000-20,000 sq km (ca 2,000-8,000 sq miles) |
| | F | 20,000-200,000 sq km (ca 8,000-80,000 sq miles) |
| | G | 200,000-2,500,000 sq km (ca 80,000-1,000,000 sq miles) |
| | H | >2,500,000 sg km (> ca 1,000,000 sq miles) |
| | U | Unknown |
| Area of Occupancy | Z | Zero (no occurrences believed extant, presumed extirpated) |
| | A | 1 4-sq km grid cell |
| | B | 2 4-sq km grid cells |
| | C | 3-5 4-sq km grid cells |
| | D | 6-25 4-sq km grid cells |
| | E | 26-125 4-sq km grid cells |
| | F | 126-500 4-sq km grid cells |
| | G | 501-2,500 4-sq km grid cells |
| | H | 2,501-12,500 4-sq km grid cells |
| | I | >12,500 4-sq km grid cells |
| | U | Unknown |
| Number of Occurrences | Z | Zero (0, presumed extinct) |
| | A | 1-5 |
| | B | 6-20 |
| | C | 21-80 |
| | D | 81-300 |
| | E | >300 |
| | U | Unknown |
| Population Size | Z | Zero (no occurrences believed extant, presumed extirpated) |
| | A | 1-50 individuals |
| | B | 50-250 individuals |
| | C | 250-1,000 individuals |
| | D | 1,000-2,500 individuals |
| | E | 2,500-10,000 individuals |
| | F | 10,000-100,000 individuals |
| | G | 100,000-1,000,000 individuals |
| | H | >1,000,000 individuals |
| | U | Unknown |
| Percent of Area Occupied with Good Viability | A | No area with excellent or good viability or integrity |
| | B | Very small percent (<5%) of area with excellent or good viability |
| | C | Small percent (5-10%) of area with excellent or good viability |
| | D | Moderate percent (11-20%) of area with excellent or good viability |
| | E | Good percent (21-40%) of area with excellent or good viability |
| | F | Excellent percent (>40%) of area with excellent or good viability |
| | U | Unknown |
| Environmental Specificity | A | Very Narrow. Specialist or community with key requirements scarce |
| | B | Narrow. Specialist or community with key requirements common |
| | C | Moderate. Generalist or community with some key requirements scarce |
| | D | Broad. Generalist or community with all key requirements common |
| | U | Unknown |

| Ranking Factor | Score | Score Value |
|---|---|---|
| Overall Threat Impact | A | Very High |
| | B | High |
| | C | Medium |
| | D | Low |
| | U | Unknown |
| Short Term Trend (100 years) And Long Term Trend (>100 years) | A | Decline of >90% |
| | B | Decline of 80-90% |
| | C | Decline of 70-80% |
| | D | Decline of 50-70% |
| | E | Decline of 30-50% |
| | F | Decline of 10-30% |
| | G | Relatively Stable (< or = 10% change) |
| | H | Increase of 10-25% |
| | I | Increase of >25% |
| | U | Unknown |
| Calculated Rank | S1 | Critically Imperiled -- at very high risk of extirpation due to very restricted range, very few occurrences, very steep declines, very severe threats, or other factors |
| | S2 | Imperiled -- at high risk of extirpation due to restricted range, few occurrences, steep declines, severe threats, or other factors |
| | S3 | Vulnerable -- at moderate risk of extirpation due to a fairly restricted range, relatively few occurrences, recent and widespread declines, threats, or other factors |
| | S4 | Apparently Secure -- at fairly low risk of extirpation due to an extensive range or many occurrences, but with possible cause for some concern as a result of local recent declines, threats, or other factors |
| | S5 | Secure -- at very low risk of extirpation due to a very extensive range, abundant occurrences, and little to no concern from decline or threats |
| | SH | Historical – known only from historical reports (not observed for 40 or more years) but still with some hope of rediscovery |
| | SX | Presumed Extirpated – known only from historical reports (not observed for 40 or more years) despite extensive searches and virtually no likelihood of rediscovery |
| | SU | Unrankable – lack of information or with substantially conflicting information |
| | SNR | Not Ranked – rank not assigned yet |
| | ? | Questionable – questions exist about the assigned rank |

There are currently no rangewide EO specifications for whitebark pine, and so the default separation distance of 1-2 km is used in NatureServe Explorer (Tomaino 2018). The 1-2 km separation distance creates several practical problems for defining natural populations. First, whitebark pine tends to occur sparsely over large geographic areas that often have few barriers to restrict gene flow. Gaps between specimen collections, observations, or plot samples of more than 1 km tend to reflect sampling intensity or bias, rather than interruptions in actual distribution (Miller 2012). Using a 1-2 km distance can result in numerous EOs occurring within the same valley or mountain slope (Marge Meijer, personal communication, 2021). Second, both the wind-borne pollen and edible seeds of whitebark pine can be readily dispersed over distances greater than 1-2 km. Clark's nutcracker is the primary dispersal vector for whitebark pine seeds and can transport them up to 12 km, though average distances range from 2-5 km (Miller 2012; Richardson et al. 2002; Tomback 2001). Lastly, strict adherence to the 1 km separation distance can result in extremely high numbers of occurrences (often in the hundreds), challenging the ability of heritage programs to enter and maintain EO data (Kristi Lazar and Jenifer Penny, personal communication, 2021).

Of the nine states and provinces within the range of whitebark pine, only Idaho currently uses the default separation distance of 1-2 km to define whitebark pine EOs (Table 3). Other programs have adopted minimum separation distances of 3 km (Nevada), 2-5 km (British Columbia), or 5 km (Alberta) based on travel distances of Clark's nutcrackers and habitat discontinuities (Miller 2012). The remaining states either do not track whitebark pine (California), do not record data as EOs (Oregon and Wyoming), or record population data as observations rather than EOs (Montana) (Table 3).

In Washington, we have chosen to follow the example of the Alberta and British Columbia heritage programs in using a 5 km minimum separation distance as a first cut for organizing our observation records into potential EOs. These extensive EOs (called "master occurrences" in Alberta) consist of over 200 subpopulations that are often clustered or connected by areas of potential habitat. With better survey information, or more refined EO criteria, several of the larger master EOs could be divided into smaller occurrences.

EO specifications can directly affect the number of whitebark pine populations recognized in a state or province. When it changed the separation distance from 2 to 5 km, the number of potential EOs in Alberta dropped from over 700 to a more manageable number of 142 (Table 3). In Nevada, the number of EOs is presently 25, but would become 7 if larger separation distances were applied. Likewise, in Idaho, more than 300 EOs would be recognized using the 1-2 km distance, but these would become 20-80 EOs with a 5 km separation distance (Table 3). For all states that have completed ranking, reducing the number of recognized EOs has not changed the projected S rank based on the NatureServe ranking calculator, or earlier "rank by inspection" methods widely used in the heritage network in the 1990s (NatureServe 2002).

California tracks whitebark pine only as a community element, rather than at the species level (Table 3). Alberta and Montana have used their EO and observation datasets to model the potential distribution of whitebark pine. In the case of Montana, the modeled output is their primary means of presenting state distribution data to the public (Table 3).

**Table 3. Element Occurrence Criteria and Status of Whitebark Pine Across its Range**

| State/ Province | S rank | # of element occurrences/ observations | Distance criteria | Comments |
|---|---|---|---|---|
| Alberta | S3 | 142 EOs | 5 km | In 2012 separation distance changed from 2 to 5 km. 780 source features identified (Marge Meijer, AB Conservation Information Management System, personal comm., Jan. 2021). |
| British Columbia | S2S3 | 137 EOs | 2-5 km | Use 2 km distance except where there is continuous high quality habitat and ongoing viable seed production (then use 5 km) (Miller 2012) – Jenifer Penny (BC Conservation Data Centre, personal comm., Jan. 2021). |
| California | SNR | Not tracked as a species, but tracked as *Pinus albicaulis* Alliance (S4) | none | Not currently tracked in California as a species (Kristi Lazar, CA Natural Diversity Database, personal comm., January 2021). Tracked at the Alliance level by the CNDD ecology program, but S rank may need to be revised to S3 (Rachelle Boule, CA Department of Fish and Wildlife, personal comm., Jan 2021). |
| Idaho | S3 | >300 EOs | 1-2 km | Using a 5 km distance, the number of ID populations would be closer to 20-80 (Lynn Kinter, ID Conservation Data Center, personal comm., Feb. 2021). |
| Montana | S3 | 6,084 observations | Not defined | EORs not defined, but observations used for modeling distribution in Montana (http://fieldguide.mt.gov/speciesDetail.aspx?elcode=PGPIN04010) (Andrea Pipp, MT Natural Heritage Program, personal comm., Jan. 2021). |
| Nevada | S3 | 25 EOs | 3 km | NV populations are restricted to 7 mountain ranges; if larger distance criteria were used only 7 EORs would be recognized (Janel Johnson, NV Division of Natural Heritage, personal comm. Jan. 2021). |
| Oregon | S3? | Not available | Not defined | Lindsey Wise, personal comm. 2021 |
| Washington | S3 | 9 EOs, ca 1000 observations | 5 km | Previously ranked SNR. |
| Wyoming | S3 | Not available | Not defined | S rank recently revised from S4 to S3. 188 specimens posted on Rocky Mountain Herbarium website – Bonnie Heidel (WY Natural Diversity Database, personal comm., Jan. 2021). |

State Rank and Status of Whitebark Pine in Washington

Using the NatureServe rank calculator tool, we derived a state rank of S3 for whitebark pine in Washington (Table 4), indicating that it is "vulnerable" and at moderate risk of extirpation due to its fairly restricted range, relatively few occurrences, recent and widespread decline, and high threats (Faber-Langendoen et al. 2012). Whitebark pine was added to the Washington state species of conservation concern list in 2021 and assigned a state status of Sensitive, based on its complete heritage rank of G3G4/S3 (Fertig 2021). Species classified as state Sensitive are considered vulnerable or declining and could become state Threatened or Endangered in the future.

Scores assigned to the individual ranking factors in the NatureServe rank calculator are summarized in Table 4 and discussed further in the sections below.

*Range Extent*

Range extent of whitebark pine in Washington was estimated at 79,000 km$^2$ based on herbarium records and range maps (Table 1, Figure 1) using the least area polygon connecting all mapped localities assigned by the GeoCat tool. This translates as a score of F (20,000-200,000 km$^2$) based on the scoring criteria of Faber-Langendoen et al. (2012) (Tables 2, 4). The actual area inhabited by this species is probably at least one-quarter less due to the inclusion of unsuitable habitat within the least area polygon, such as the area connecting the disjunct Olympic Mountains from the Cascade Range, or isolated peaks in northeastern Washington (Figure 1). A score of F is the third-highest possible score in the NatureServe system (Table 2).

*Area of Occupancy*

Although rangewide estimates are available (Nicholas 2018), there is no current estimate of the area of occupied habitat of whitebark pine in Washington. We used habitat modeling (Appendix A) based on known presence and absence locations of whitebark pine to calculate the area of occupancy within the state at 12,712 km$^2$ (Figure 2). The modeled area covers 3,178 4-km$^2$ grid cells. Based on NatureServe ranking criteria, this number of grid cells corresponds to a score of H, which is the second-highest possible score (Tables 2, 4). As with range extent, area of occupancy can be an over-estimate if sites of potential but unutilized habitat are included (Gaston and Fuller 2009). Both are useful proxies, however, for assessing overall distribution of a species and reduced risk from stochastic events (higher redundancy, *sensu* Nicholas 2018).

*Number of Occurrences*

For the purposes of ranking, we defined element occurrences of whitebark pine in Washington as clusters of verified (present) observation records separated from other records by less than 5 km of potential habitat. This definition follows the guidance developed for British Columbia (Miller 2011) which has been adopted by several other western heritage programs. Based on these criteria, we recognize 10 potential element occurrences for whitebark pine in Washington (Figure 3, Table 5), ranging in size from 11,000 to 2.1 million acres in extant. Ultimately, the larger occurrences may need to be subdivided based on local criteria, such as specific mountains or peaks. We are not recognizing occurrences for areas of predicted suitable habitat identified by

**Table 4. NatureServe Rank Calculator Form for Whitebark Pine in Washington.**

| Ranking Factor | Score | Score Value | Comments |
|---|---|---|---|
| Range Extent | F | F = 20,000-200,000 $km^2$ (8,000-80,000 sq mi) | Range extent estimated at 79,000 $km^2$ based on GeoCat tool |
| Area of Occupancy | H | H = 2,501-12,500 4 $km^2$ grid cells | Washington distribution estimated at 3,178 4 $km^2$ grid cells based on habitat modeling (12,712 $km^2$) |
| Number of Occurrences | B | B = 6-20 | 10 potential element occurrences recognized based on habitat modeling using distance criteria of 5 km. |
| Population Size | H | H = >1,000,000 individuals | Based on population of 21,764 mature trees in 1,431 ha in Mt. Rainier NP (15.2 plants/ha), and recent rates of mortality (50%) statewide abundance is probably 1 million to 9 million mature trees |
| Percent of Area Occupied with Good Viability | E | E = 21-40% of area with excellent or good viability | Extensive areas of habitat are found in designated Wilderness Areas, but these sites are still vulnerable to current and future threats related to climate change |
| Environmental Specificity | B | B = Narrow. Specialist or community with key requirements common | Mostly found at treeline on rocky, wind-exposed slope; also found in upper subalpine but may be at a competitive disadvantage compared to other conifer species |
| Overall Threat Impact | AB | AB = High to very high | Significant threats from white pine blister rust, mountain pine beetles, climate change, increased wild fire, and community succession |
| Short Term Trend | E | E = decline of 30-50% | Reported decline of 50% since 2000 rangewide; populations have been declining from white pine blister rust since it appeared in 1910. |
| Long Term Trend | U | U = Unknown | Probably stable, but not well-documented. |
| Calculated Rank | S3 | S3 = Vulnerable (at moderate risk of extirpation due to a fairly restricted range, relatively few occurrences, recent and widespread declines, threats, or other factors | Despite a wide range in Washington, there has been a steep decline in abundance in the last 20 years and this is likely to continue in the near future due to high threats |
| Assigned Rank | S3 | | |
| Ranking Author | Walter Fertig | | |
| Ranking Date | June 2021 | | |

**Table 5. Whitebark pine occurrences in Washington.**

| EO # | EO Name | Estimated Acres | Number of Modeled Presence Points Contained | Counties | Latitude centroid | Longitude centroid |
|---|---|---|---|---|---|---|
| 1 | Monte Cristo | 11,121 | 1 | Snohomish | 47.96711191 | -121.3585521 |
| 2 | Olympic Mountains East | 69,198 | 6 | Clallam, Jefferson | 47.84661785 | -123.3077731 |
| 3 | Salmo-Priest | 86,746 | 2 | Pend Oreille | 48.83123642 | -117.1603811 |
| 4 | Pend Oreille NW | 33,115 | 1 | Pend Oreille, Stevens | 48.88972704 | -117.4756559 |
| 5 | Naneum Ridge | 25,949 | 1 | Chelan, Kittitas | 47.26338193 | -120.4769846 |
| 6 | Mount Olympus | 18,040 | 3 | Clallam, Jefferson | 47.82113248 | -123.6116912 |
| 7 | Kettle Range | 49,181 | 2 | Ferry | 48.63565837 | -118.4446978 |
| 8 | Mount Rainier-South Cascades | 594,125 | 85 | King, Kittitas, Lewis, Pierce, Skamania, Yakima | 46.78775511 | -121.4475676 |
| 9 | North Cascades | 2,170,813 | 228 | Chelan, King, Kittitas, Okanogan, Skagit, Snohomish, Whatcom | 48.39178665 | -120.6902798 |
| 10 | Mount Adams | 83,030 | 0* | Skamania, Yakima | 46.2340 | -121.5247 |
| Total | | 3,141,318 | 329 | | | |

*Known from herbarium and iNaturalist records (plot data not available)

our modeling that do not have any known presence points (plot data, herbarium vouchers, or iNaturalist photo observations), such as the Blue Mountains of southeast Washington (Figures 2, 3). The number of occurrences we recognize translates as a B score using the NatureServe rank calculator (Tables 2, 4). Using NatureServe's default separation distance of 1-2 km (Tomaino 2018), the number of whitebark pine occurrences in Washington would be more than 200, which creates significant logistical challenges for data management.

*Population Size*

There is currently no statewide estimate of the abundance of whitebark pine in Washington (Nicholas 2018). Population counts are difficult due to the wide range of the species, its remote habitat, and the challenge of detecting saplings and seedlings. Cottone and Ettl (2001) estimated the number of adult whitebark pine trees in Mount Rainier National Park using aerial photography and 67 randomly located plots. They recorded 21,764 adults in 1,431 ha or 15.2 adults per hectare. Extrapolating from this figure to the whole state (based on our modeled estimate of 3,141,318 acres or 1,271,246 ha of predicted habitat, Table 5), we estimate a potential population of 19,323,000 adult plants. Based on projections of a 50% decline of mature adults over the past two decades (Jules et al. 2020), the actual number of surviving mature whitebark pines in Washington is likely closer to 1,000,000 to 9,000,000. In the NatureServe ranking calculator, this translates to the maximum score of H (>1,000,000) (Table 4).

*Percent of Area Occupied with Good Viability*

About 96% of the known and predicted habitat of whitebark pine in Washington is found in designated wilderness areas or national parks (Table 4, EOs 1-3, 6, and 8-10). Historically, these areas have been largely protected from direct impacts by humans (such as habitat conversion, logging, or crop agriculture) due to their remoteness, short growing season, and harsh winter climate. In the past several decades, however, whitebark stands across its range have become increasingly vulnerable to impacts from white pine blister rust, mountain pine beetle, wildfire, succession, and climate change (Tomback et al. 2001). Declines of 21-44% have been observed in protected, high elevation populations in Washington (Jules et al. 2020; Rochefort et al. 2018). Rangewide, whitebark mortality is over 50% (Goeking and Fuller 2009). Based on these estimates, we rank the percentage of area in Washington with good viability for whitebark pine to be between 21-40% (Tables 2, 4).

*Environmental Specificity*

In Washington, whitebark pine is found primarily at upper tree line in subalpine areas of the higher mountains of the state (Franklin and Dyrness 1973). Most populations occur in the Northern Rocky Mountain Subalpine Woodland and Parkland ecological system (Rocchio and Crawford 2015), where whitebark pine is dominant or co-dominant with subalpine fir (*Abies lasiocarpa*), subalpine larch (*Larix lyallii*), or occasionally Engelmann spruce (*Picea engelmannii*) in open woodlands or stunted tree clumps interspersed with herb or dwarf-shrub-dominated vegetation. This ecological system has a relatively small geographic distribution and is mostly restricted to drier sites or early successional conditions at treeline (Arno 2001; Franklin and Dyrness 1973). Less frequently, whitebark pine is a minor component of the North Pacific Mountain Hemlock Forest ecological system in cold, snowy areas on the windward side of the Cascade Range or the Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland ecological system in the mountains of northeast Washington (Rocchio and Crawford 2015). Whitebark pine also has a specialized relationship with Clark's nutcrackers for seed dispersal (Tomback 2001). For these reasons, we rank whitebark pine as a narrow specialist using the NatureServe ranking calculator (Tables 2, 4).

*Overall Threat Impact*

The most significant threat to whitebark pine in Washington is mortality from the introduced pathogen white pine blister rust (Rochefort et al. 2018). Additional threats include impacts from mountain pine beetles, increased wildfire in dead stands, fire suppression favoring competition from more shade tolerant conifers, warmer average winter temperatures and changes in snowpack due to climate change, and combinations of these factors (Goeking and Izlar 2018; Nicholas 2018; Tomback et al. 2001; US Fish and Wildlife Service 2020). We ranked threats to whitebark pine as high to very high (AB) (Table 4).

*Short Term Trend*

In Washington, whitebark pine has been declining for nearly 100 years, following the introduction of white pine blister rust in Mount Rainier National Park in the 1920s (Cottone and Ettl 2001; Rochefort et al. 2018). From 2004 to 2016, mortality of whitebark pine has increased from 7 to 21% in the North Cascades National Park Service Complex (North Cascades NP and adjacent NPS-managed lands) and from 38 to 44% in Mount Rainier National Park (Rochefort et al. 2018). Rangewide, the percentage of dead whitebark pine trees has increased from less than 25% in the early 1990s to 51% in 2016 (Goeking and Izlar 2018). In surviving stands, the size-class distribution has become skewed towards smaller diameter trees (Keane et al. 2012; Rochefort et al. 2018). Due to its decline of 30-50%, we scored whitebark pine as "E" using the NatureServe calculator (tables 2, 4).

*Long Term Trend*

Long term (>100 years) trends of whitebark pine are poorly known in Washington, and so we scored this factor as U or "unknown" (Tables 2, 4). The species has probably increased since the end of the Pleistocene, as larger areas of suitable habitat became available following the retreat of mountain glaciers in the state. Populations are presumed to be stable during the period of first European settlement in Washington, but began to decline following the introduction of white pine blister rust in North America in 1910 (Nicholas 2018).

<u>Element Occurrences of Whitebark pine in Washington</u>

Based on separation distance criteria of 5 km, we recognize 10 potential EOs of whitebark pine in Washington (Figure 3, Table 5). Each of these is briefly summarized below:

**EO 1. Monte Cristo** (Figure 4, Table 5)
<u>Location</u>: North Cascades Range, vicinity of Big Four Mountain and Morning Star Peak and adjacent high peaks near former mining town of Monte Cristo, south of Silverton and the Mountain Loop Highway.
<u>Ownership/Management</u>: Morning Star NRCA? Henry M Jackson Wilderness Area, Mount Baker Snoqualmie National Forest, Wild Sky Wilderness Area?
<u>First/Last Year Observed</u>: 1983/1995.
<u>Abundance</u>: Not known, but presumed uncommon.
<u>Comments</u>: Known from one plot sample in vicinity of Big Four Mountain, with additional potential habitat identified by modeling in the mountains near Monte Cristo and in the Morning Star Natural Resource Conservation Area.

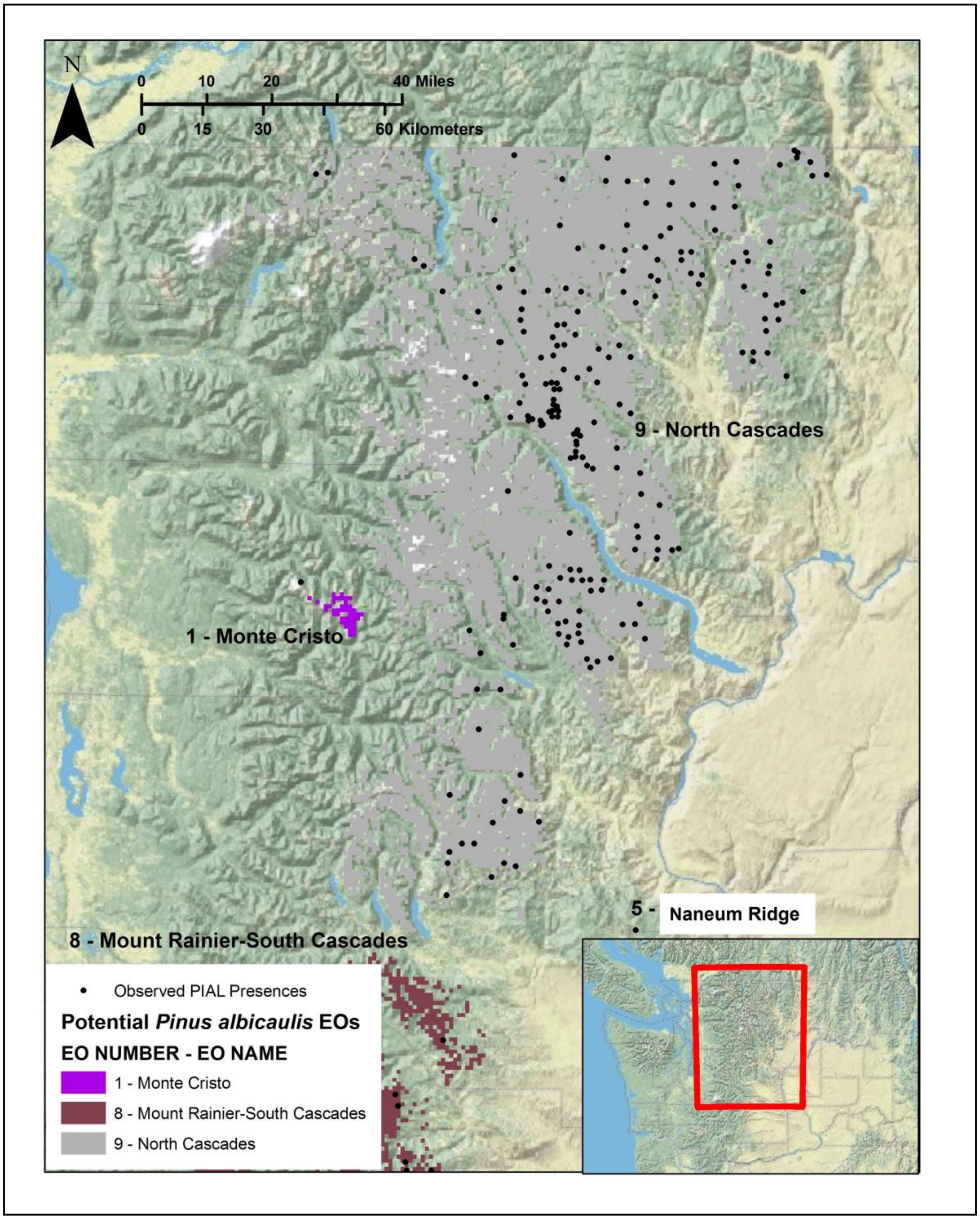


**Figure 4. Monte Cristo (EO 1) and North Cascades (EO 9) Occurrences of Whitebark Pine in Washington.**

**EO 2. Olympic Mountains East** (Figure 5, Table 5)
Location: East side of the Olympic Range including Hurricane Ridge, Obstruction Peak, Mount Townsend, Buckhorn Mountain, Marmot Pass, and Constance Pass.
Ownership/Management: Buckhorn Wilderness, Olympic National Forest, Olympic National Park
First/Last Year Observed: 1938/2021
Abundance: Not known, but probably uncommon.
Comments: Known from at least 6 plots, 2 herbarium records, and 5-8 iNaturalist records (some of which may be *Pinus monticola*). This EO could be subdivided into 2-4 occurrences, though most are connected by extensive areas of under-surveyed habitat.

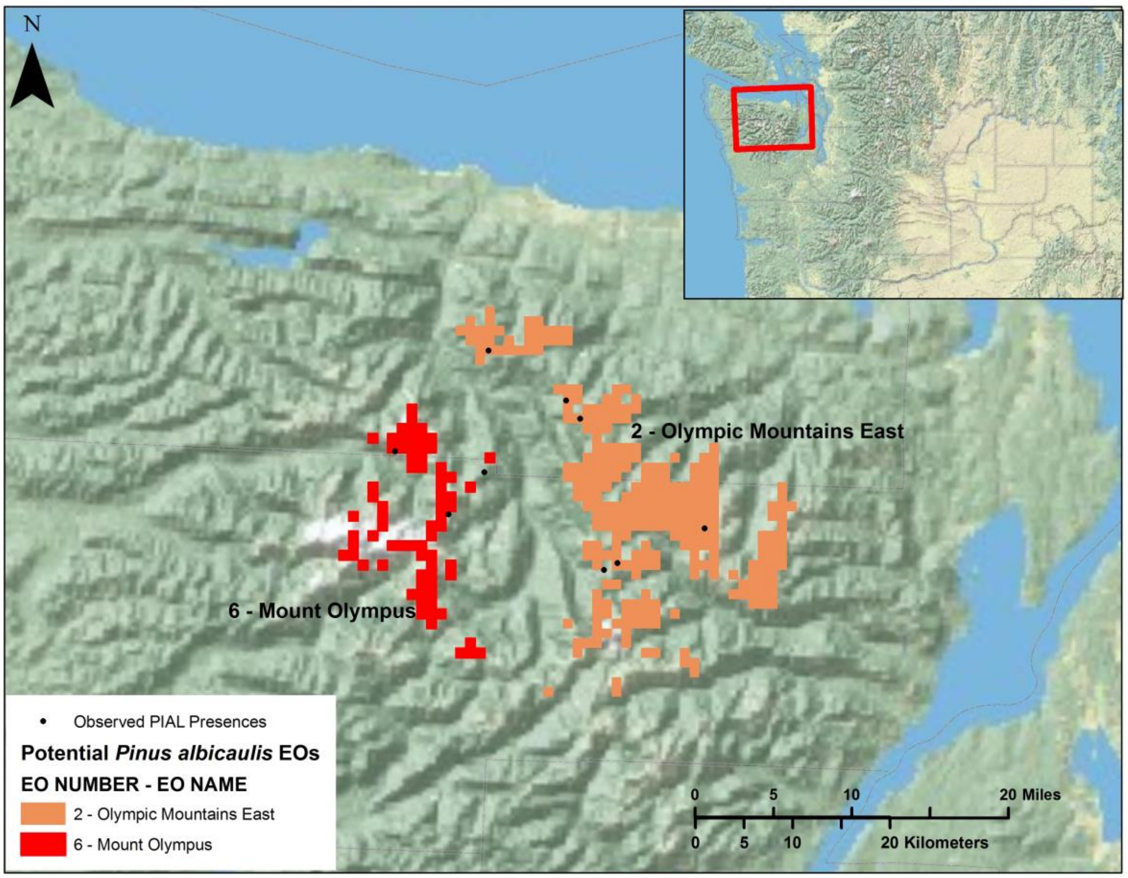


**Figure 5. Mount Olympus (EO 6) and Olympic Mountains East (EO 2) Occurrences of Whitebark Pine in Washington.**

**EO 3. Salmo-Priest** (Figure 6, Table 5)
Location: Seilkirk Range, at Salmo Mountain and Crowell Ridge.
Ownership/Management: Colville National Forest, Kaniksu National Forest?, Salmo Priest Wilderness Area
First/Last Year Observed: 1993/2019
Abundance: Not known, but presumed to be uncommon. Transect data from Salmo Mountain in 2004-05 notes 38 trees in one 262 meter transect with 21.1% mortality and 23.3% of surviving trees with white pine blister rust (Shoal and Aubry 2006). In the same study, 67 trees were observed in a 50 meter transect on Crowell Ridge with 32.8% mortality from blister rust.
Comments: Known from 2 USFS plots from Round Top Mountain area and herbarium collections at Salmo Mountain. Extensive areas of potential and under-surveyed habitat occur throughout the range. A disjunct report from South Baldy is based on an iNaturalist record that needs confirmation (https://www.inaturalist.org/observations/3282426) and could represent a separate EO.

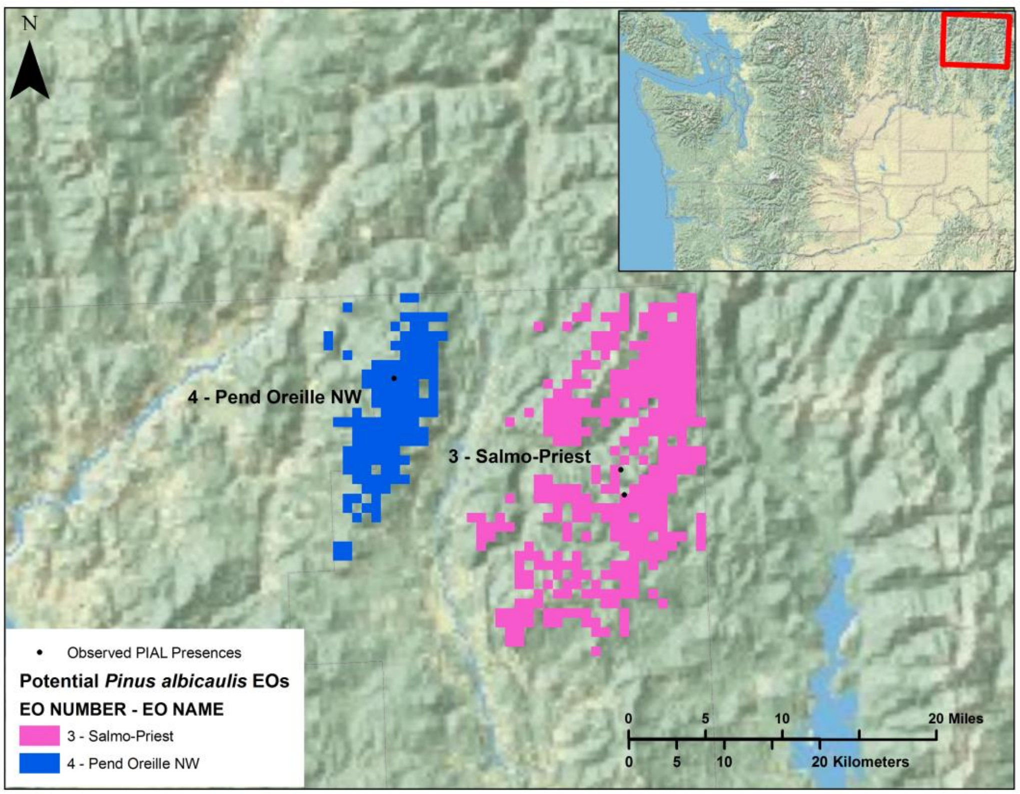


**Figure 6. Pend Oreille (EO 4) and Salmo Priest (EO 3) Occurrences of Whitebark Pine in Washington.**

**EO 4. Pend Oreille NW** (Figure 6, Table 5)
Location: Mountains west of the Pend Oreille River and Metaline Falls, including vicinity of Linton Mountain, Abercrombie Mountain, and Sherlock Peak in Pend Oreille and Stevens counties.
Ownership/Management: Colville National Forest, WA Department of Natural Resources
First/Last Year Observed: 1995/2019
Abundance: Not known, but probably uncommon. Shoal and Aubry (2006) report 51 trees from a 61 meter transect on Abercrombie Mountain in 2004/05 with 19.6% mortality and 26.8% of living trees infected by white pine blister rust.
Comments: Known from one USFS plot, two herbarium specimens (*Wood 3686*, and *Wood 7270* RM on SEINet), and one verified iNaturalist record (https://www.inaturalist.org/observations/29154038). An additional disjunct population from Calispell Peak in southern Stevens County is based on a vegetative specimen (*Wood 2801*, RM) that needs confirmation. If authenticated, this record would represent a separate EO.

**EO 5. Naneum Ridge** (Figure 7, Table 5)
Location: Southern Wenatchee Range, Naneum Ridge, Lion Rock, and Table Mountain east of US Hwy 97 ca 10 air miles SSW of Wenatchee.
Ownership/Management: Colockum State Wildlife Area, Okanogan-Wenatchee National Forest, WA Department of Natural Resources
First/Last Year Observed: 1980/2020
Abundance: Not known, but probably uncommon.
Comments: Known from at least one USFS survey plot on Naneum Ridge and an historical herbarium specimen at Lion Rock (*Grable 7976* WS). In 2020, whitebark pine was documented at Table Mountain (https://www.inaturalist.org/observations/18881978#data_quality_assessment) within the area predicted by our habitat model.

**EO 6. Mount Olympus** (Figure 5, Table 5)
Location: Olympic Range, Northeast slope of Mount Olympus and the Bailey Range.
Ownership/Management: Olympic National Park
First/Last Year Observed: 2005/2019
Abundance: Not known, but apparently uncommon.
Comments: Known from 3 plot locations from Bailey Ridge and one verified iNaturalist record from the northeast slope of Mount Olympus (https://www.inaturalist.org/observations/29858387#data_quality_assessment). Surveys are needed in other areas of potential habitat.

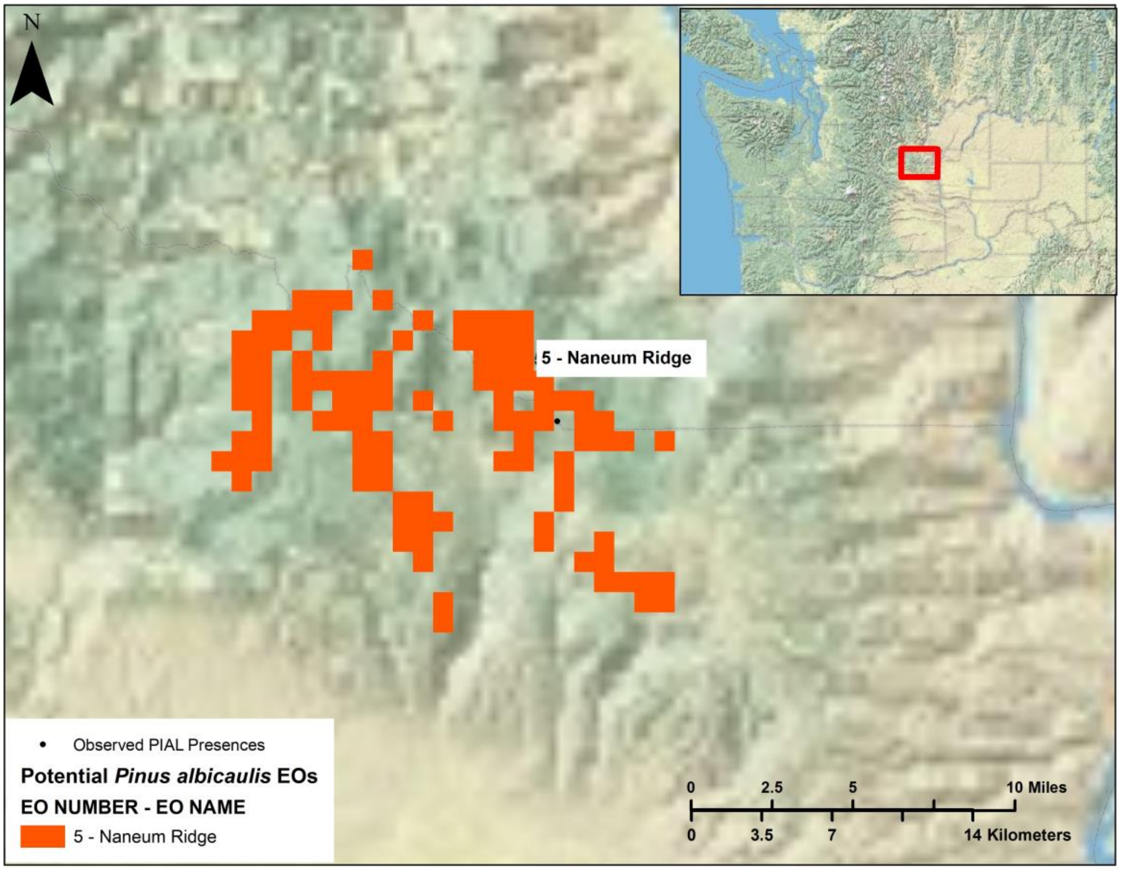


**Figure 7. Naneum Ridge (EO 5) Occurrence of Whitebark Pine in Washington.**

**EO 7. Kettle Range** (Figure 8, Table 5)
Location: Kettle Range, vicinity of Scar Mountain, Copper Butte, Sherman Peak and White Mountain, west of Kettle Falls.
Ownership/Management: Colville National Forest, WA Department of Natural Resources
First/Last Year Observed: 1985/2021
Abundance: Not known, but probably uncommon. Shoal and Aubry (2006) note 69 trees in a 50 meter transect on Copper Butte in 2004/05 with 203% mortality and 43.6% of living trees with white pine blister rust.
Comments: Known from at least two USFS plots near Scar Mountain, three herbarium records from Copper Butte (*Peterson and Annable 3718* WS from CPNWH website), Sherman Peak and White Mountain (*Wood 2579* RM and *Wood and Pavek 6965* RM, from SEINet), and one confirmed iNaturalist report. Additional habitat extends south to White Mountain.

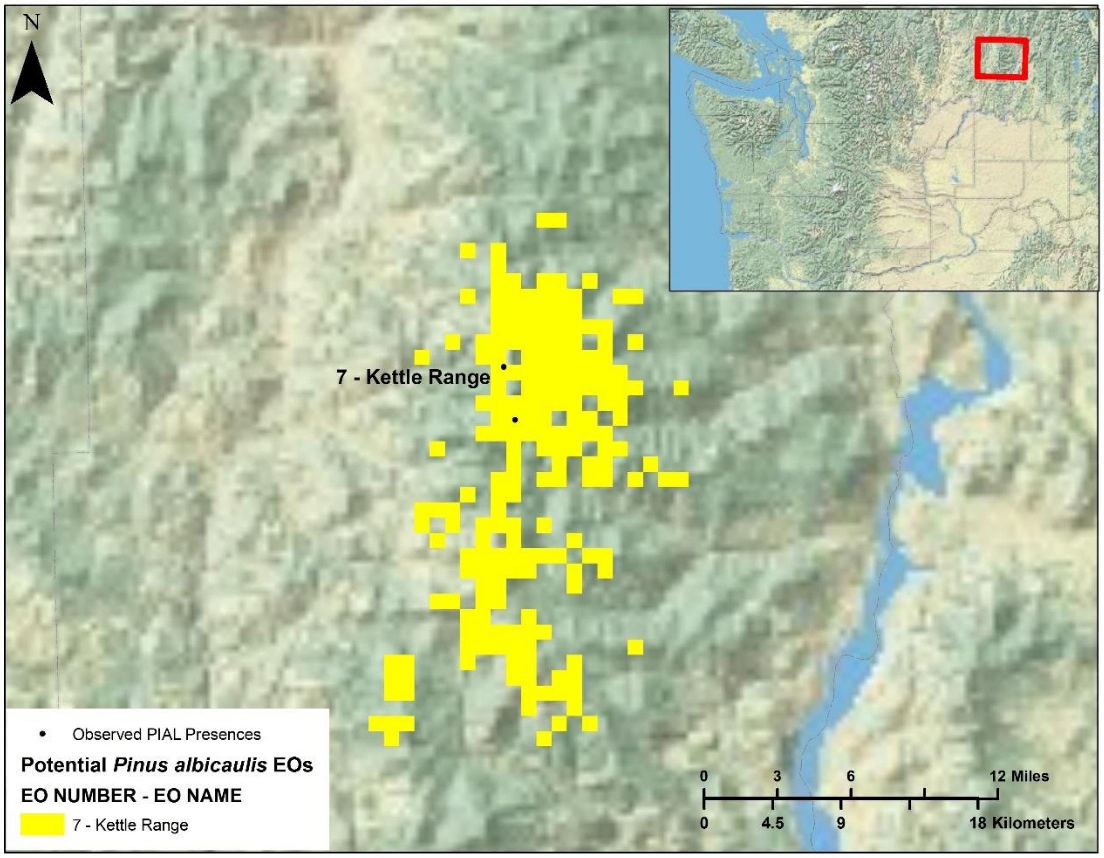


**Figure 8. Kettle Range (EO 7) Occurrence of Whitebark Pine in Washington.**

**EO 8. Mount Rainier-South Cascades** (Figure 9, Table 5)
Location: Southern Cascades Mountains, including Mount Rainier, Castle Mountain, White Pass, high peaks of the Goat Rocks Wilderness south of White Pass, Castle Mountain, Timberwolf Mountain, Burnt Mountain, Bald Mountain, and one disjunct site on Manastash Ridge south of Cle Elum.
Ownership/Management: Clearwater Wilderness Area, Gifford Pinchot National Forest, Glacier View Wilderness Area, Goat Rocks Wilderness Area, LT Murray State Wildlife Area?, Mount Rainier National Park, Norse Peak Wilderness Area, Oak Creek State Wildlife Area, Okanogan-Wenatchee National Forest, Rock Creek State Wildlife Area, Tatoosh Wilderness Area, WA Department of Natural Resources, William O Douglas Wilderness Area, Yakama Indian Reservation.
First/Last Year Observed: 1890/2021
Abundance: The abundance of mature whitebark pine trees in Mount Rainier was estimated at ca 22,000 mature plants over 1431 ha in 2001 based on aerial photograph interpretation and ground truthing (Cottone and Ettl 2001). Data are not available for other areas within the occurrence.

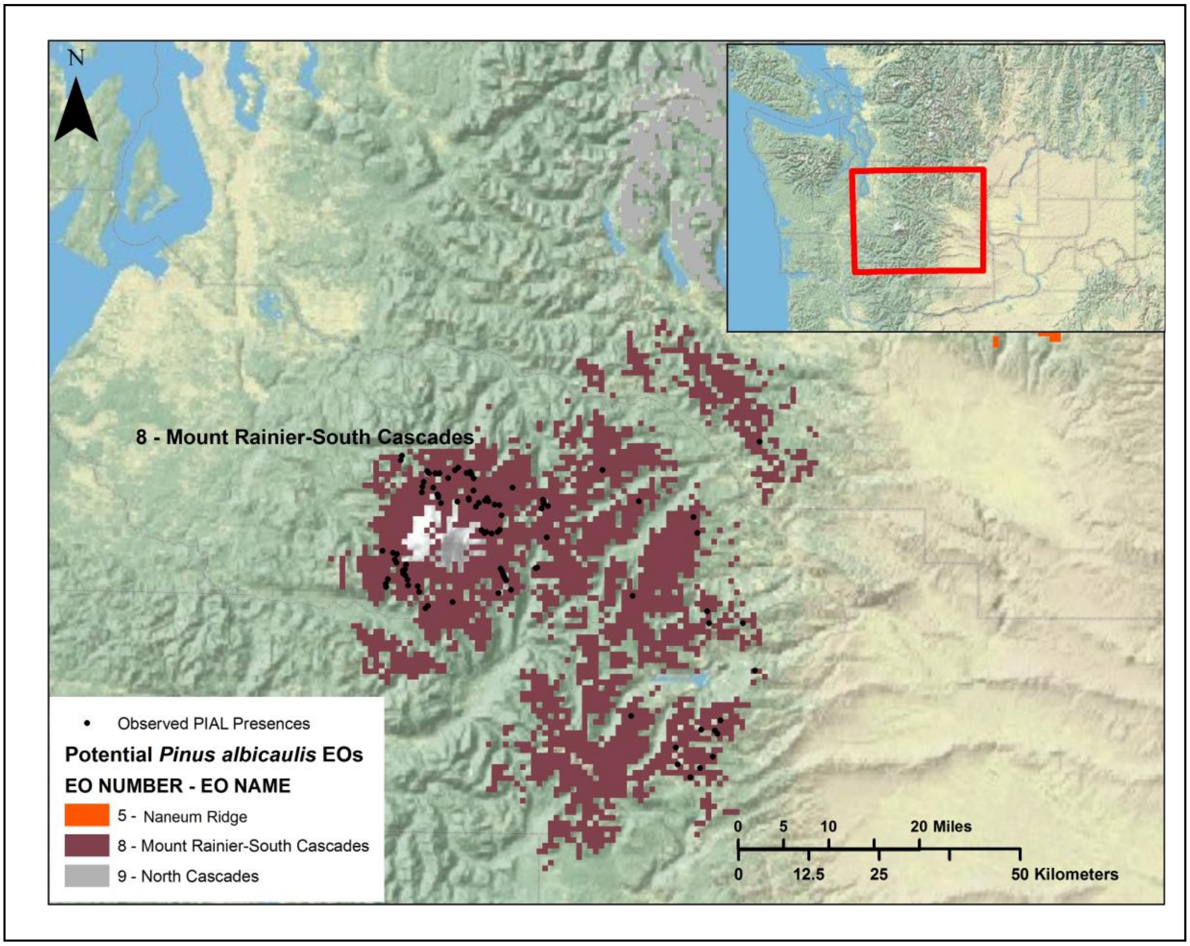


**Figure 9. Mount Rainier-South Cascades (EO 8) Occurrence of Whitebark Pine in Washington.**

Comments: Known from at least 85 NPS and USFS plots, 13 herbarium records, and more than 30 iNaturalist locations. This occurrence could be subdivided into at least 5 smaller EOs using separation distance criteria of 3 km.

**EO 9. North Cascades** (Figure 4, Table 5)
Location: North Cascades, from the Canadian border near Copper Mountain south to Iron Mountain in the Wenatchee Range and east to Mount Chopaka in the Okanogan Mountains. Includes at Mount Baker, Glacier Peak, Desolation Peak, Hart Pass, Washington Pass, Tiffany Mountain, White Chuck Mountain, Tiffany Mountain, and Chumstick Mountain.
Ownership/Management: Alpine Lakes Wilderness Area, Chopaka Mountain NAP, Glacier Peak Wilderness Area, Henry M Jackson Wilderness, Lake Chelan National Recreation Area, Lake Chelan Sawtooth Wilderness Area, Loomis Natural Resource Conservation Area, Mount Baker Snoqualmie National Forest, Mount Baker Wilderness Area, North Cascades National

Park, Okanogan-Wenatchee National Forest, Pasayten Wilderness Area, Ross Lake National Recreation Area, Spokane BLM, WA Department of Natural Resources.
First/Last Year Observed: 1923/2021
Abundance: Not known, but likely the most abundant occurrence based on acreage and number of subpopulations (probably over 1,000,000 mature trees). Shoal and Aubry (2006) cite 11 plots containing 37 to 109 treeswith 5.9-45.5% mortality and 13.7-73.3% infection in living trees of white pine blister rust.
Comments: Known from at least 207 USFS and NPS plots, 45 herbarium collections, and over 50 observation reports from iNaturalist (many of which need confirmation). This extremely large EO could be divided into 11 or more occurrences using smaller minimum distance criteria (3 km) or recognizing river valleys as barriers.

**EO 10. Mount Adams** (Figure 10, Table 5)
Location: Southern Cascades Range, vicinity of Mount Adams
Ownership/Management: Gifford Pinchot National Forest, Mount Adams Wilderness Area, Yakama Indian Reservation
First/Last Year Observed: 1881/2020
Abundance: Not known.

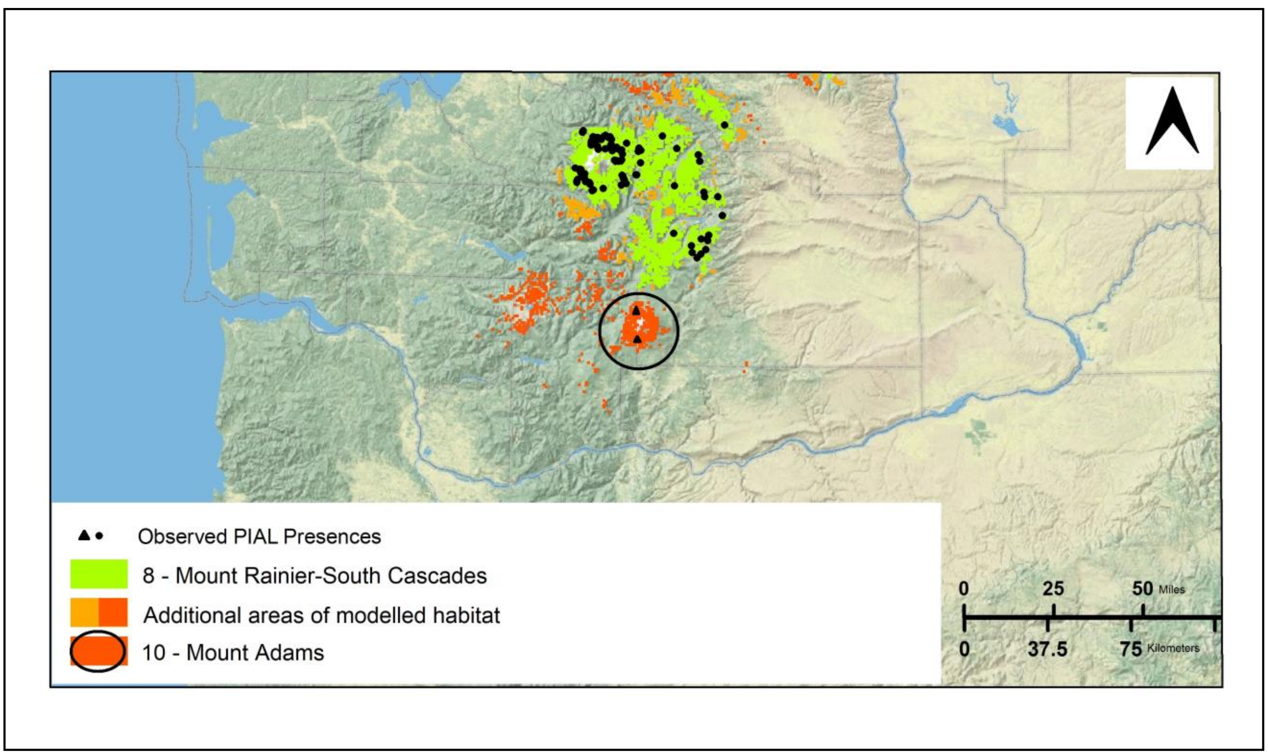


**Figure 10. Mount Adams (EO 10) Occurrence of Whitebark Pine in Washington.**

Comments: Known from 5 herbarium collections and 6 iNaturalist records. Biek and McDougall (2007) cite several locations on the south and north sides of Mount Adams. No USFS plots were available for this area. The earliest collection of whitebark pine in Washington was made by Wilhelm Suksdorf on Mount Adams in 1881 (*Suksdorf s.n.*, MO, SEINet database).

## Discussion

Until recently, whitebark pine was considered widespread and secure in its alpine treeline and subalpine forest habitat across the mountains of northern and central Washington and elsewhere in northwestern North America. Over the past 20-30 years the species has declined by nearly 50% rangewide primarily due to mortality from the introduced fungal pathogen white pine blister rust (Nicholas 2018, Rochefort et al. 2018). Other threats include mortality from mountain pine beetles related to warmer winter temperatures, increased drought, and loss of habitat from wildfires (Jules et al. 2020; Nicholas 2018; Rochefort et al. 2018; Tomback et al. 2001; US Fish and Wildlife Service 2020). These threats are only expected to worsen in the coming decades due to climate change (Jules et al. 2020; Nicholas 2018). Due to its persistent decline, USFWS proposed listing whitebark pine as Threatened under the ESA in December 2020, and WNHP added the species to its state Sensitive list in 2021 (Fertig 2021; US Fish and Wildlife Service 2020).

Although it is clearly declining and at high risk, whitebark pine is still numerically abundant and widely distributed in Washington, making it a challenge to track using natural heritage program methodology. Unlike most rare plant species that are geographically limited, have highly specialized habitat requirements, or relatively few and readily mappable population clusters (EOs), whitebark pine occurs sparsely over a large geographic area (nearly 3 million acres) with at least 300 locations identified from research plots, herbarium specimens, or iNaturalist observations. From a data management perspective, whitebark pine is more like large-bodied animal species with extensive home ranges. Maintaining hundreds of EOs for such species can be impractical and draw limited resources from other species or data management obligations.

Other states and provinces managing whitebark pine data have adopted three main strategies for dealing with this species. Alberta, British Columbia, and Nevada have adopted EO criteria based on fairly large (3-5 km) separation distances that result in the recognition of fewer, but bigger, occurrences (Table 3). The EO definitions have sound biological underpinnings (being based on average travel distances by Clark's nutcrackers, the primary seed disperser of whitebark pine) and recognize the reality that whitebark pine has a naturally diffuse distribution pattern. Recognizing fewer EOs makes it easier to store information, though the records themselves may become complicated due to the existence of numerous subpopulations (source features) scattered over a large geographic extent.

The Montana Natural Heritage Program records information on whitebark pine distribution in a GIS-based observation database, rather than using EOs. Individual observation records contain information on the date, location, abundance, and presence of whitebark pine that can be displayed graphically to depict the species distribution. An advantage of observation records is that they are easy to enter, require little additional maintenance, and can be easily queried and resorted to answer different questions.

Montana Natural Heritage has also used observation data to model the potential habitat and distribution of whitebark pine based on correlations between presence and a suite of environmental variables, including substrate, land cover, and climate (http://mtnhp.org/models/files/Pinus_albicaulis_PGPIN04010_20200802_ modelHex.lpk). Models have multiple applications, including identifying new areas of potential habitat for project clearance, survey, or conservation action. When intersected by known locality data, models can help define the boundaries of EOs.

In Washington, we have been fortunate to draw from the experience of other natural heritage programs for embarking on our own effort to assemble whitebark pine data and assess its conservation status. We have adopted the EO definitions and separation criteria used by Alberta and British Columbia (Miller 2012) to recognize 10 large EOs in the state (Table 5, Figure 3). Following the lead of the Montana program, we have gathered more than 16,000 presence and absence records of whitebark pine in Washington for an observation database (Kleinknecht and Fertig 2021). Also, like the Montana Natural Heritage Program, we have used our presence and absence observations in conjunction with environmental datasets to develop a statewide potential habitat mode for whitebark pine. The output of the model (Figures 2-10) has allowed us to estimate the amount of occupied acreage and abundance of whitebark pine in the state and to better define the potential boundaries of our EOs. This information, coupled with data on environmental specificity, habitat viability, threats, and trends, have allowed us to use the NatureServe rank calculator to assign a S rank of S3 for this species.

In the coming years, we hope to refine the boundaries of our EOs and perhaps subdivide some of the larger ones into a manageable number of subunits based on more locally-defined ecological and biological criteria. We also hope to deploy the model to help identify areas for more detailed survey and monitoring and to answer database queries related to the potential distribution of whitebark pine in areas undergoing various proposed management actions. The array of data products (EOs, observations, and modeled distribution) will also assist USFWS and other federal and state agency partners in assessing the status of whitebark pine in Washington. Ideally, the databases and model will lead to new discoveries that will help further calibrate the model and improve our collective understanding of the species and its conservation needs.

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# Appendix A.

# Developing a Potential Habitat and Distribution Model for Whitebark Pine in Washington

Potential habitat and distribution modeling is a tool for mapping the potential range of a species based on relationships between known occurrences and various environmental variables, such as topography, edaphic properties, land cover, or climate. Models can be used to predict additional areas where a species might occur and to describe the ecological conditions that explain their distribution and realized niche (Franklin 2009).

We used Random Forest modeling (Breiman 2001; Franklin 2009) with presence and absence location points to create a potential habitat model for whitebark pine in Washington. Random Forests are a variation of Classification and Regression (CART) Models in which a computer algorithm partitions predictor variables into ever smaller subsets that are increasingly homogenous relative to a response variable (such as presence/absence) (Breiman et al. 1984). The result is a dichotomously branched "tree" that describes the environmental attributes that correlate with the presence of a species, much as a dichotomously branched taxonomic key describes a specific plant taxon (Fertig 2011). Whereas conventional CART modeling produces a single, best-fitting tree, Random Forests produce numerous trees (each comprised of random subsets of predictor variables) that are averaged to create a final model. Random Forest methods have higher prediction accuracy, but are more difficult to interpret than CART models due to the averaging of tree data (Franklin 2009).

Our intent was to identify additional areas of suitable habitat for whitebark pine beyond the areas where the species has been documented by plot, herbarium, or observation data. The modeled area helped us delineate potential element occurrences, estimate the acreage occupied by the species, and extrapolate population numbers, which in turn were used to derive the state rank using the NatureServe ranking calculator (Faber-Langendoen et al. 2012).

We briefly describe the methods used to develop the model in the following sections.

## Model Development

### *Data used in the model*

Our first step in building the model was to assemble presence and absence data for whitebark pine in Washington. We used Forest Inventory and Analysis (FIA) and vegetation classification plot data from the US Forest Service (Smith 2002), Forest Resource Inventory System (FRIS) data from the Washington Department of Natural Resources, and vegetation plot data from the North Coast and Cascades Network (NCCN) Inventory and Monitoring Program of the National Park Service. These plots are part of a systematic network to record species composition, cover, density, canopy height, and other attributes for dominant tree species established across the state. Our initial data set contained 16,168 records, of which 971 were presence points (6%) and 15,197 were absence points (94%) (Figure 11). Presence and absence data used in the model were added to the WNHP observation database (Kleinknecht and Fertig 2021).

We used 32 standard environmental predictor variables relating to geology, soils, vegetation (land) cover, topography, elevation, and climate (precipitation, temperature, solar radiation, heat moisture index, etc.). These variables and their sources are summarized in Table 6. The variables were selected due to their utility in predicting the distribution of plant species (Franklin 2009) and their availability in digital format across the entire state. The Montana Natural Heritage Program used comparable environmental predictor variables in their habitat model for whitebark pine (http://mtnhp.org/models/files/Pinus_albicaulis_PGPIN04010_20200802_modelHex.lpk).

Each presence and absence point for whitebark pine was intersected with the selected environmental attributes to create a master dataset for modeling. All datasets were projected into Washington State Plane South, NAD 1983 HARN (WKID 2927).

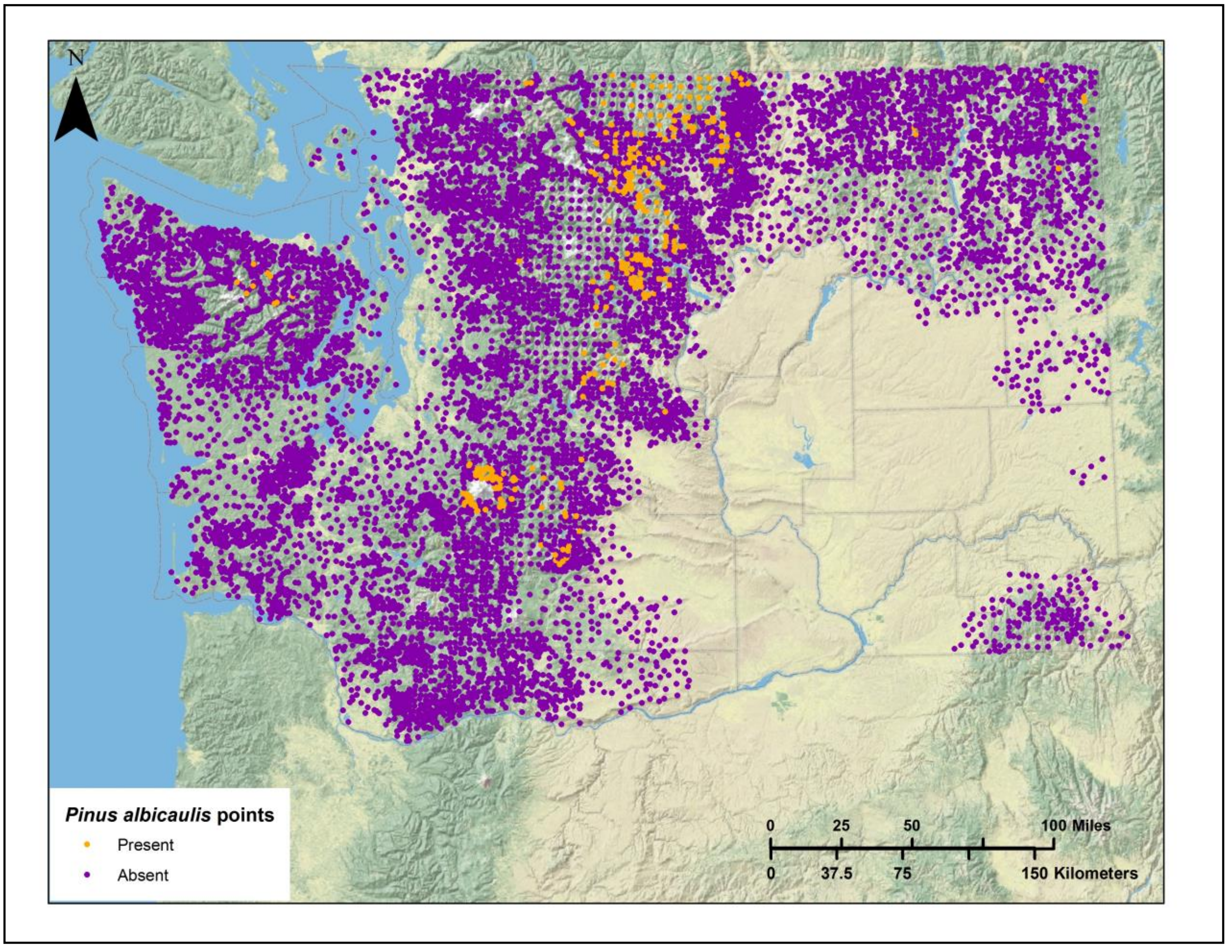


**Figure 11. Presence and Absence Points Used to Develop the Potential Habitat Model for Whitebark Pine in Washington.**

**Table 6. Environmental Variables Used in Model Construction**

| Environmental Variable | Source |
|---|---|
| Surface Geology | DNR Geology Program (https://www.dnr.wa.gov/programs-and-services/geology/geologic-maps/surface-geology) |
| Soil Suborders | Natural Resource Conservation Service (NRCS) Gridded Soil Survey Geographic (gSSURGO) (Soil Survey Staff 2020) |
| Land Cover (Ecosystems_NVC Divisions) | National Landcover Dataset (NLCD) (Dewitz 2019), NatureServe Ecological Systems data (Comer et al 2003) |
| Tree Canopy | National Landcover Dataset (NLCD) (Dewitz 2019) |
| Elevation (WA_10 m DEM) | US Geological Survey (2020) |
| Local Relief (from 10 m DEM) | US Geological Survey (2020) |
| Aspect (WA 780 m relief from 10 m DEM) | US Geological Survey (2020) |
| January mean monthly precipitation (PPT01) | AdaptWest (2015) for time period 1980-2010 |
| April mean monthly precipitation (PPT04) | AdaptWest (2015) for time period 1980-2010 |
| July mean monthly precipitation (PPT07) | AdaptWest (2015) for time period 1980-2010 |
| October mean monthly precipitation (PPT10) | AdaptWest (2015) for time period 1980-2010 |
| Mean Summer (May-Sep) Precipitation (MSP) | AdaptWest (2015) for time period 1980-2010 |
| Average winter precipitation – December to February (PPT_wt) | AdaptWest (2015) for time period 1980-2010 |
| Average summer precipitation – June to September (PPT_sm) | AdaptWest (2015) for time period 1980-2010 |
| Precipitation as Snow (PAS) | AdaptWest (2015) for time period 1980-2010 |
| January mean monthly temperature (Tave01) | AdaptWest (2015) for time period 1980-2010 |
| April mean monthly temperature (Tave04) | AdaptWest (2015) for time period 1980-2010 |
| July mean monthly temperature (Tave07) | AdaptWest (2015) for time period 1980-2010 |
| October mean monthly temperature (Tave10) | AdaptWest (2015) for time period 1980-2010 |
| Average winter temperature- December to February (Tave_wt) | AdaptWest (2015) for time period 1980-2010 |
| Average summer temperature- June to September (Tave_sm) | AdaptWest (2015) for time period 1980-2010 |
| Extreme Minimum Temperature (EMT) | AdaptWest (2015) for time period 1980-2010 |
| Extreme Maximum Temperature (EXT) | AdaptWest (2015) for time period 1980-2010 |
| Degree Days below 0˚ C (DD_0) | AdaptWest (2015) for time period 1980-2010 |
| Degree Days above 5˚ C (DD5) | AdaptWest (2015) for time period 1980-2010 |
| Number of Frost Free Days (NFFD) | AdaptWest (2015) for time period 1980-2010 |
| Continentality or TD (difference between mean temperature of warmest and coldest month) | AdaptWest (2015) for time period 1980-2010 |
| January Daily Potential Solar Radiation | AdaptWest (2015) for time period 1980-2010 |
| July Daily Potential Solar Radiation | AdaptWest (2015) for time period 1980-2010 |
| Mean Annual Solar Radiation (MAR) | AdaptWest (2015) for time period 1980-2010 |
| Annual Heat Moisture (AHM) index | AdaptWest (2015) for time period 1980-2010 |
| Summer Heat Moisture (SHM) index | AdaptWest (2015) for time period 1980-2010 |

*Data modifications prior to running model*

We reduced the original number of absence points by removing locations that were unlikely to contain suitable whitebark pine habitat. Such records ('naughty nots' *sensu* Austin and Meyers 1996) can artificially inflate prediction success in model validation (Pirathiban et al. 2015). We eliminated all absence points associated with unsuitable surface geology, including Ice, Water, Tectonic Zone, Holocene Artificial Fill, and Modified Land, since none of these geologic features were expected to be whitebark pine habitat. From the land cover data, we removed absence points that intersected with Developed-Open Space, Developed-Low Intensity, Developed-Medium Intensity, Developed-High Intensity, Deciduous Forest, Hay/Pasture, Cultivated Crops, Woody Wetlands, Emergent Herbaceous Wetlands, Open Water, or Perennial Snow/Ice. Likewise, we removed location points from the Ecological Systems layer that overlapped with Non-Specific Disturbed, Open Water, Developed-Low Intensity, Developed-Medium Intensity, Developed-High Intensity, Quarries/Strip Mines/Gravel Pits Inter-Mountain Basins Montane Sagebrush Steppe, Recently Logged Timberland-Shrubland Cover, North Pacific Serpentine Barren, Inter-Mountain Basins Cliff and Canyon, Recently Burned Forest and Woodland, and Recently Logged Timberland. The latter two types were omitted because whitebark pine mostly occurs at elevations higher than most recent fires or timber-harvest areas, though this could differ in the future with climate change.

In order to reduce pseudoreplication that might over-inflate prediction success or failure, we randomly eliminated points that were within 1 km of other points. The first iteration of data cleaning focused on absence points that were too close to other absence points, followed by a second round removing presence points that were too close to other presence points. Presence and absence points within 1.5 km were retained, however. Removing spatial pseudoreplicates and eliminating absence points from unsuitable habitat decreased the number of points in our input dataset from 16,168 to 9,438. Absence points comprised 96.5% of the total (9,109 points).

*Model Training and Selection*

After extracting our predictor values to our post-processed presence-and-absence points dataset, we began running it through ESRI's Forest-Based Regression and Classification, a type of Random Forest model (Breiman 1996, 2001; Breiman et al. 1984; Grömping 2009; Ho 1995; James et al. 2013; LeBlanc and Tibshirani 1996; Loh and Shih 1997; Nadeau and Bengio 2000; Strobl et al. 2008). Random Forest models consist of multiple classification trees, each produced using a subset of input data points (with their associated environmental predictor values) randomly chosen with replacement (also known as bagged or bootstrap samples). Each individual tree consists of multiple "nodes" in which the input data are subdivided into two smaller subsets based on the single environmental variable that best differentiates between presence and absence points. Each resulting subset of data points is further subdivided again, based on whatever environmental value best separates the remaining presence and absence points. This process continues along each successive dichotomous branch of the tree until individual subsets become too small to divide, or all remaining points represent either presence or absence. Once the trees are completed, the values for each environmental variable at each node of a branch can be intersected in GIS to identify geographic areas where these features co-occur. A potential distribution map can then be created by combining the individual maps for all of the branches in which the target species was predicted to be present (Breiman et al. 1984; Franklin 2009). In Random Forests, the final model is derived from averaging the results of multiple trees. The more trees used, the smaller the amount of predicted area, and the more likely that independent cross validation data (not used in model construction) may be misclassified, especially known present points mischaracterized as absent (false negatives) (Fertig 2011).

To identify the optimal number of trees, we ran the Random Forest procedure seven different ways, using 1, 2, 5, 10, 25, 50, and 100 trees. Table 7 depicts the results of these different runs. Points categorized as true positive and true negative were correctly classified by the model as being present or absent for whitebark pine. False positive denotes known absent points incorrectly classified by the model as being present (commission error) and false negative refers to known present points incorrectly classified as being absent (omission error). All of the model runs had high overall classification success, ranging from 88.1% for the model with 1 tree to 92.1% for the model with 100 trees. The seven model runs differed primarily in their success in classifying presence points correctly. Starting at 5 trees, the misclassification (omission error) rate for false negatives dropped significantly, from 6.1% to 1.5%. Omission error is often considered the costliest from a conservation perspective, as it can result in known populations of a rare species being mistakenly considered absent, and thus not protected (Fielding 2002). Using additional trees (10, 25, 50, or 100) did not significantly reduce omission error further (Table 7), but added to the complexity of the model and a reduction in the area predicted as potential whitebark pine habitat. Based on the tradeoff between reducing omission error and keeping the model simple enough to improve field validation success, we chose the model constructed with 5 trees to create our final whitebark pine model.

**Table 7. Comparison of Classification Success for Different Iterations of Random Forest Models of Whitebark Pine in Washington.** Total number of presence points in all runs is 329 and absence points in 9109 (total of 9438 points).

| **Number of Trees** | **Total Correctly Classified** | **True Positive** (known & modeled present) | **True Negative** (known & modeled absent) | **False Positive** (known absent, modeled present) | **False Negative** (known present, modeled absent) |
|---|---|---|---|---|---|
| 1 | 8378 (88.8%) | 308 (93.6%) | 8070 (88.6%) | 1039 (11.4%) | 21 (6.4%) |
| 2 | 8437 (89.4%) | 309 (93.9%) | 8128 (89.2%) | 981 (10.8%) | 20 (6.1%) |
| 5 | 8644 (91.6%) | 324 (98.5%) | 8320 (91.3%) | 789 (8.7%) | 5 (1.5%) |
| 10 | 8667 (91.8%) | 326 (99.1%) | 8341 (91.6%) | 768 (8.4%) | 3 (0.9%) |
| 25 | 8684 (92.0%) | 327 (99.4%) | 8357 (91.7%) | 752 (8.3%) | 2 (0.6%) |
| 50 | 8684 (92.0%) | 328 (99.7%) | 8356 (91.7%) | 753 (8.3%) | 1 (0,3%) |
| 100 | 8691 (92.1%) | 327 (99.4%) | 8364 (91.8%) | 745 (8.2%) | 2 (0.6%) |

Modeling Results

Our final whitebark pine model was constructed using 5 classification trees averaged together. These trees ranged from 17 to 23 branches in size, with the average being 19 branches. Surface geology was the single most important environmental variable in predicting the distribution of whitebark pine, followed by the amount of precipitation falling as snow, number of sub-freezing degree days, soil suborders, and July daily potential solar radiation (Table 8).

Based on the model output, we created a map of potentially suitable and unsuitable habitat for whitebark pine in Washington (Figure 12). This map was produced by identifying all tree branches that predicted presence for whitebark pine and intersecting the specific values or thresholds for all environmental variables associated with those branches. Intersections were done in Arc-GIS. We overlaid the final model with known presence points of whitebark to identify clusters of observations that could be potential EOs (Figures 2, 3). It is important to note that the clusters of present points define the EO, and that the modeled areas surrounding and connecting point clusters represent potential (but unsurveyed) whitebark pine habitat. In the absence of detailed, polygon-based mapping, the potential habitat model and map can define the likely boundaries of each occurrence and highlight areas for future survey or conservation attention.

Model Validation

The final step in model construction was to test the model with independent presence and absence data. During each iteration of our Random Forest models, 10 percent of the input data points were randomly removed for validation of the individual decision trees comprising that run of the model. Subsequent runs were tested with a different, randomly selected set of validation

**Table 8: Ten Most Important Environmental Variables for Predicting Presence of Whitebark Pine in Washington Based on Random Forest Modeling.**

| Variable rank | Variable name | Importance |
|---|---|---|
| 1 | Surface geology | 0.94 |
| 2 | Precipitation as snow (PAS) | 0.89 |
| 3 | Degree-days below 0°C (DD_0) | 0.82 |
| 4 | Soil suborders | 0.76 |
| 5 | July daily potential solar radiation | 0.75 |
| 6 | Elevation | 0.74 |
| 7 | Local relief | 0.71 |
| 8 | July mean monthly precipitation | 0.64 |
| 9 | January mean monthly precipitation | 0.47 |
| 10 | April mean monthly temperature | 0.45 |

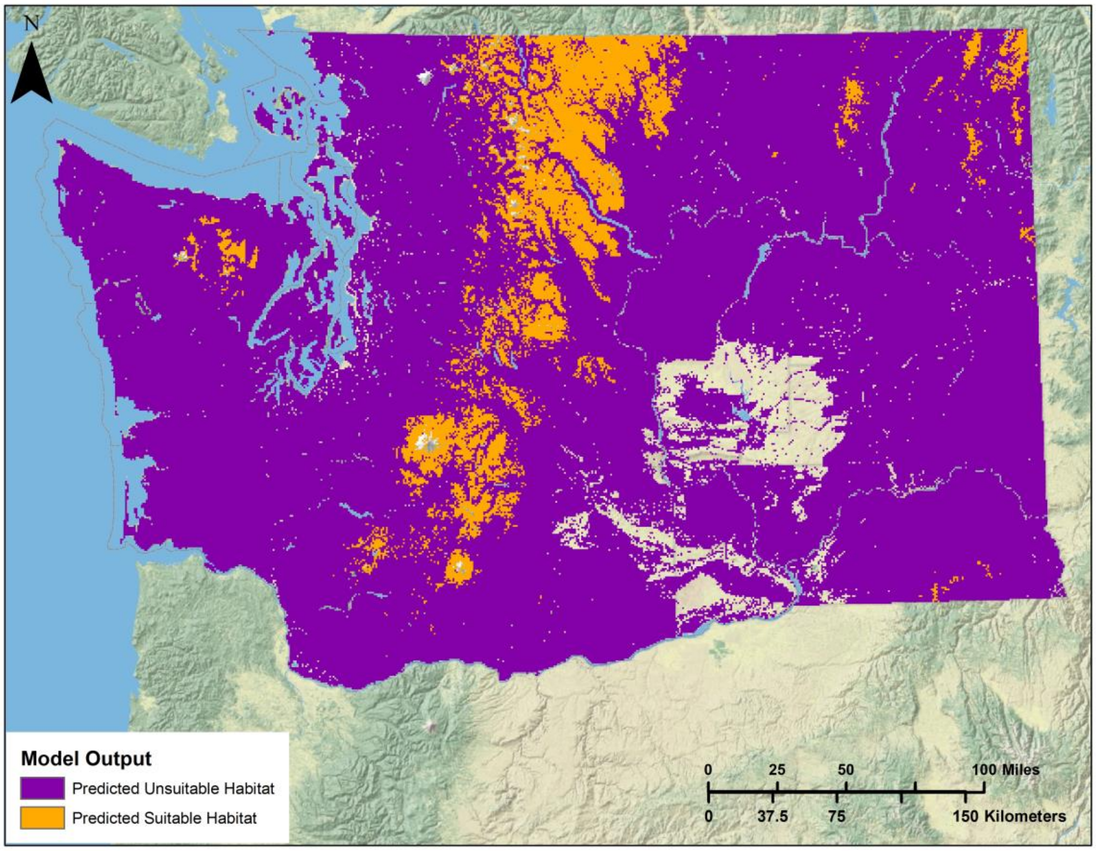


**Figure 12. Predicted Suitable and Unsuitable Habitat of Whitebark Pine in Washington**. White areas are unsuitable habitat with missing data.

points drawn (with replacement) from the original pool. These "out-of-bag" validation points can be used to assess the overall predictive performance of the model. Table 9 summarizes the validation success rates for iterations of the Random Forest model using 1, 2, 5, 10, 25, 50, and 100 trees. Mean square error (MSE) assesses the overall predictive success of the model, with lower numbers indicating greater success. We found a sharp improvement in model validation between models created with 2 and 5 individual decision trees, but only modest improvement in subsequent versions. Overall, the models were very successful at correctly predicting present points, but had higher error rates with absent points. The validation data used to test the models are not truly independent, as out-of-bag samples may be used for model-building in later runs. Validation with truly independent data (cross validation) or with newly acquired field data overlaid on the predicted habitat map may be the best means to test the utility of these models.

**Table 9: Out-of-Bag Validation Error Rates For Seven Iterations of the Random Forest Model of Whitebark Pine in Washington.**

| | Number of Trees per Random Forest Model | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mean Square Error (MSE)** | **1** | **2** | **5** | **10** | **25** | **50** | **100** |
| **Total** | 11.231 | 10.443 | 8.394 | 8.008 | 7.911 | 8.006 | 7.656 |
| **Predicted absence** | 11.43 | 10.515 | 8.673 | 8.368 | 8.197 | 8.295 | 7.881 |
| **Predicted presence** | 5.743 | 8.446 | 0.676 | 0.338 | 0.000 | 0.000 | 0.000 |