

Final Report

**Assessing the Impacts of Climate Change on Urban Forests in the Puget
Sound region: Climate Suitability Analysis for Tree Species**

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Executive Summary

Climate change can create both challenges and opportunities for sustaining urban forests. A critical appraisal of climate impacts is important for successful restoration and conservation of urban forests and provision of their ecosystem services in a changing climate. Limited information is available to guide decisions on species selection for reforestation, seed source selection, and other restoration and management practices. In this project, our aim was to evaluate climate change impacts on habitat suitability of native tree species that are commonly considered for restoration and reforestation of urban forests in the Puget Sound region. We focused on western redcedar, western hemlock, and Douglas-fir to illustrate the potential geographic shifts of their climate suitability. We applied Geographic Information Systems (GIS) techniques coupled with bioclimatic envelope modeling to develop “predicted zone maps” (i.e., plant hardiness zone maps, seed transfer zone maps) that illustrate potential climate impacts.

First, we created current and future plant hardiness zone maps for the State of Washington that may be used for selection of woody and herbaceous plants for restoration and horticultural purposes in the region. Based on a moderate regional climate change scenario in Pacific Northwest, plant hardiness zones are likely to rise by a half zone (e.g., from zone 8a to zone 8b) in the Puget Sound area. This means that the Puget Sound area is projected to experience an increase of 5 to 6 °F in annual minimum temperatures. This result implies that less hardy species may be able to grow in the region and they could alter ecological dynamics in urban forests.

Second, we performed an assessment of the impacts of climate change on habitat suitability and seed transfer zones of three tree species native to the Puget Sound region: Western redcedar, western hemlock, and Douglas-fir that are commonly selected for urban forest restoration. Our result suggests that the current range of these species in the Puget Sound and other areas in WA State are likely to continue to provide climate conditions that are suitable for these species by the end of this century under various climate projections. However, when individual seed transfer zones of these species within WA State are considered separately, the bioclimatic envelope that is matching the current seed zones in the Puget Sound is likely to disappear by the end of the century. This means that for restoration and reforestation purposes in the Puget Sound area, considering diverse seed sources—not only from current seed transfer zones in the Puget Sound but also from adjacent seed transfer zones (e.g., Toutle)—could ensure that the future climate matches suitable climate conditions for specific ecotypes.

Third, we evaluated if and how urbanization relates to recent increases in temperatures in the cities of the Puget Sound region. We attempted this by relating recent temperature changes with increases in urban population in a subset of cities throughout the WA State. Our results indicate that both urban populations and air temperatures have increased in the cities of Puget Sound in recent decades. The link between the increases in urban temperature and urban population was more pronounced in the cities in the east side of the Cascades than those in the Puget Sound area. More extensive analysis covering more cities and their surrounding areas will be needed to be able to separate the urban heat island effect from the impacts of global climate change in the region. Bioclimatic envelope models for urban ecosystems may be improved by accounting for population density and other urbanization effects.

In summary, regional climate projections suggest that plant hardiness zones in the Puget Sound region are likely to increase by a half zone towards the end of the century. The bioclimatic conditions that make up the current seed transfer zones around the Puget Sound for western redcedar, western hemlock, and Douglas-fir are likely to diminish, shift further northwest towards Canadian islands, or disappear by the end of the century. This suggests that careful considerations should be made to diversify seed sources for restoration and reforestation of urban forests in the region and to adapt existing plant ecotypes to novel bioclimatic conditions in a changing climate.

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1 Introduction

Climate change creates both challenges and opportunities for sustaining urban forests. The recent Washington Climate Change Impacts Assessment projected sea level rise, temperature increase, and change in precipitation for Washington State (UW-CIG, 2009). Little research, however, has been done to guide decisions on how to best manage today's forests including urban forests while adapting for changes in the future climate. The conservation and restoration of urban forests are becoming increasingly important for their ecosystem and socio-economic services. On the other hand, urban forests may be impacted by warmer and drier summers, flooding and high winds from increased winter storm events, and shoreline erosion. To maximize the urban forest's ability to mitigate climate-change impacts as well as adapt to the impacts, an assessment of vulnerabilities and opportunities is needed to inform our management strategies.

Adapting management and restoration of urban forests to climate change is likely to require innovative solutions to overcome uncertainties associated with climate change. An important step in developing plans for urban forest management and restoration in light of climate change is to identify the impacts of projected climate change on habitat suitability and distribution of commonly used tree species that are integral part of the ecosystem as providers of ecosystem services. The impacts of climate change on individual species' distributions and their climate suitability are often studied using bioclimatic envelope models (Thuiller et al., 2008, Thuiller et al., 2005). This approach is particularly effective at large spatial scales (e.g., regional, continental, or global) but can also provide useful insights at finer, local scales (e.g., Gottfried et al., 1999). Zone maps are another type of tool that can be useful in forest management and restoration (e.g., plant hardiness zone maps and seed transfer zones). This approach has been used for making planting recommendations in horticulture, forestry, and in ecological restoration (Withrow-Robinson and Johnson, 2006). It is likely that both conventional and novel strategies are needed for restoration and conservation planning in response to the rapidly changing climate (Dunwiddie et al., 2009).

The objective of this project was to evaluate climate change impacts on habitat suitability of native tree species in the Puget Sound region. We focused on western redcedar, western hemlock, and Douglas-fir to exemplify the potential shifts in their climate suitability and address adaptive options. We applied Geographic Information Systems (GIS) techniques coupled with a bioclimatic envelope modeling to develop "predicted zone maps" (i.e., plant hardiness zone maps, seed transfer zone maps) that illustrate the climate impacts and vulnerability in response to climate change. In addition, we also evaluated if and how

urbanization has contributed to recent warming in the Puget Sound region using increases in population density as surrogate measure of urbanization.

2 Methods

2.1 Future Plant Hardiness Zones

2.1.1 Climate Data Acquisition

We used historical (1915 – 2006) climate data for creating past and current plant hardiness zone maps. These were daily data at 6 km (1/16 degree) resolution obtained from the University of Washington Climate Impacts Group (CIG) Columbia Basin Climate Change Scenarios Project (CBCCSP). CIG produced the dataset from primary data recorded by the National Climatic Data Center (NCDC), Cooperative Observer (COOP) network and Environment Canada (EC). The CIG has used data from the US Historical Climatology Network and the Adjusted Historical Canadian Climate Database to correct bias and inconsistencies in the NCDC, COOP, and EC data as well as making topographic adjustments to temperature and precipitation. Figure 1 displays the locations of climate recording stations and the boundary of the final primary dataset produced by CIG and used for this study. More detailed information can be found in chapter 3 of the CBCCSP study report (see Chap.3, UW-CIG, 2010).

Future climate projections were also produced by CIG using Global Climate Models (GCM). Ten GCMs were used by CIG, each with a different ability to accurately predict 20th century climate conditions (referred to as bias) and climate conditions in the North Pacific (NP). Ranking a GCM by its bias and NP allows discrimination between models that accurately predict climate and the important ocean weather patterns that affect the Pacific Northwest. Based on a ranking of combined bias and NP, three of the ten GCMs scored well and equally overall because they predicted with smaller bias or better NP, or were middle of the road on both. For creating predicted plant hardiness zone maps, a middle of the road GCM: ECHAM5/MPI-OM (ECHAM) was used. Data predicted by ECHAM were then downscaled by CIG using a combination of two traditional downscaling methods in order to maximize the strengths of both methods. More details can be found in chapter 4 of the CBCCSP study report (UW-CIG, 2010; chap. 4).

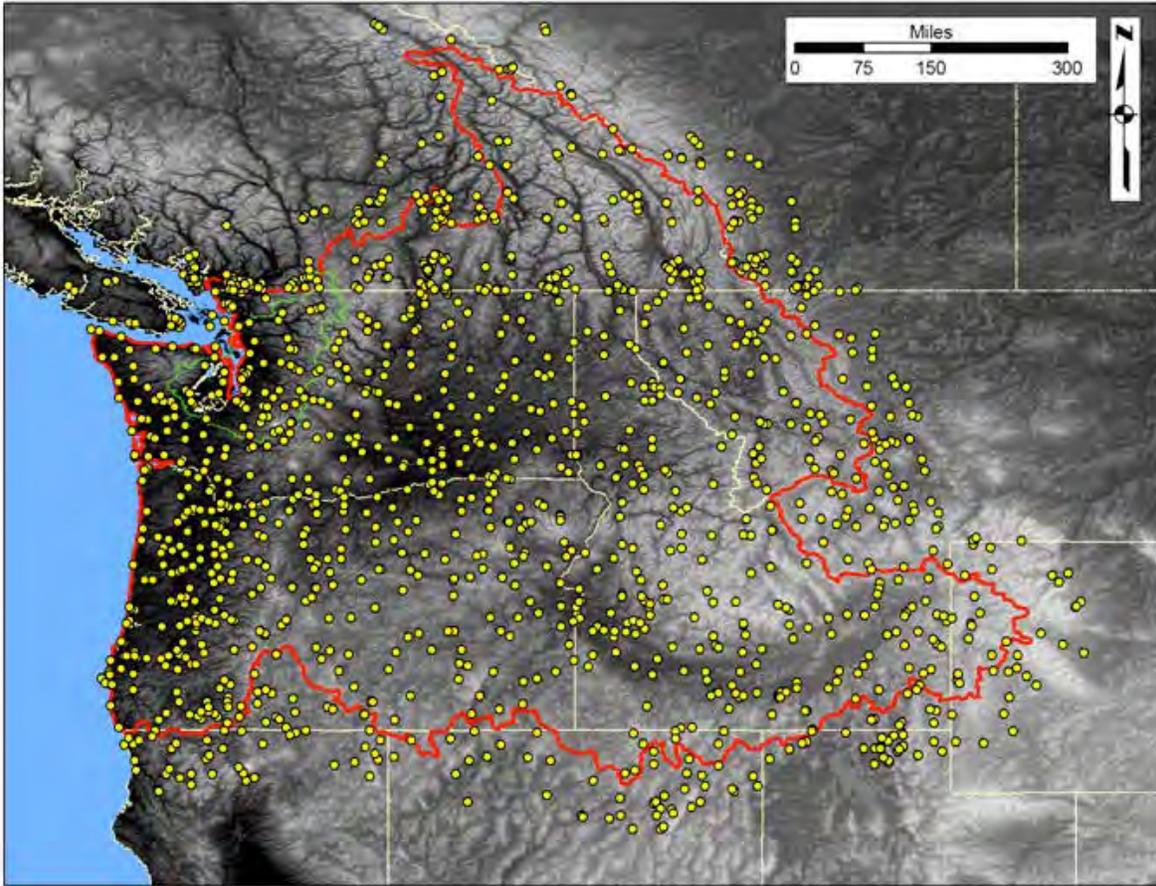


Fig. 1. Locations of weather stations and boundary of dataset produced by CIG and used in this study (taken from chapter 3 of UW-CIG, 2010)

2.1.2 Plant hardiness zone maps (PHZMs)

We created plant hardiness zone maps for the past and present in WA State based on historical weather data from 1971 to 2000 at a daily time step acquired from CIG. We followed the USDA Plant Hardiness Zone Map (PHZM) conventions with uniform 5.6°C (10°F) zones from Zone 1 to Zone 10 based on the annual extreme minimum temperatures – lowest daily minimum temperature of the year – averaged over the 30-year period (See Daly et al., 2012 and table 1 therein). As in the 1990 version of USDA PHZM, we subdivided zones 2–10 into 2.8°C (5°F) half zones. Zone 11 was introduced to represent areas with PH > 4.4°C (40°F) that are essentially freeze free.

Similarly, the future plant hardiness zone maps for WA state were produced for projected climate of 30-year averaged normal years: 2020, 2040, and 2080 (Fig. 3) using downscaled daily climate projections (6 by 6 km resolution). The climate projections provided by the UW Climate Impacts Group were derived from a GCM: ECHAM5/MPI-OM (ECHAM) run for the SRES A1B emission scenario developed for the 2007 IPCC fourth assessment report.

2.2 Modeling tree distribution and seed transfer zones

2.2.1 Climate and tree data

We acquired past and future regional climate data (6 by 6 km resolution) from the UW-CIG as previously described. In addition to the UW-CIG climate data, we obtained future climate projections at finer spatial resolution (1 km by 1km) from CGIAR (Consultative Group on International Agricultural Research). More information about the data and downscaling procedures of these data can be found at: http://ccafs-climate.org/download_sres.html. These data sets included projections from three general circulation models (GCM): MPI-ECHAM5, CCCMA-CGCM2, and UKMO-HADCM3 for three IPCC emission scenarios: A1B, A2 and B2 using Delta statistical downscaling method (http://www.ccafs-climate.org/statistical_downscaling_delta/).

We obtained current distribution maps of three native conifer species that are commonly used for urban forest restoration in the Puget Sound region: western redcedar (*Thuja plicata*), Douglas-fir (*Pseudotsuga menziesii*), and western hemlock (*Tsuga heterophyllum*). Distribution data for these species were acquired from the USGS “Atlas of United States Trees” written by Elbert L. Little, Jr. More detailed information may be found at: <http://esp.cr.usgs.gov/info/veg-clim/>. These data were used for training bioclimatic envelope models described below.

We also obtained current seed transfer zones of these species within the State of Washington through personal communications with Mr. Jeffrey Debell at WA Dept. of Natural Resources (Figure 2). See also: http://www.dnr.wa.gov/ResearchScience/Topics/ForestResearch/Pages/lm_tree_seed_zones.aspx.

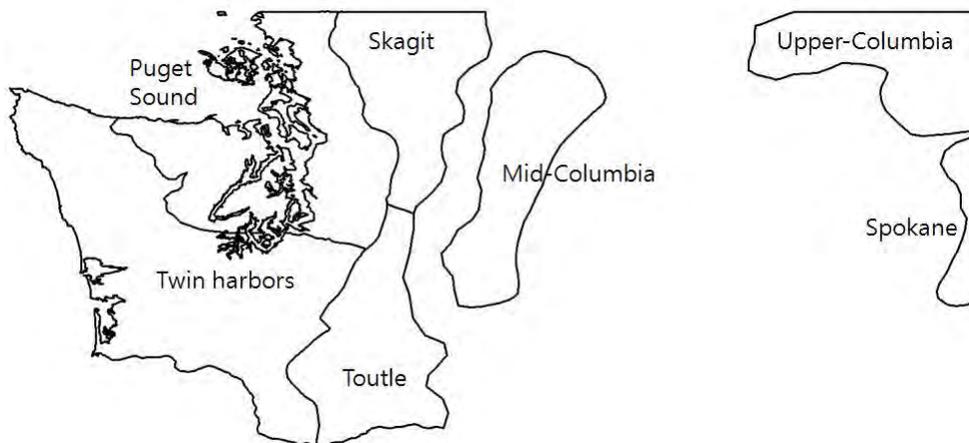


Fig. 2. An example of seed transfer zones for Western redcedar (*Thuja plicata*) in Washington State. Our work focuses on the three seed zones: Puget Sound, Skagit, and Twin harbors.

In addition, we acquired land-use and soil data from USDA Geospatial Data gateway (<http://datagateway.nrcs.usda.gov/>) and the Soil Survey Geographic (SSURGO) Database from

National Cartography and Geospatial Center (NCGC) at the Natural Resources Conservation Service (NRCS) (Figure 3).

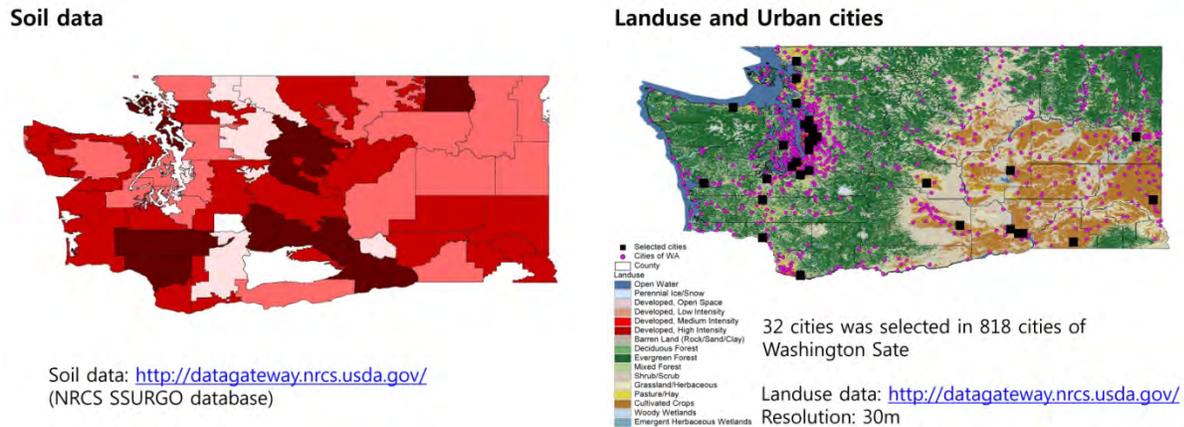


Fig. 3. Soil and landuse data from NRCS Data gateway at 30 by 30 m spatial resolution.

2.2.2 Bioclimatic envelopes for current and future species ranges

We applied a statistical approach, Random Forests (hereafter RF), for modeling current and future ranges of three native conifer species (western redcedar, western hemlock, and Douglas-fir) in the State of Washington. RF is a regression- and classification-tree-based technique widely used in ecology, bioinformatics, and medicine (Breiman, 2001, Cutler et al., 2007a). This method is an effective classifier, capable of handling large data sets with many variables. It is seen as a gray box (as opposed to black box) approach because it can provide some information on how the model works. That is, it provides a rating on the variable importance and proximity but does not explicitly account for the underlying mechanisms and relationships among variables. In ecology, as ensemble classification tree analysis approach, RF is often used for predicting the habitat suitability and distribution of a species (Cutler et al., 2007b). This method has been found superior to other classification methods for modeling species distributions for animals as well as trees (Lawler et al., 2006, Prasad et al., 2006).

Climate suitability of habitats for three tree species – Douglas-fir, Western hemlock, and Western redcedar – native to Puget Sound area was modeled in current and projected climates using the RF package in the R programming environment (R Development Core Team, <http://www.R-project.org>). We trained the RF models of the current distribution of each species using topographical data – slope and aspect – and climate data – monthly precipitation from January to December (MP), mean annual precipitation (MAP), and monthly average temperature in January to December (TAVG), the difference between August and January mean temperatures (TD), monthly maximum and minimum temperatures from January to December, respectively (TMAX and TMIN). After testing the performance with the current distribution data, we applied the resulting model for each species to predict the habitat suitability into the future (2020s, 2050s, and 2080s) based on A1B, B2, and A2 scenarios from the projections of two

general circulation models: CGCM2 and ECHAM5 obtained from the CCAFS data portal (Figure 3).

2.2.3 Bioclimatic envelopes for seed transfer zones within WA

We also used RF models to predict future changes in seed transfer zones of the tree species in and around the Puget Sound region in a similar fashion described in the previous section. We first modeled and tested climatic envelopes for current seed zones in the region using RF. We then predicted the potential shift of these seed zones under 12 different combinations of GCM and SRES scenarios that were available from the CCAFS data portal as shown in Table 1.

Table 1. General circulation models (GCMs) and SRES emission storylines used for tree seed transfer zone predictions in the Puget Sound region. The combinations marked with a circle were available from CCAFS data portal and used for seed transfer zone predictions.

| Model name | MPI-ECHAM5 | | | CCCMA-CGCM2 | | | NIES99 | | | NCAR-PCM | | | CSIRO | | | HADCM | | |
|---------------|------------|-----|----|-------------|-----|----|--------|-----|----|----------|-----|----|-------|-----|----|-------|-----|----|
| SRES emission | B2 | A1b | A2 | B2 | A1b | A2 | B2 | A1b | A2 | B2 | A1b | A2 | B2 | A1b | A2 | B2 | A1b | A2 |
| Available | X | ○ | X | ○ | ○ | ○ | ○ | X | ○ | X | ○ | X | ○ | X | ○ | ○ | ○ | ○ |

2.3 Evaluation of urbanization effects on urban temperatures

2.3.1 Urban population changes and urban heat island effect in the Puget Sound

Increases in temperature and urban population are commonly found to have a close relationship. We adopted a method used in Choi et al. (2003) and Chung et al. (2004) to evaluate urban heat island effects on urban climate in the WA State. Briefly, we acquired land-cover data of urban, agriculture, forestry, grass, wetland, bare ground, and water body at 30m x 30m resolution from USGS GIS gateway (<http://datagateway.nrcs.usda.gov>) and extracted only those pixels relevant to urban land use in Washington State. Among 818 cities in Washington State, 32 cities that had more populations that exceeded 10,000 with sufficient population records for the past four decades (i.e., 1980, 1990, 2000, and 2010) were selected and their population data were obtained from the Census of United States Census (<http://www.census.gov>). Changes in population for each of the 32 cities have been calculated, expressed in logarithm, and paired with the changes in monthly mean temperatures of that city over the same period. Using data from all 32 cities, we evaluated if recent population changes as surrogate of urbanization could explain recent temperature increases in the region by examining the relationship between the log transformed changes in population and the changes in temperature for the same period in each month. If increases in temperature were related to population increase, one would expect to see a positive correlation between the two variables. If warming took place regionally independent of urban population increases one would expect no correlation between the two variables but mean temperature changes would be significantly greater than zero. We

performed this analysis for all 32 cities combined that are dispersed throughout the State, then with a subset of 21 cities that are located in and around the Puget Sound region, and with the remaining 11 cities that are mostly located in the east-side of the Cascades and south-west Washington (see Table 2). This analysis could give us insights on whether or not and to what degree urbanization has contributed to recent temperature changes in the region.

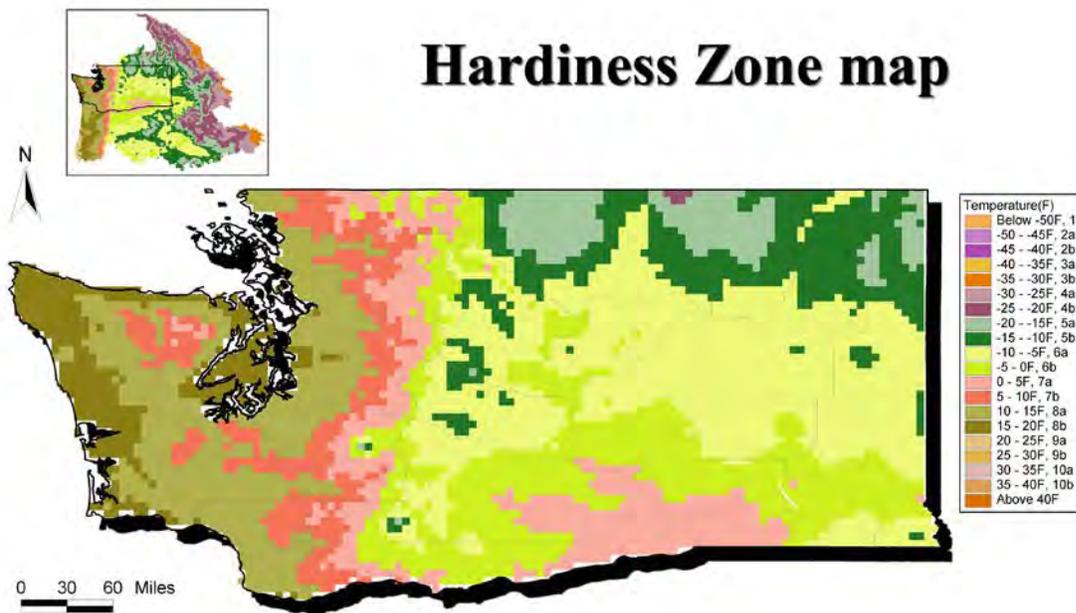
3 Results and Discussion

3.1 Plant Hardiness Zones in the Puget Sound and Washington State

The relationship between plant survival and temperature is commonly characterized by various zone maps such as USDA plant hardiness zones. The USDA hardiness zone map is arguably the most widely used and recognized tool for plant selection in horticulture, arboriculture, and urban forestry. We have created current and future hardiness zone maps for the Puget Sound and Washington State.

The PHZM we developed for recent climate compared well with the USDA map for Pacific Northwest matching the zone identifications (version 1990) (See **Fig. 4. top**). The projected future hardiness zone maps suggest that **there will likely be an increase of roughly half a hardiness zone across most of the Puget Sound region** (e.g., from zone 8a to zone 8b, or zone 8b to 9a etc.) by year 2080 (Fig.4. bottom). This translates to an increase of approximately 2 to 3 °F in annual extreme minimum temperatures in the region by 2080s. The shifting PHZMs have implications for plant selection for urban forestry, horticulture and restoration purposes as well as for plant invasion risks (Widrlechner et al., 2012, Bradley et al., 2012).

Hardiness Zone map



These temperatures are based on the lowest temperatures recorded for each of the years 1974 to 1986 in data set, which is from the University of Washington Climate Impacts Group (CIG). The temperature legend in this map is made using those of "Plant Hardiness Zone Map" of USDA".

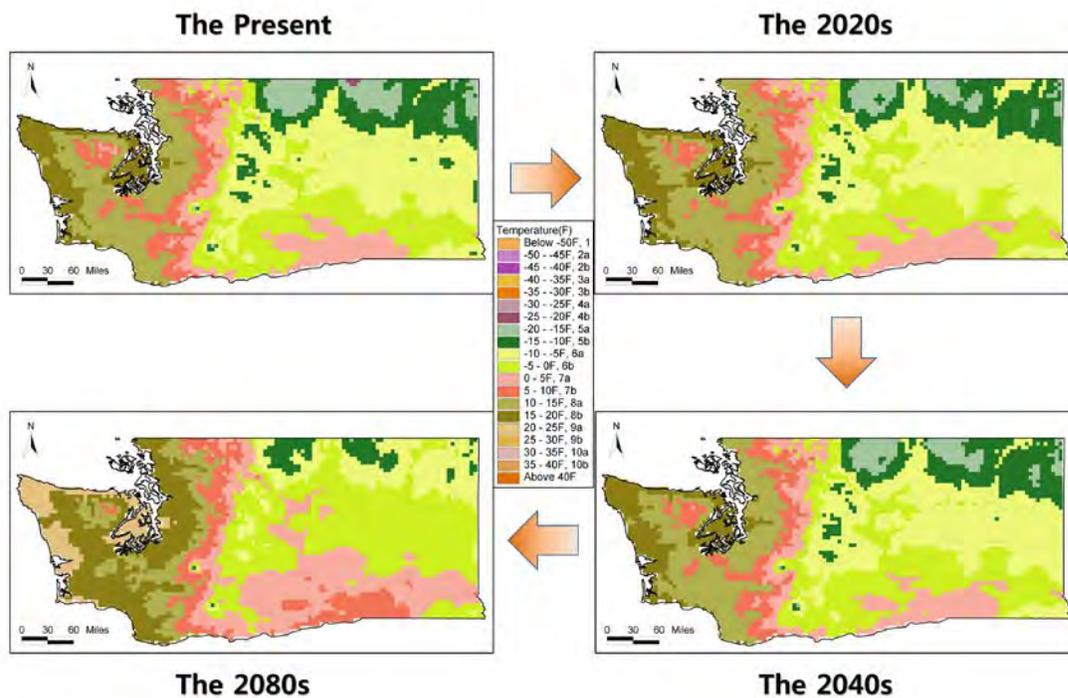


Fig. 4. Plant hardiness zone maps for the past, present, and future in Washington State.

3.2 *Climate suitability predictions for tree habitat and seed transfer zones*

3.2.1 Current range of selected native tree species

Current distributions of Douglas-fir, western hemlock, and western redcedar are shown in Fig. 5. Douglas-fir ranges from British Columbia, Canada through coastal and inland western US regions, and down to Mexico whereas western hemlock and western redcedar distributions are limited to Pacific Northwest region. The current distributions of the three native conifer species within WA State overlap quite extensively; all of them widely growing on the west side of cascades including Puget Sound area. Based on current distributions of these tree species, we trained random forests models to predict climate suitability for each species under future climate projections within WA State. After training, the RF approach successfully modeled current distribution of these species in their entire range as well as their distribution within WA.

3.2.2 Modeled native tree species range within WA State

Using the RF models, we predicted the range of the three native conifers in WA State for 2020s, 2050s, and 2080s. When the model was trained using data from the entire range of currently known distributions of western redcedar and applied to three different climate projections based on A2, A1B, and B2 emission scenarios, the RF model indicated that overall climate suitability for this species would encounter little change over this century within WA State (Fig. 6; left-side column). This result is likely because the distribution of the species extends well beyond WA State (see Fig. 5). However, when the RF models were trained using climate data only from the current seed transfer zones (all seedzones combined) within WA State, the model output indicated that a majority of areas in the current “Puget Sound” seed zone will experience climates that are different than those found within any current seed zones (Fig. 6; right-side column). That is, considerable mismatches between current and future climates of seed zones within WA State are predicted to emerge in the middle of 21st century mostly from the Puget Sound area where urbanization is concentrated and most urban forests for restoration and conservation are located. Very similar results emerged for western hemlock and to a lesser extent for Douglas-fir (See Appendix 1).

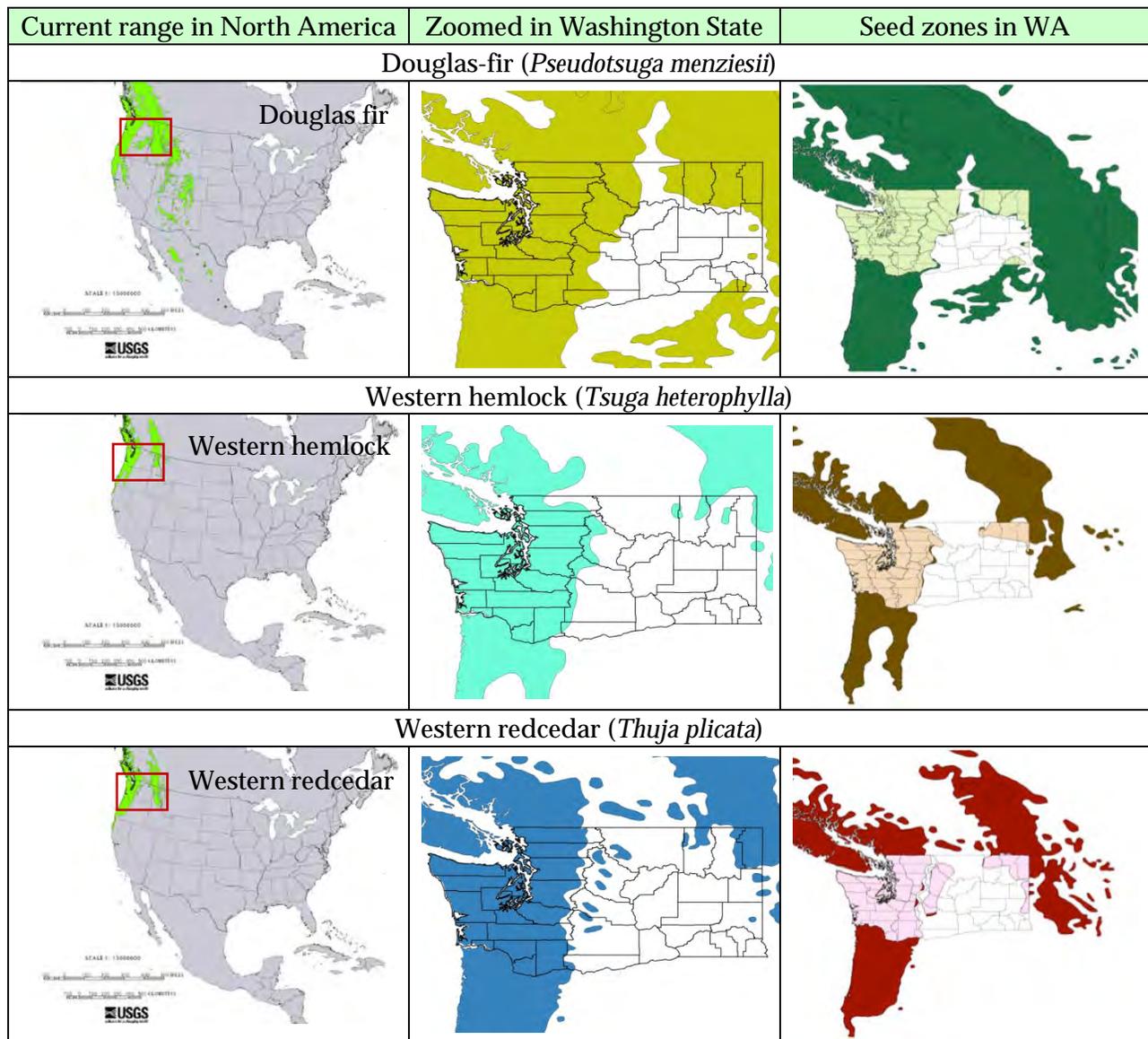


Fig. 5. Current range of Douglas-fir, western hemlock, and western redcedar in North America. Maps in the middle column are zoomed into WA State. Maps on the right-side column show the seedzones for each species within WA state. Data source: USGS “Atlas of United States Trees” written by Elbert L. Little, Jr. (<http://esp.cr.usgs.gov/info/veg-clim/>); Seed zones from Randall and Berrang (2002) (http://www.dnr.wa.gov/ResearchScience/Topics/ForestResearch/Pages/lm_tree_seed_zones.aspx)

(A) Predicted climate suitability for WRC as species considering its entire range

(B) Predicted climate suitability for WRC seed zones in WA

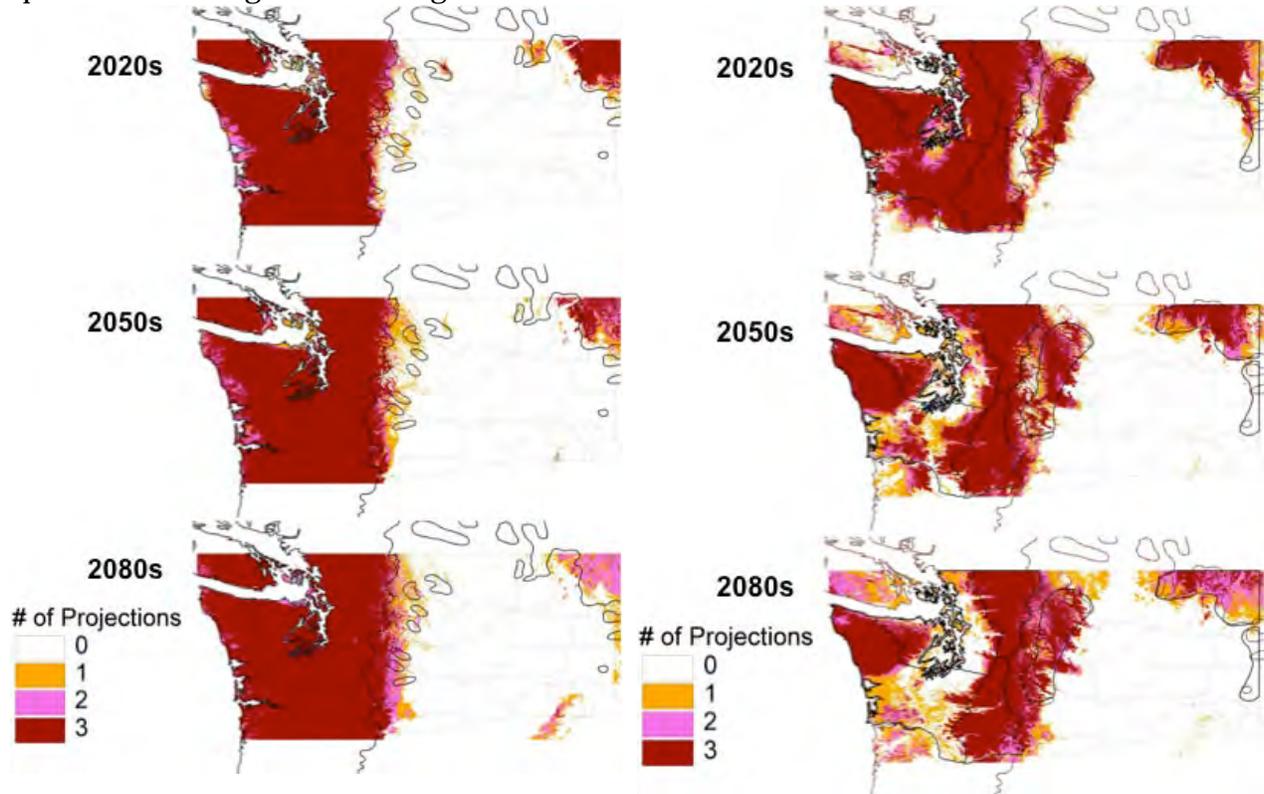


Fig. 6. Predicted climate suitability for Western redcedar (WRC) as species (A) and for seed zones within WA State (B). Three future climate projections (CCCMA-CGCM2 for A2 and B2 emission scenarios and MPI-ECHAM5 for A1B emission scenario) were used and their agreement is noted by colors: **dark red** (all three agreed), **pink** (two agreed), **orange** (one predicted this area to match the climate conditions of current range), and **white** (non predicted this area to match the current range climate conditions). Little shift in range for suitable climate is predicted when distribution for whole species is considered. This is likely because the distribution of the species extends reaches a greater range beyond WA State (see Fig. 6). However, mismatch between current and future climates of seed zones within WA State is predicted to emerge in the mid 21st century mostly from the Puget Sound area where urbanization is concentrated. Predicted climate suitability for Douglas-fir and western hemlock is also available in Appendix 1.

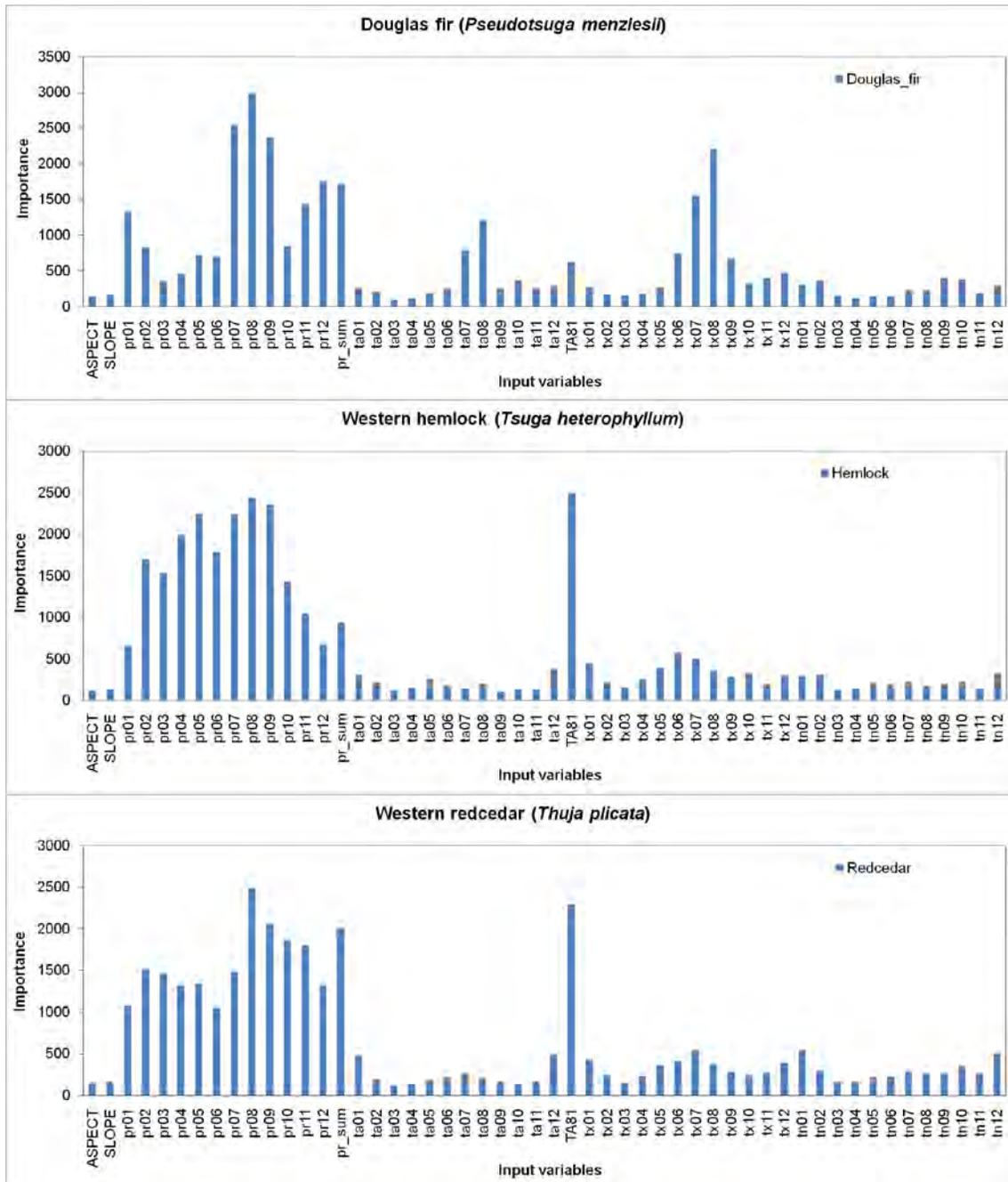


Fig. 7. Variable importance chart for determining climate suitability for current range of three conifer species Douglas-fir, Western redcedar and Western hemlock. This information is generated by Random Forests (RF) package in R statistical software. Precipitation in summer months scored high for their importance in determining the range of all three species and this trend was strongest for Douglas-fir. The difference between August and January average temperatures (TA81) also scored high for western redcedar and western hemlock while maximum temperature of summer months (tx07 and tx08) were important for Douglas-fir. ©

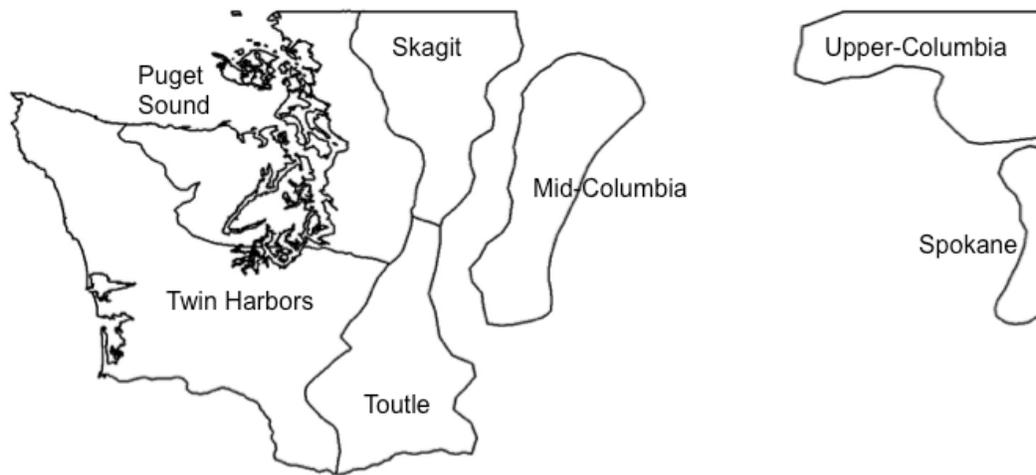
3.2.3 Modeled tree seed transfer zones: A case study for Western redcedar

To identify which areas will be most impacted by climate change and how this is related to the individual current seed transfer zones, we performed more detailed analyses on climate suitability with respect to seed transfer zones in native tree species focusing on Puget Sound region using twelve different combinations of SRES storylines and global climate models listed in Table 1.

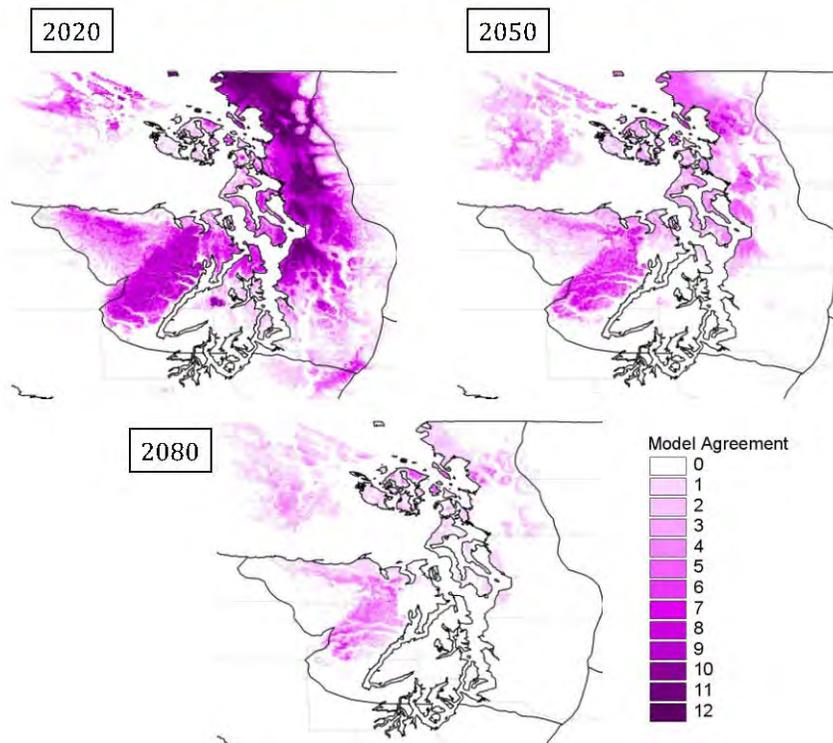
The current and projected seed zones of Western redcedar in the region are illustrated in Figure 8. The areas with more models agreeing to meet the bioclimatic envelopes of the current seed zones are shown with darker colors in Fig. 8. The model result indicates that the bioclimatic envelope that meets the Puget Sound seed zone for western redcedar is likely to shrink or disappear rapidly from the region towards the end of the century under all three scenarios (Fig. 8b) but is not entirely replaced by the climate conditions from other seedzones confirming the void adjacent to the Puget Sound shown in Fig. 6b. The bioclimatic conditions meeting the current seedzones of Skagit and Twin Harbor also are predicted to diminish gradually from the region whereas the climate conditions currently similar to Toutle seedzone are likely to prevalent throughout the region that are currently designated by Puget Sound, Skagit, and Twin Harbors seed transfer zones. This means that seed sources from Toutle seed transfer zones may be considered for other seed zones in the Puget Sound region for reforestation and restoration purposes. Increasing the diversity of seed sources that include current seed zones as well as future seed zones may enhance and ensure the probability of successful reforestation and restoration of western redcedar and other native tree species in the region. Similar results to western redcedar are found for western redcedar and Douglas-fir (See appendix C and D, respectively).

Recently, we have identified an online tool called “Seedlot Selection Tool (SST)” that was recently developed by Oregon State University and US Forest Service (see: <http://sst.forestry.oregonstate.edu/PNW/index.html>). This tool may be useful for identifying seedlots of native tree species that are suitable for a given planting site under different climate change projections and could provide helpful information for restoration planning of urban forests in the Puget Sound area.

(A) Current western redcedar seed zones in WA State



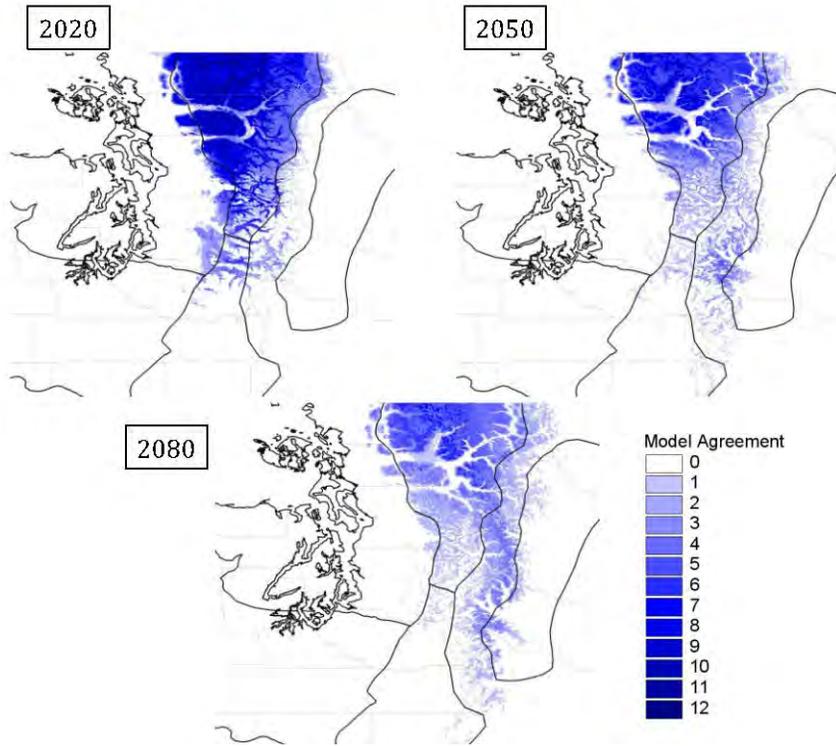
Predicted climate envelope for WRC seedzone: Puget Sound



(B)

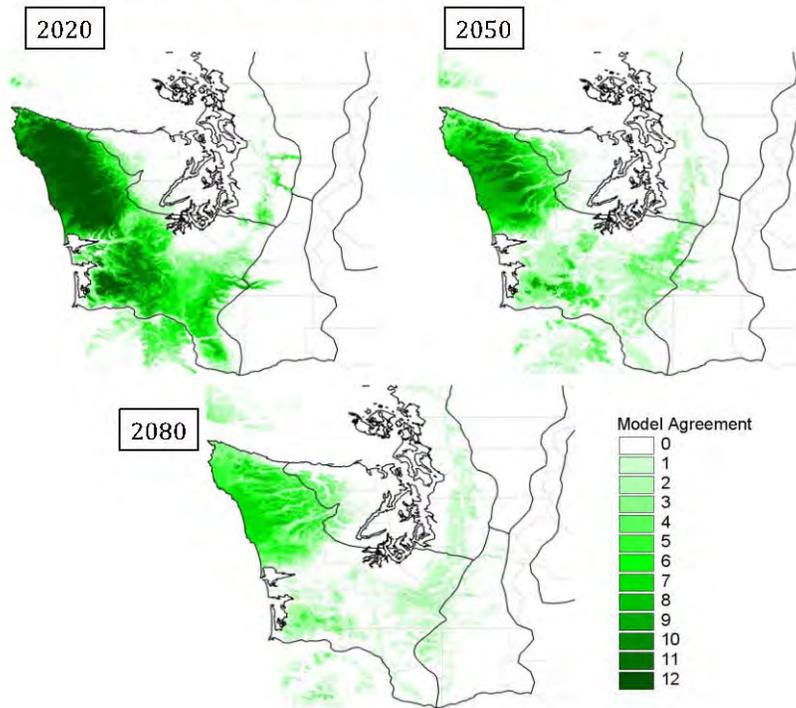
Fig 8. Current (A) and projected seed transfer zones (B-E) of western redcedar in Washington State. The future zones were predicted using 12 climate projections based on six GCMs and three SRES storylines as described in Table 1.

Predicted climate envelope for WRC seedzone: Skagit



(C)

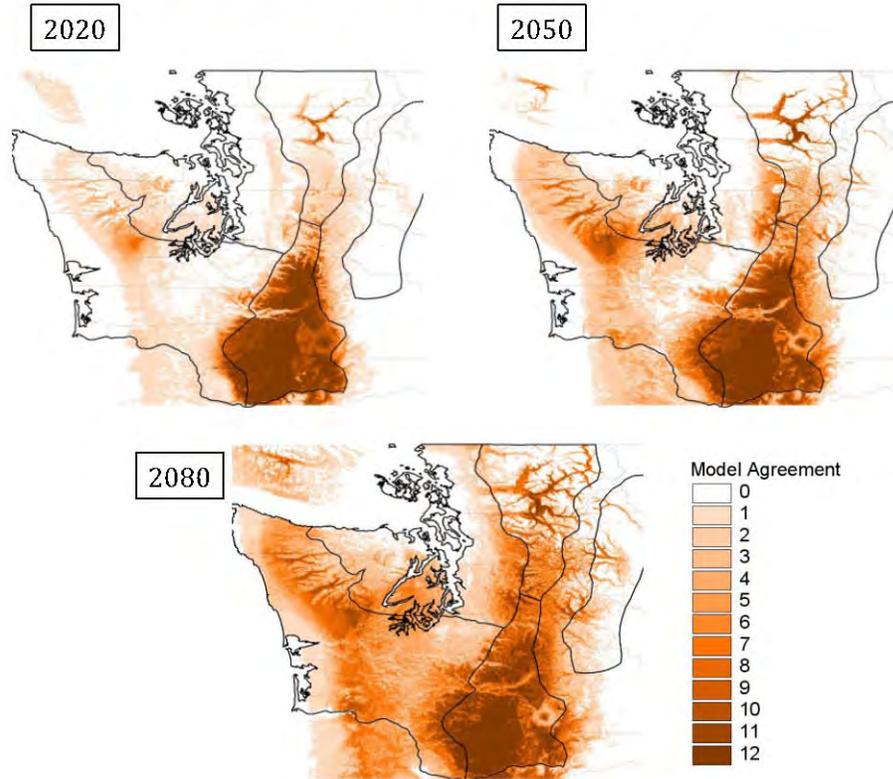
Predicted climate envelope for WRC seedzone: Twin Harbor



(D)

Fig 8. Cont'd

Predicted climate envelope for WRC seedzone:Toutle



(E)

Fig 8. Cont'd. Note: some climate projections predict that most areas of the Puget Sound are likely to experience bioclimatic conditions that are similar to that of Toutle seed transfer zone by the end of the century.

3.3 Changes in urban population and urban temperatures

The population of the 32 cities included in our analysis has increased by 51% on average from 1990 to 2010 (Table 2). Several cities experienced more than doubling of their population during this period; these cities include Camas, Pasco, Mukilteo, and Kenmore. Bremerton was the only city among the 32 cities that has experienced population decrease by 1%. Seattle, the most populated city of the region, has seen an increase of 18% from 516,259 in 1990 to 608,660 in 2010 (Table 2). Urban heat island effects are usually more pronounced in winter months than summer months. The temperatures of many cities (December temperature as example) have increased during this period but this trend is not universal. The relationship between population changes as surrogate of urbanization and temperature changes of the 32 cities is illustrated in Fig. 9 for winter months and in Fig. 10 for summer months.

Table 2. Changes in population and December mean temperature (°C) of 32 cities in Washington State from 1990 to 2010. Cities in and around the Puget Sound are marked as West in their direction.

| NAME | Direction | POP1990 | POP2000 | POP2010 | Temp. difference |
|-------------------|------------|---------|---------|---------|------------------|
| Seattle | West | 516259 | 563377 | 608660 | -0.35 |
| Tacoma | West | 176664 | 193585 | 198397 | 0.39 |
| Bellingham | West | 52179 | 67449 | 80885 | 0.59 |
| Redmond | West | 35800 | 45657 | 54144 | -0.19 |
| Kirkland | West | 40052 | 45054 | 48787 | -0.36 |
| Olympia | West | 33840 | 43016 | 46478 | 0.44 |
| Bremerton | West | 38142 | 37267 | 37729 | 0.18 |
| Puyallup | West | 23875 | 34321 | 37022 | 0.44 |
| Lynnwood | West | 28695 | 33859 | 35836 | -0.29 |
| University Place | West | 27701 | 29975 | 31144 | 0.42 |
| Spanaway | West | 15001 | 21588 | 27227 | 0.45 |
| Mercer Island | West | 20816 | 22036 | 22699 | -0.28 |
| Oak Harbor | West | 17176 | 19731 | 22075 | -0.06 |
| Kenmore | West | 8917 | 18678 | 20460 | -0.24 |
| Mukilteo | West | 7007 | 18019 | 20254 | -0.32 |
| Mountlake Terrace | West | 19320 | 20418 | 19909 | -0.28 |
| Tukwila | West | 11874 | 17181 | 19107 | 0.19 |
| Port Angeles | West | 17710 | 18449 | 19038 | 0.17 |
| Aberdeen | West | 16565 | 16461 | 16896 | 0.46 |
| Centralia | West | 12101 | 14867 | 16336 | 0.76 |
| Anacortes | West | 11451 | 14514 | 15778 | 0.22 |
| Longview | South West | 31499 | 34665 | 36648 | 0.8 |
| Camas | South West | 6442 | 12805 | 19355 | 0.73 |
| Spokane | East | 177196 | 197070 | 208916 | 1.39 |
| Kennewick | East | 42155 | 59196 | 73917 | 1.85 |
| Pasco | East | 20337 | 33845 | 59781 | 1.87 |
| Richland | East | 32315 | 38736 | 48058 | 1.72 |
| Walla Walla | East | 26478 | 30538 | 31731 | 1.1 |
| Pullman | East | 23478 | 24994 | 29799 | 0.93 |
| Moses Lake | East | 11235 | 15378 | 20366 | 1.94 |
| Ellensburg | East | 12361 | 15487 | 18174 | 2.65 |
| Sunnyside | East | 11238 | 14224 | 15858 | 1.31 |

The 21 cities in and around the Puget Sound showed little temperature increases in winter months (Fig. 9 bottom row) but slight warming in summer months (Fig. 10 bottom row). Temperature increases in the cities located in the east-side of the Cascades were more pronounced during winter months (Fig. 9 middle row) and slight warming was also observed in July (Fig. 10 middle row). There was a moderate tendency of increasing winter month temperatures coinciding with population increases in the east-side cities (Fig. 9 middle row) but this trend was less apparent in the Puget Sound cities (Fig. 9 middle row). A more comprehensive analysis that expands to more cities and their surrounding areas in the region over longer periods will be needed to thoroughly assess the local warming effect due to urbanization in comparison with the global or regional warming due to climate change. This may be achieved by comparing the temperatures of cities and the temperatures of the surrounding areas to determine 1) if the city exhibits an increase in temperature at a greater rate than the surrounding landscape and 2) if trend was more pronounced for those cities with more rapidly growing populations. Bioclimatic envelope models for urban ecosystems may be improved by explicitly accounting for urbanization effects such as an increase in population density and associated local warming.

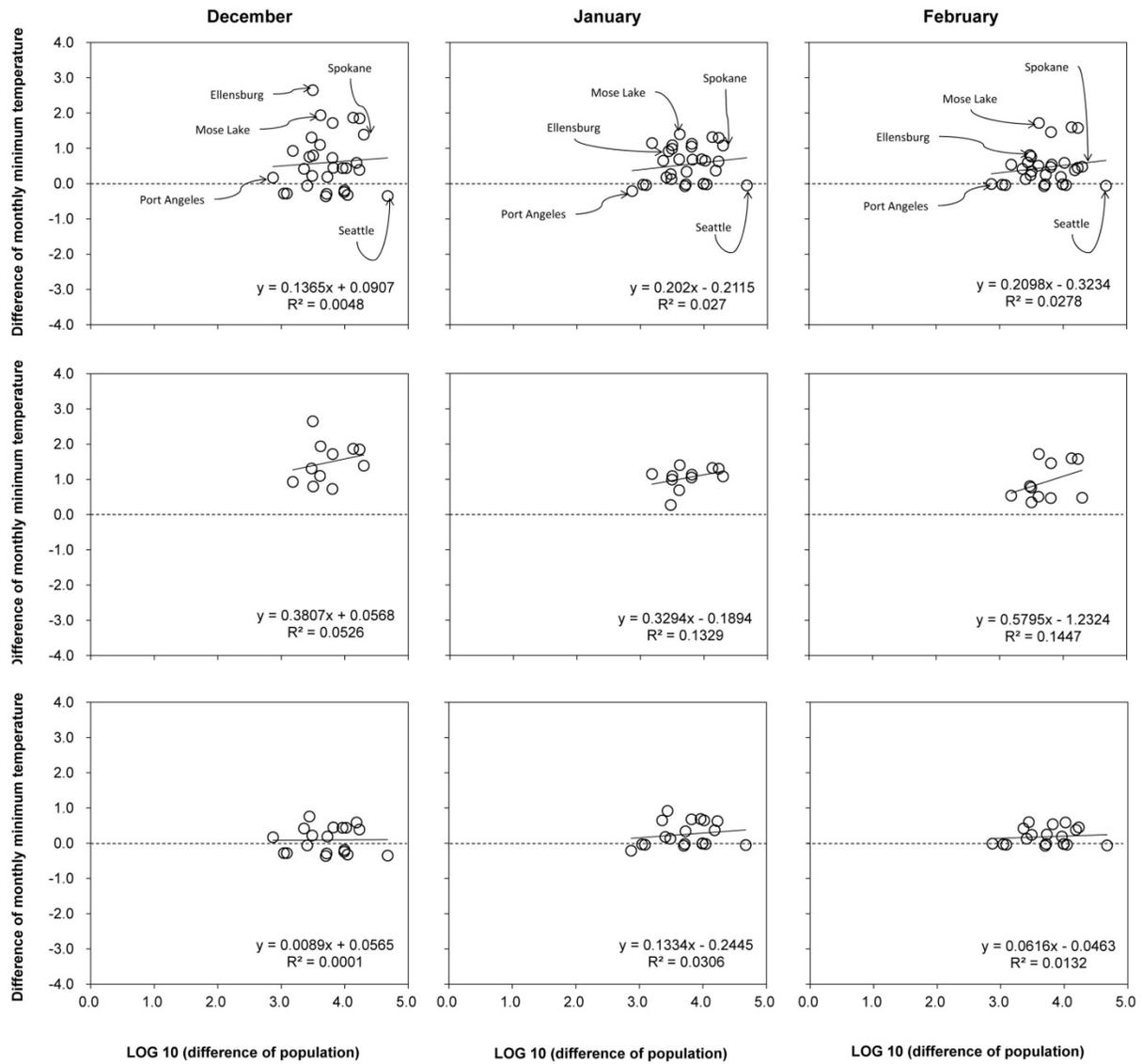


Fig. 9. Relationship between recent population changes and temperature changes during winter months in 32 cities in WA State. Top rows: all 32 cities combined; Middle row: 11 cities in the east and south-west; Bottom row: 21 cities in and around the Puget Sound. See table 2 for the list of cities included in the analysis.

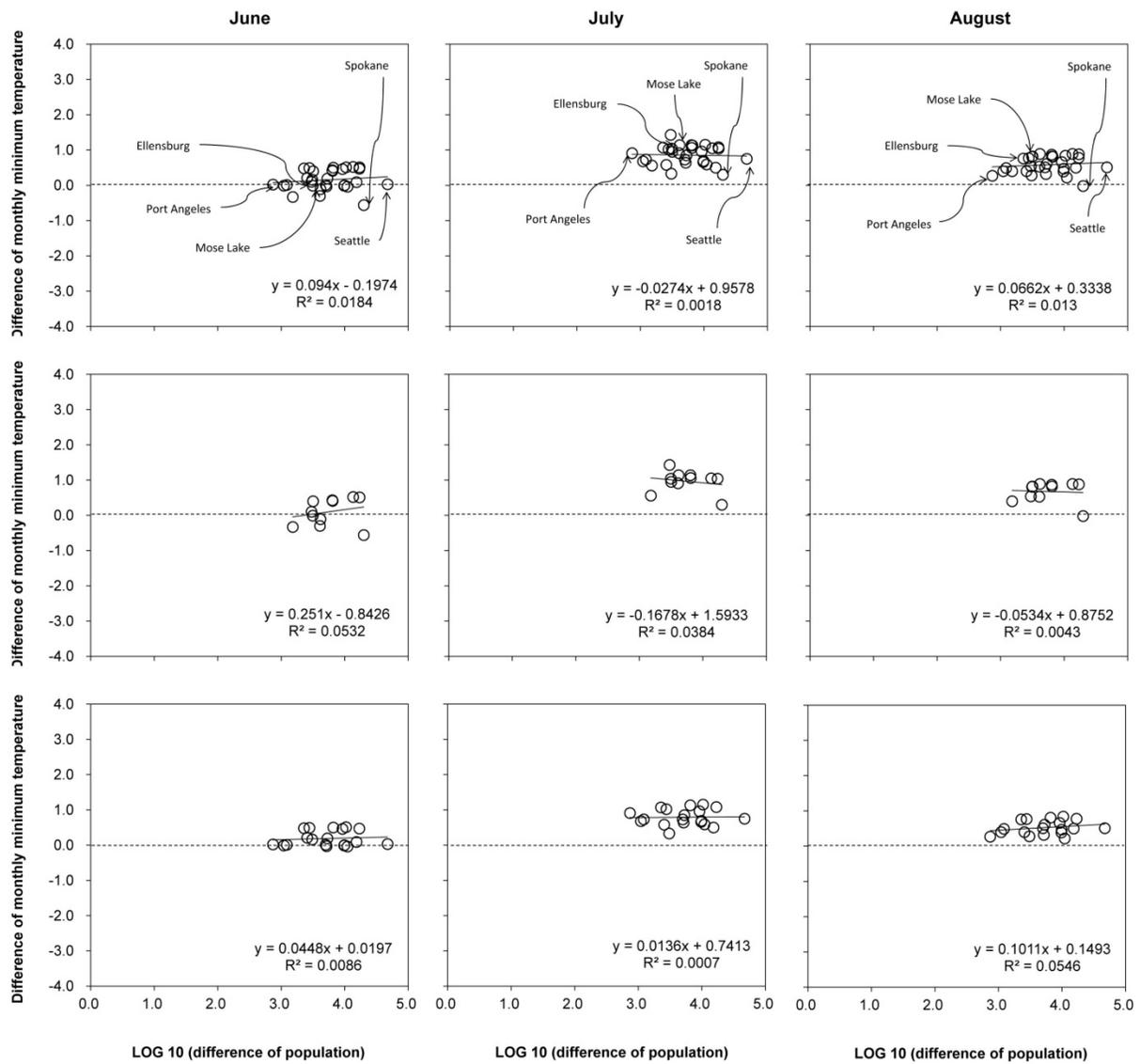


Fig. 9. Relationship between recent population changes and temperature changes during summer months in 32 cities in WA State. Top rows: all 32 cities combined; Middle row: 11 cities in the east and south-west; Bottom row: 21 cities in and around the Puget Sound. See table 2 for the list of cities included in the analysis.

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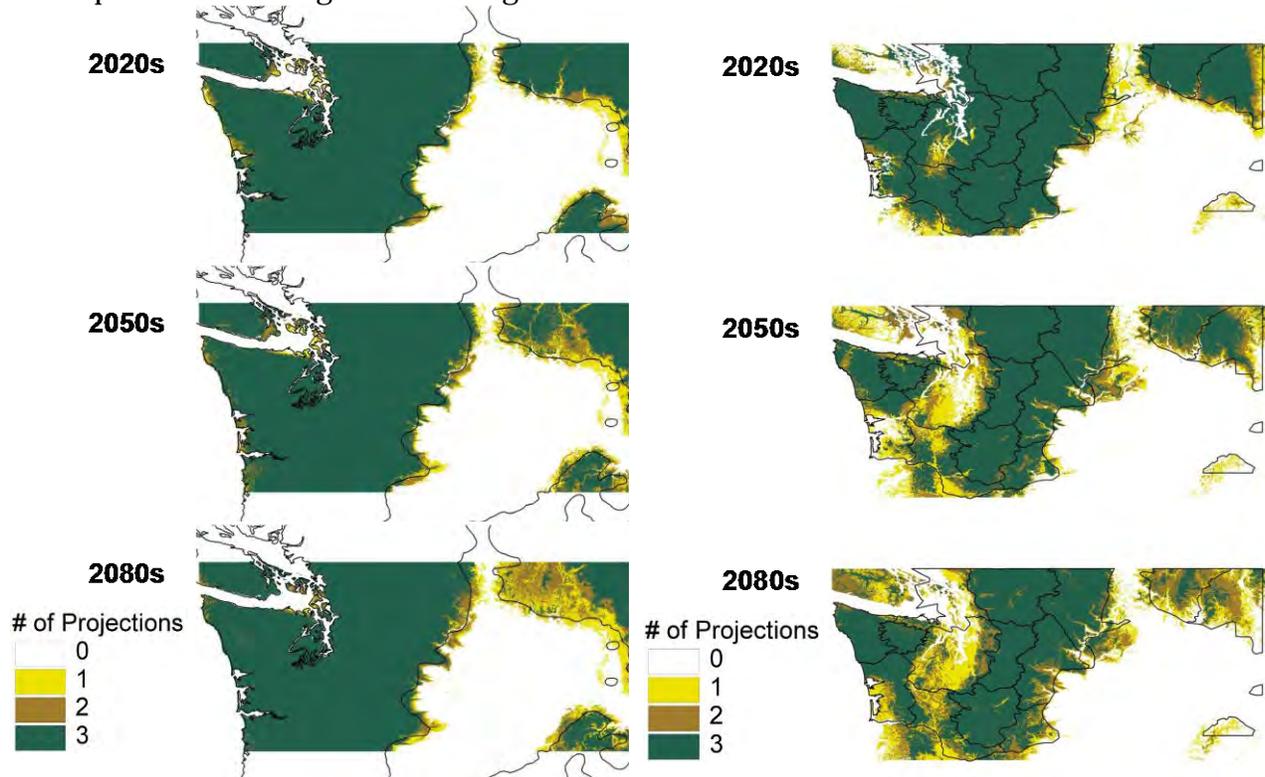
Appendices

Appendix 1. Predicted future climate suitability for Douglas-fir and western hemlock

1.1 Douglas-fir

(A) Predicted climate suitability for Douglas-fir as species considering its entire range

(B) Predicted climate suitability for Douglas-fir seed zones in WA

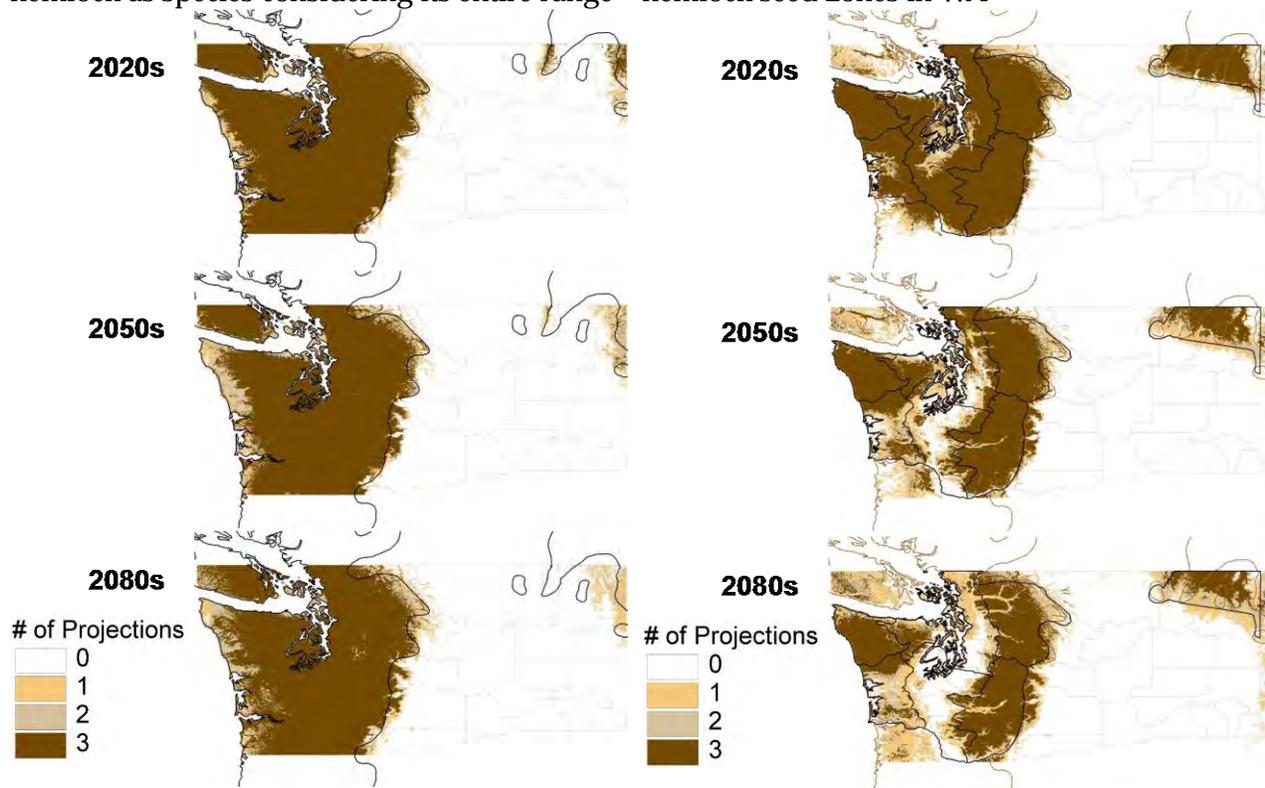


Suppl. Fig. 1.1. Predicted climate suitability for Douglas-fir as species (A) and for seed zones within WA State (B). Three future climate projections (CCCMA-CGCM2 for A2 and B2 emission scenarios and MPI-ECHAM5 for A1B emission scenario) were used and their agreement is noted by colors: green (all three agreed), light brown (two agreed), yellow (one predicted this area to match the climate conditions of current range), and white (non predicted this area to match the current range climate conditions).

1.2 Western hemlock

(A) Predicted climate suitability for western hemlock as species considering its entire range

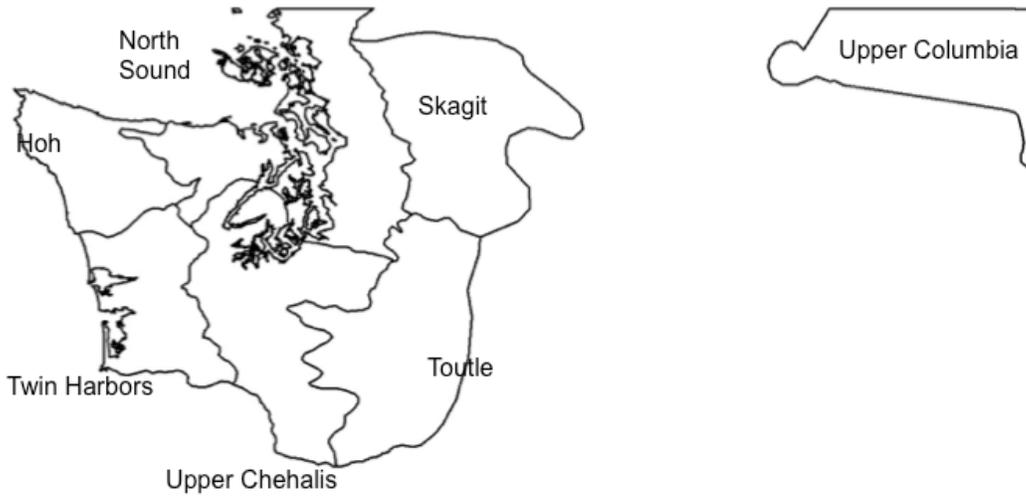
(B) Predicted climate suitability for western hemlock seed zones in WA



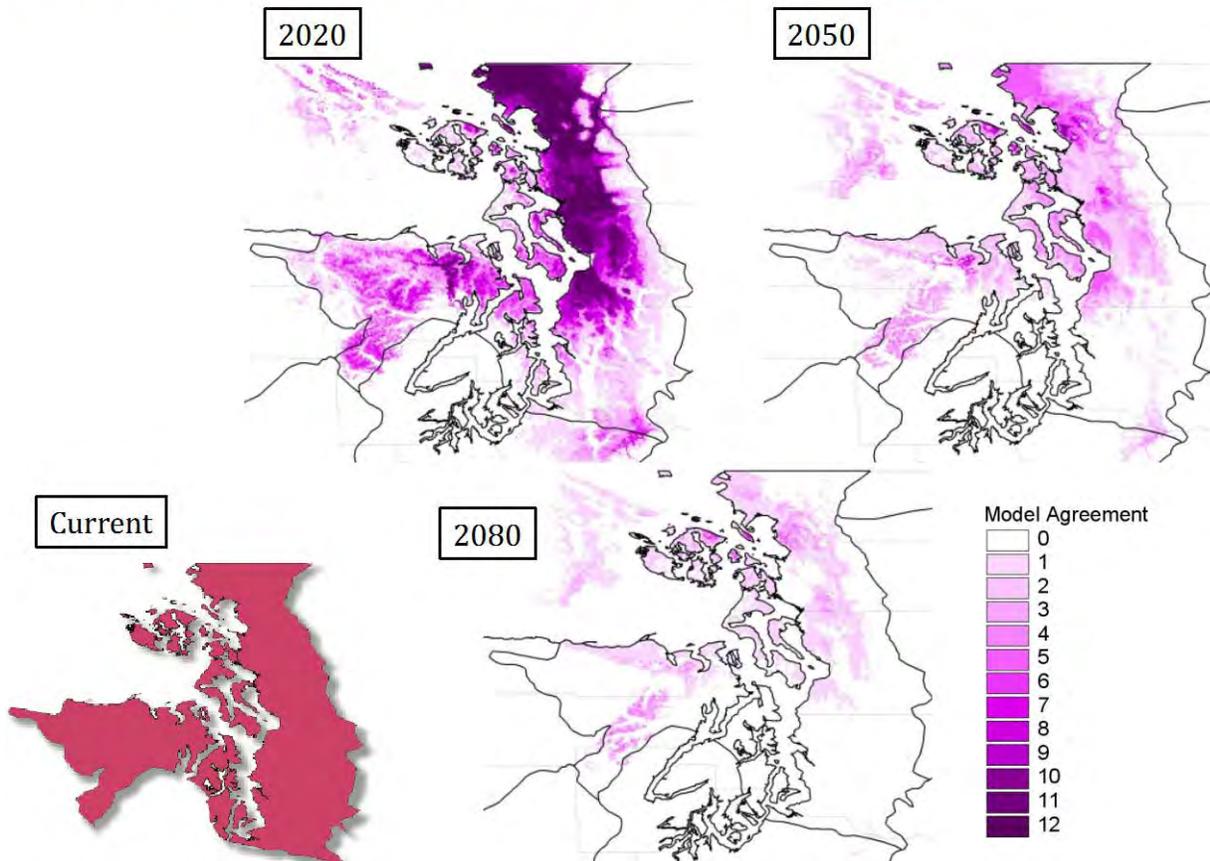
Suppl. Fig. 1.2. Predicted climate suitability for western hemlock as species (A) and for seed zones within WA State (B). Three future climate projections (CCCMA-CGCM2 for A2 and B2 emission scenarios and MPI-ECHAM5 for A1B emission scenario) were used and their agreement is noted by colors: green (all three agreed), light brown (two agreed), yellow (one predicted this area to match the climate conditions of current range), and white (non predicted this area to match the current range climate conditions).

Appendix 2. Changes in seed transfer zones for western hemlock

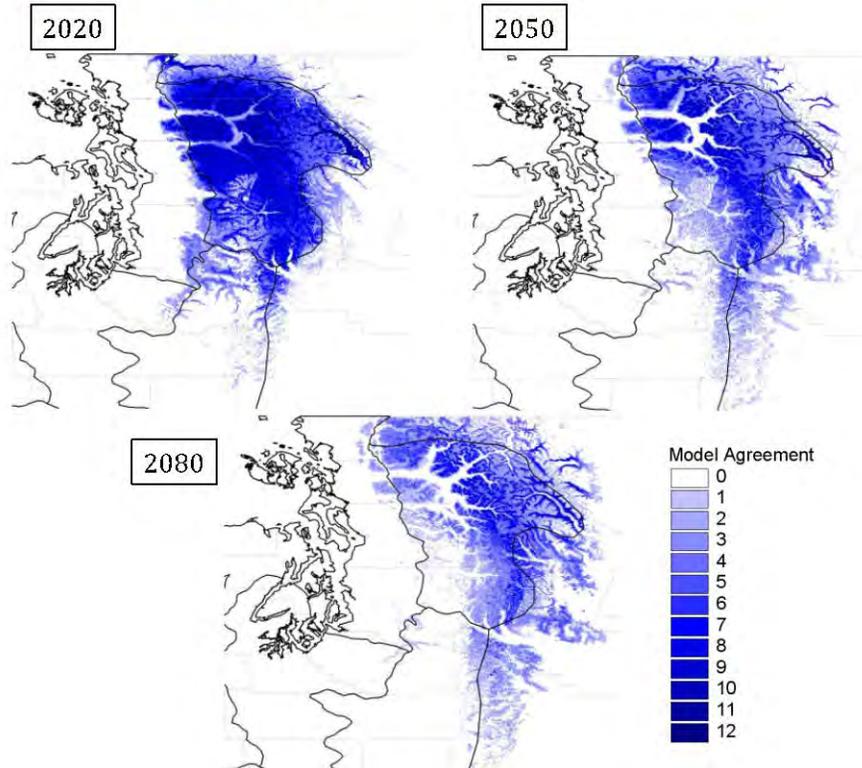
Current seed transfer zones



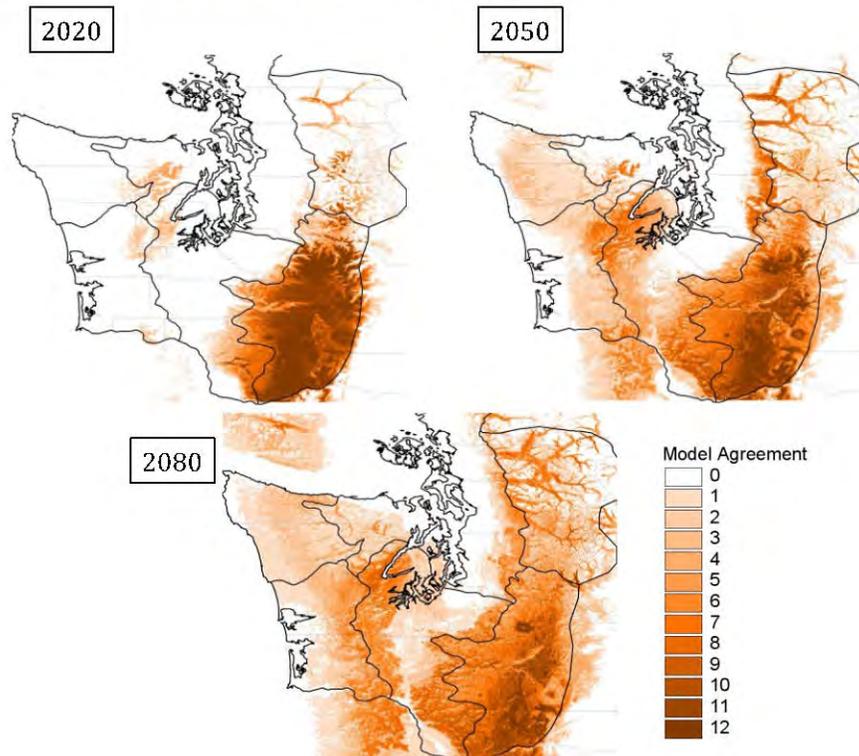
Predicted climate envelope for WH seedzone: North Sound



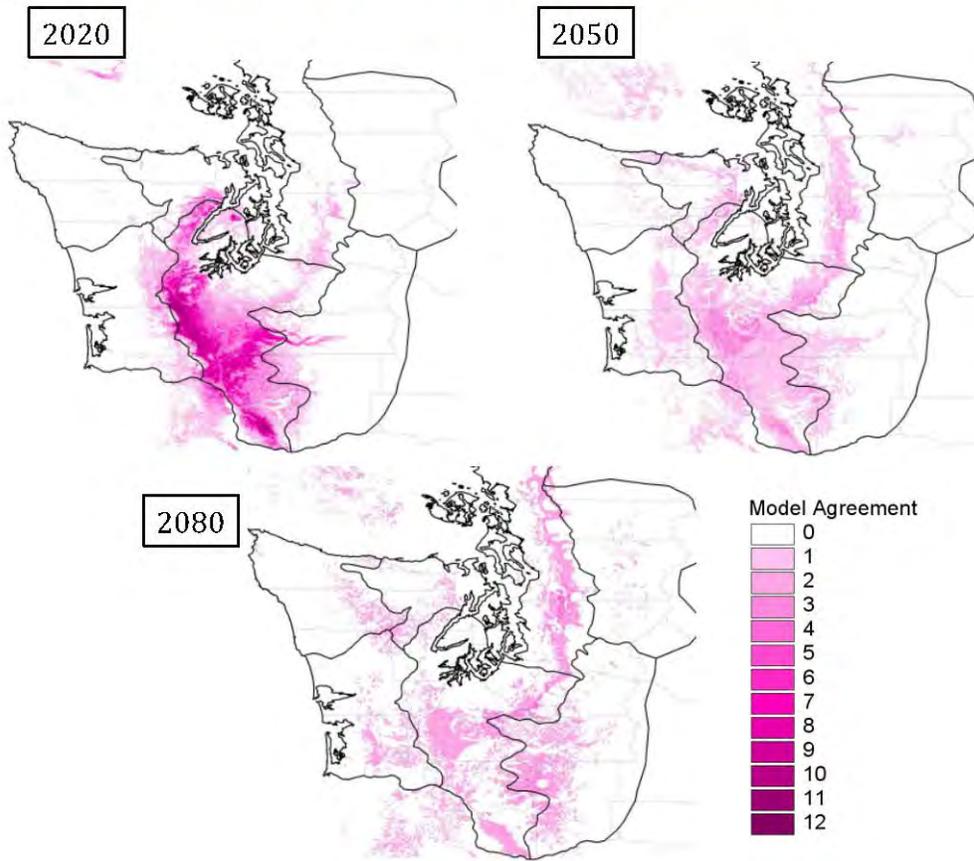
Predicted climate envelope for WH seedzone: Skagit



Predicted climate envelope for WH seedzone: Toutle



Predicted climate envelope for WH seedzone: Upper-Chehalis

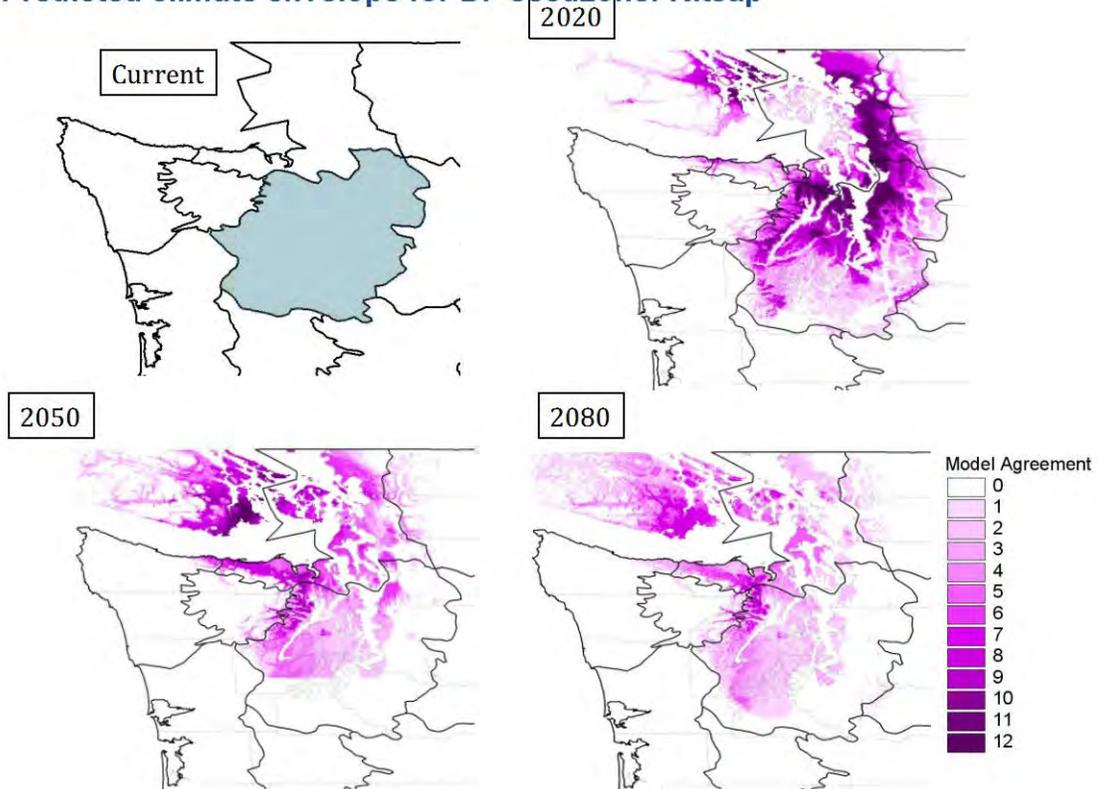


Appendix 3. Changes in seed transfer zones for Douglas-fir

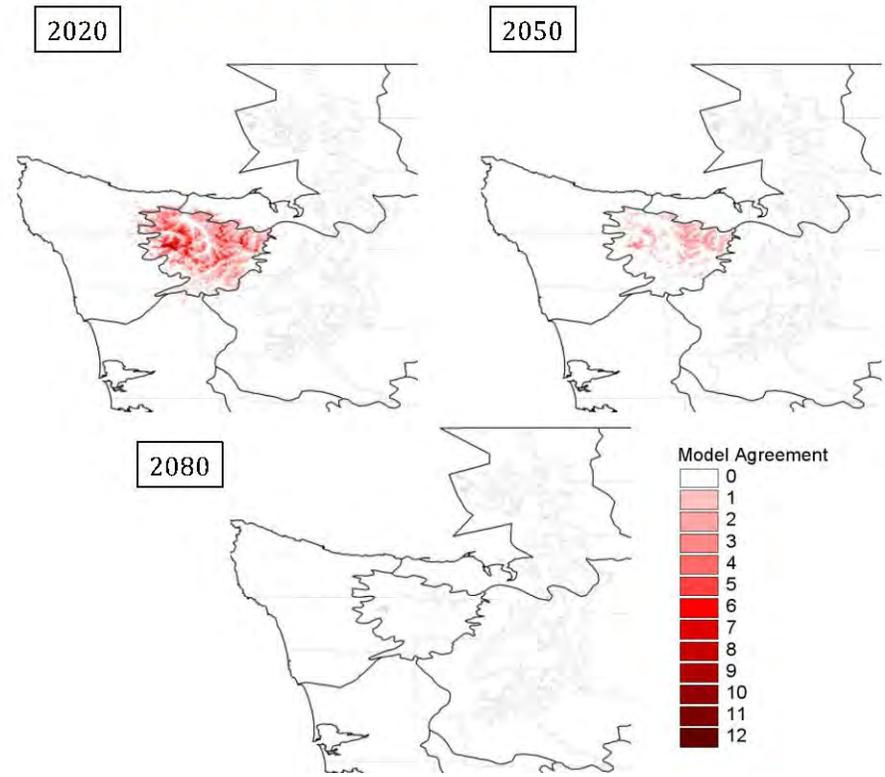
Current Seed transfer zones



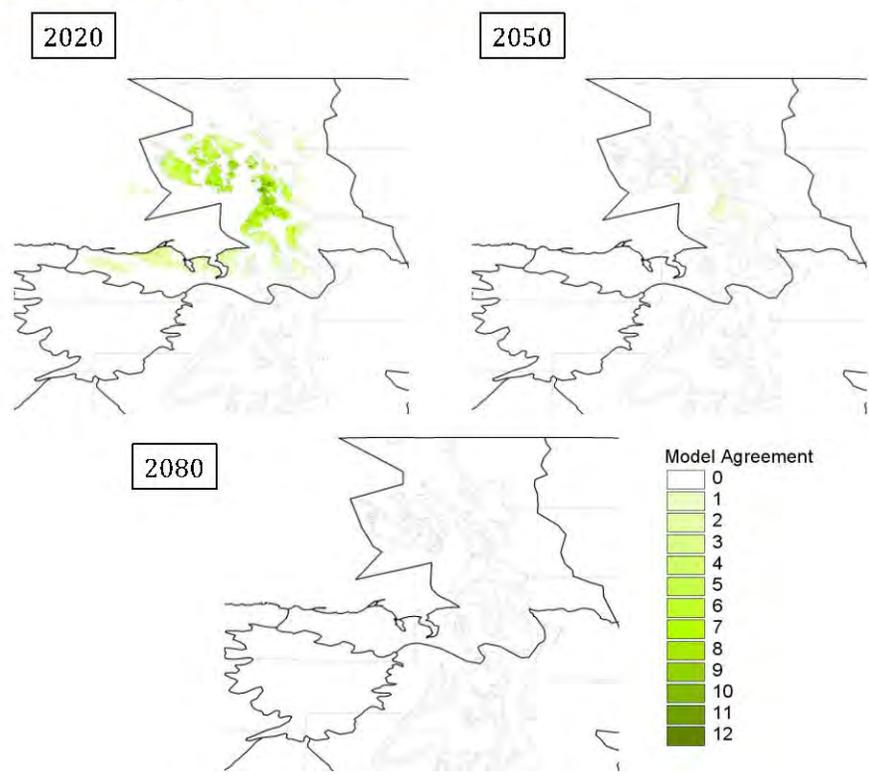
Predicted climate envelope for DF seedzone: Kitsap



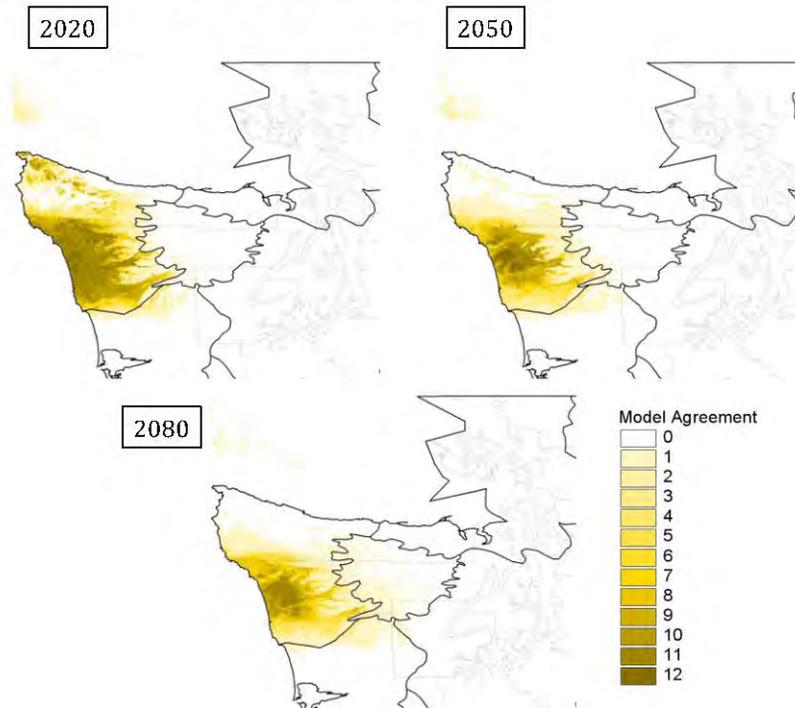
Predicted climate envelope for DF seedzone: Elwha



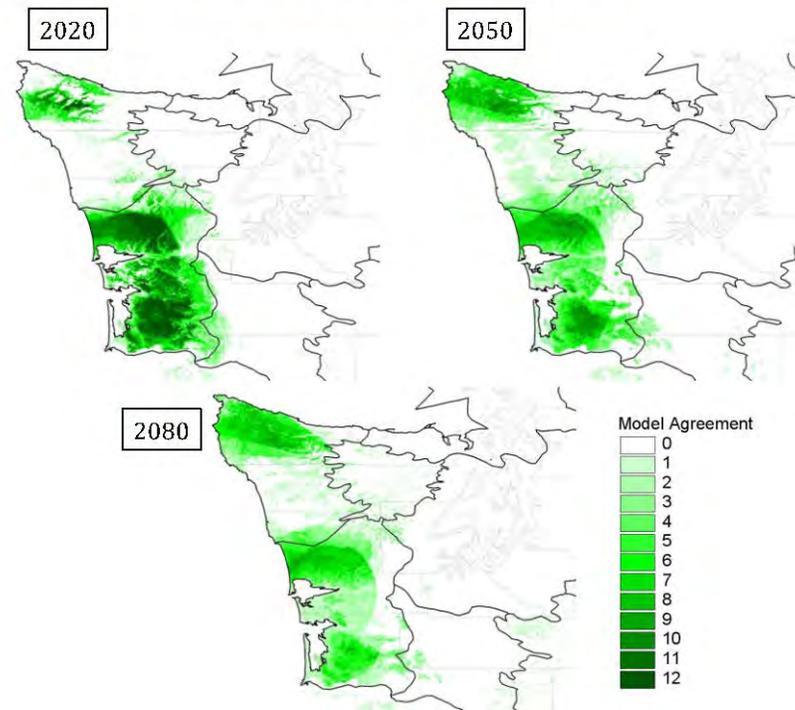
Predicted climate envelope for DF seedzone: Islands



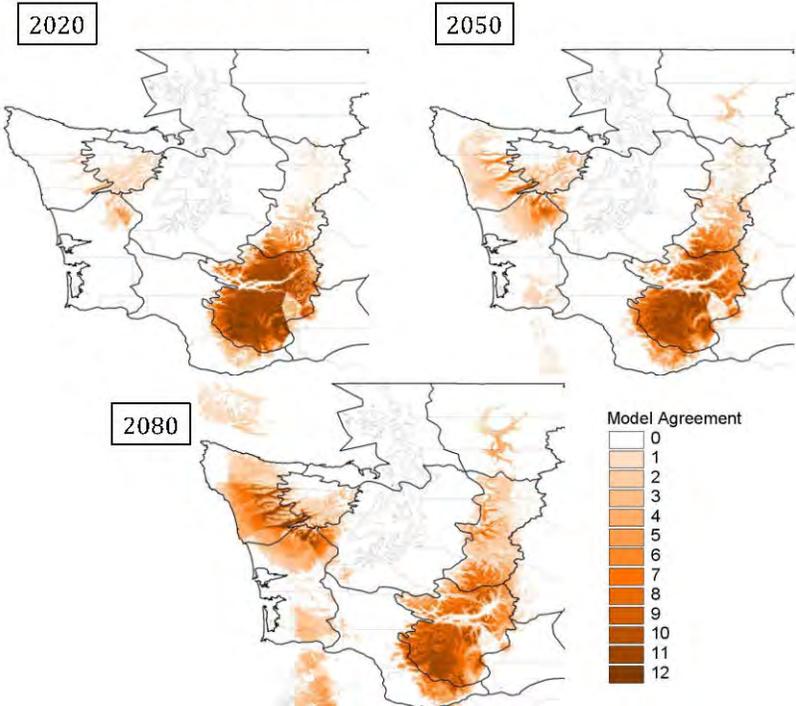
Predicted climate envelope for DF seedzone: Hoh



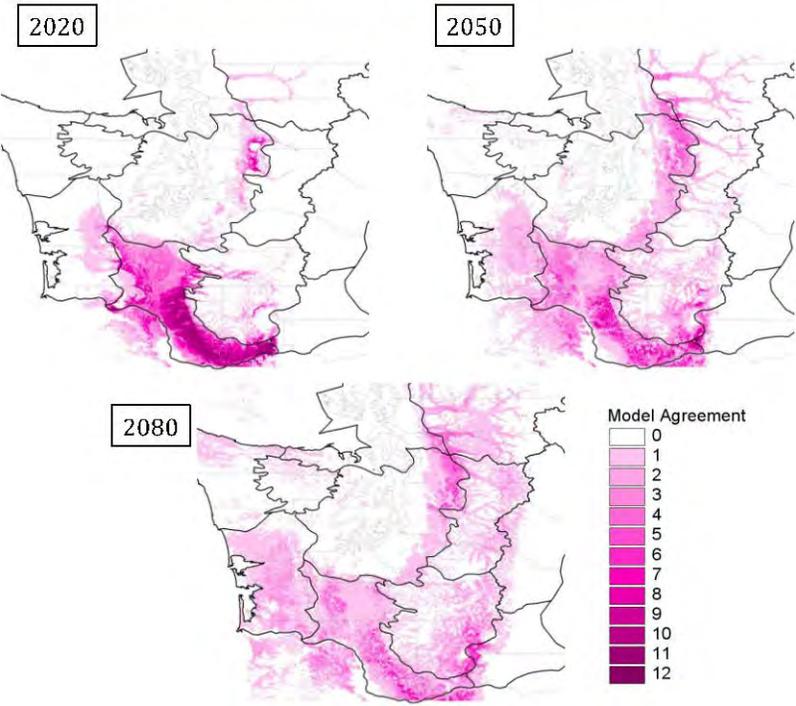
Predicted climate envelope for DF seedzone: Twin Harbors



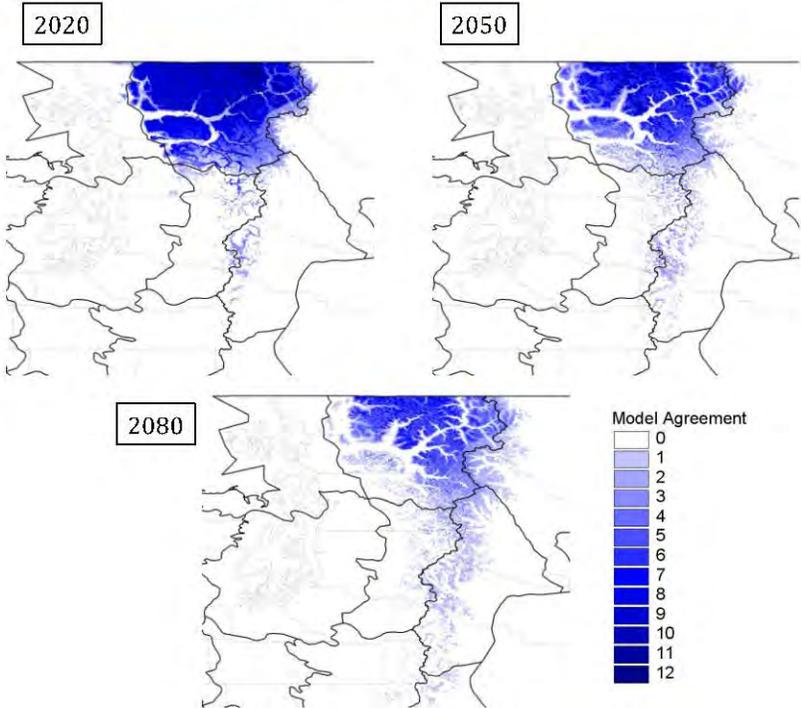
Predicted climate envelope for DF seedzone: Toutle



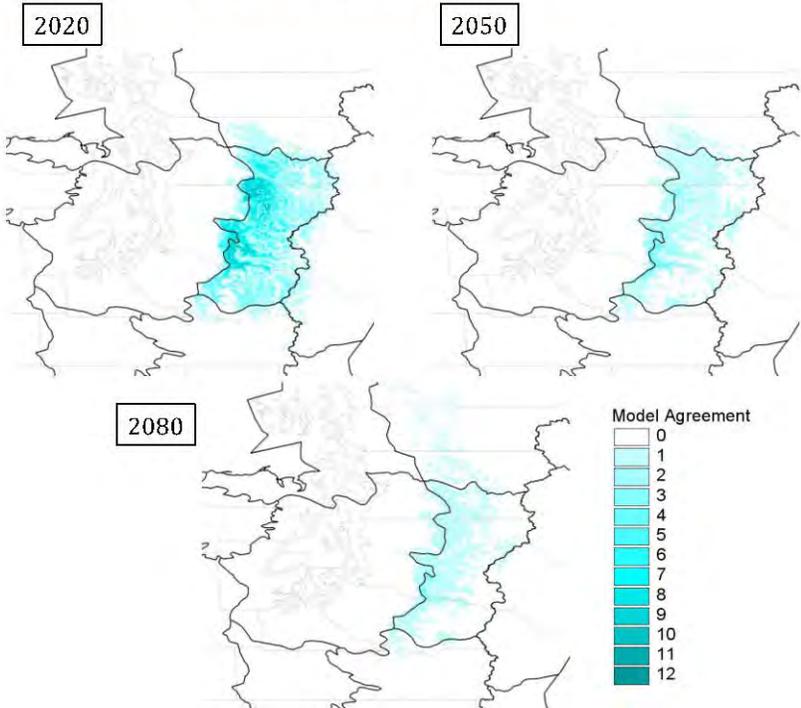
Predicted climate envelope for DF seedzone: Lower-Columbia



Predicted climate envelope for DF seedzone: Skagit



Predicted climate envelope for DF seedzone: Snoqualmie



Kitsap seed zone

