
THE STATE OF CLIMATE ADAPTATION SCIENCE FOR ECOSYSTEMS IN THE NORTHWEST U.S.



Prepared by the Climate Impacts Group for the
Northwest Climate Adaptation Science Center

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NORTHWEST
Climate Adaptation
Science Center

W UNIVERSITY of WASHINGTON

Welcome to ***The State of Climate Adaptation Science for Ecosystems in the Northwest U.S.***

This report is customized by selecting topics, ecosystems, and ecoregions of interest from [The State of Climate Adaptation Science for Ecosystems in the Northwest U.S. website](#).

Report options consist of

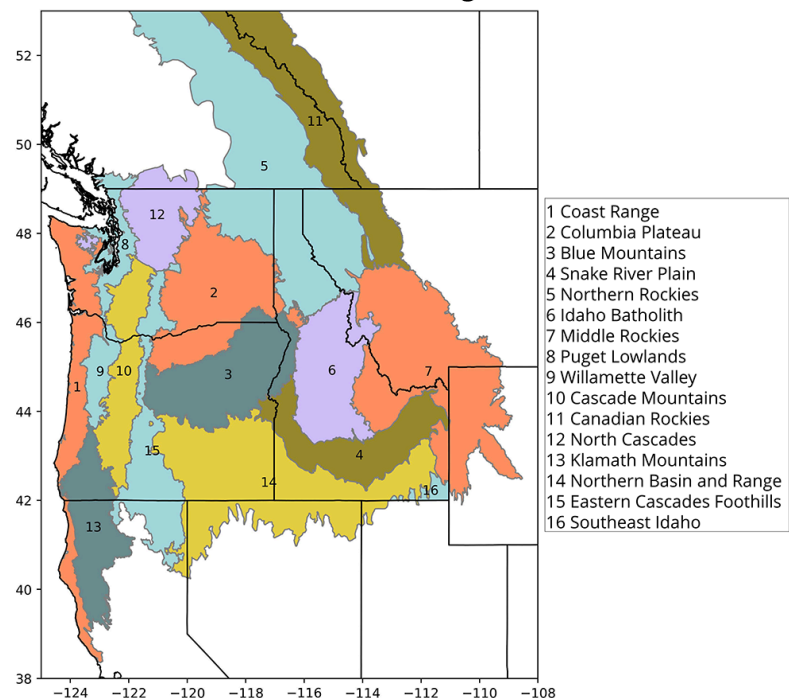
Four topic areas (1) *Climate Projections*, (2) *Hydrologic Change*, (3) *Climate Effects on Ecosystems*, and (4) *Climate Adaptation*. For topic areas one to three, report sections (12-14 pages) synthesize the latest science on the impacts of climate change in the Northwest in an easy to access format. To the extent possible, the synthesis is based on the most recent climate model projections and peer-reviewed articles from the last 10 years.

Climate Effects on Ecosystems are summarized for four ecosystem types: (1) Forest, (2) Aquatic, (3) Shrublands/Grasslands, and (4) Coastal/Marine.

Climate Adaptation for Ecosystems consist of 4-5 page summaries in a fact sheet format for each of the four ecosystem types. Summaries include descriptions of select adaptation actions, why they work based on ecological theory and practice, and key scientific sources for the action. Regionally-relevant case studies are also described.

Ecoregion factsheets (2 pages) summarize climate projections, hydrologic change and ecosystem effects specific to 16 modified Omernik Level III ecoregions in the Northwest. Climate and hydrologic projections are available for all 16 ecoregions. Ecosystem effects are available only if an ecosystem is relevant to an ecoregion: 10 for forests and 2 for coastal/marine. Ecoregions were combined into larger areas over which ecosystem effects are expected to be relatively consistent for aquatic (5) and shrubland/grassland (3) ecosystems.

Modified Omernik Level III Ecoregions in the Northwest



Additional data resources and references are available from the website and can be filtered by topic area, ecosystem, and climate change stressors. Download the full report at the [University of Washington ResearchWorks](#).

Access a full list of data resources and supporting methodology for the ecoregion-specific climate projections and hydrologic changes at the [Northwest Climate Adaptation Science Center website](#).

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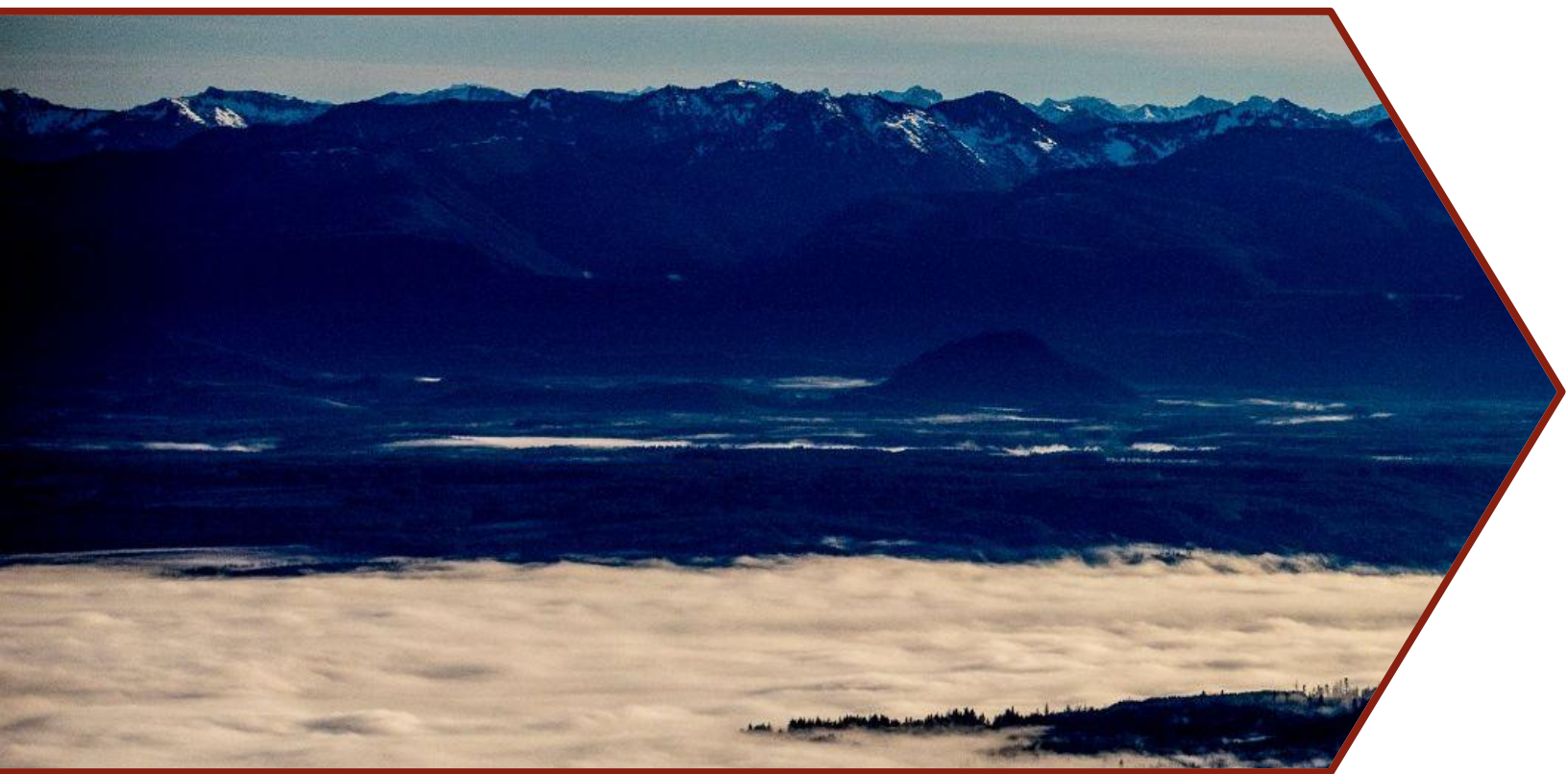
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See section cover pages for individual citations.

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The State of Climate Adaptation Science for Ecosystems in the Northwest U.S.

CLIMATE PROJECTIONS



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CLIMATE PROJECTIONS OVERVIEW: EVALUATING THE USE OF THE NEWEST CMIP6 PROJECTIONS

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IMPLICATIONS OF THE HIGHLY SENSITIVE CMIP6 MODELS

INTRODUCTION

The [Coupled Model Intercomparison Project](#) (CMIP) recently released a new ensemble of climate simulations (Bock et al., 2020; Intergovernmental Panel On Climate Change (IPCC), 2023) that can be used to better understand and integrate the potential effects of a changing climate on ecosystems for management, planning, and research (**Box 1**). The Localized Constructed Analogs downscaling method (LOCA) has been applied to both the Phase 5 (CMIP5) and Phase 6 (CMIP6) models to increase usability at regional scales (**Box 2**). These data are readily available and are used in other relevant climate assessments (Pierce et al., 2018), (NCA5 *Chapter 1*, 2023). This overview compares projected changes in temperature and precipitation from the previous (CMIP 5) and most recent (CMIP6) CMIP phases, and the associated downscaled LOCA projections, for the Northwest U.S. The goal of this comparison is to help users of the climate projections determine if updating to the new phase of projections is needed for research, management, and planning efforts. We also explore the extent to which potentially unrealistic warming in some of the CMIP6 model simulations impact the results of the projected temperature and precipitation changes in the Northwest.

BOX 1: INTRODUCTION TO CLIMATE MODELS

Global Climate Models (GCMs)

Global climate models combine interactions between the atmosphere, ocean, and biosphere, with scenarios of future emissions or concentrations of greenhouse gases and aerosols to simulate possible future climates. Many different global climate models exist, and all are different in their approaches and performance, particularly when analyzed at the regional level. The multitude of available models can be difficult for application purposes because model ensembles can have a large range of answers for some metrics (e.g., precipitation). This is because each individual model may perform well in some aspects of simulating the climate, and worse in others, due to the design of the model and inherent limitations that come from representing the Earth system with a computer model. Since individual models may be biased in different ways, leveraging the breadth of available simulations from a range of models to estimate future climate conditions is the most effective way to quantify the range of possible future (Hawkins & Sutton, 2009; Knutti et al., 2010; Tebaldi & Knutti, 2007).

Coupled Model Intercomparison Project (CMIP)

The Coupled Model Intercomparison Project (CMIP), an effort run by the World Climate Research Programme, was established to study and compare state-of-the-art climate simulations (Meehl et al., 2000). CMIP sets standards and facilitates the release of a coordinated set of historical and future climate simulations from modeling groups around the world. These climate model simulations are run under a range of different scenarios – which specify future concentrations of greenhouse gases and pollutants, as well as future changes in land use and land cover. The simulations are regularly updated and each new CMIP phase is evaluated by determining how well simulations of historical climate reflect observed historical climate trends. Evaluation efforts compare a wide variety of metrics, ranging from total seasonal precipitation, diurnal range in temperature, and even precipitation patterns associated with atmosphere-ocean phenomena (Bock et al., 2020; Davini & D'Andrea, 2020; Tian & Dong, 2020). Advancements in models between CMIP phases include increased spatial or temporal resolution of simulations, improved individual process models (e.g., ocean dynamics), and refined representations of fine scale features (e.g., clouds and vegetation cover) (Eyring et al., 2016; O'Neill et al., 2016; Stouffer et al., 2017).

CLIMATE PROJECTION UPDATES

KEY CMIP AND LOCA MODEL UPDATES

There is evidence showing improved confidence in the temperature and precipitation projections for the Northwest U.S. On a global scale, however; improvements in both confidence and performance between the CMIP5 and CMIP6 ensemble of models are relatively modest (Bock et al., 2020; Intergovernmental Panel On Climate Change (IPCC), 2023).

- There is more confidence in the CMIP6 ensemble mean over North America compared to the CMIP5 ensemble mean. There are also limited improvements in ensemble confidence for temperature and precipitation extremes for the Northwest (Kim et al., 2020; Li et al., 2022; Srivastava et al., 2020). Confidence improvements are indicated by a reduced model spread in the CMIP6 ensemble.
- Regional differences between the historical CMIP6 simulations and observed historical climate trends remain, particularly differences in precipitation patterns (Intergovernmental Panel On Climate Change (IPCC), 2023).

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- Regional climate models still offer improvement over global models for regional applications, especially for variables that are strongly affected by topography such as precipitation.

The LOCA method, which was used to downscale CMIP5, and the LOCA2 method, which was used to downscale CMIP6, rely on similar data and methodology, with some minor changes.

- LOCA2 uses the same dataset (Livneh et al., 2015) as used in LOCA for temperature except that it is extended through 2018.
- LOCA2 uses a slightly different bias-correction approach that is intended to better capture precipitation extremes (Pierce et al., 2021; Risser et al., 2021).

Greenhouse gas scenarios have been updated from Representative Concentration Pathways (RCPs) in CMIP5 to Shared Socio-economic Pathways (SSPs) in CMIP6.

- RCPs range from a low (RCP 2.6) to a high (RCP 8.5) scenario, and SSPs range from a low (SSP245) to a high (SSP585) scenario as well.
- SSPs are roughly comparable to RCPs but have different pathways that lead to similar end-of-century greenhouse gas concentrations and pollutants.
- SSPs include more complex assumptions about how humans will respond to climate change by linking narratives with each scenario pathway. This allows for consideration of factors such as population, technological and economic growth throughout the next century (Riahi et al., 2017).

Some global climate models in the CMIP6 ensemble show a potentially unrealistic amount of warming throughout the century.

- About a quarter of the models in the CMIP6 ensemble are more sensitive to greenhouse gasses than any climate model in the previous CMIPensembles (Gettelman et al., 2019; Intergovernmental Panel On Climate Change (IPCC), 2023; Meehl et al., 2020; Zelinka et al., 2020), and are even outside of the estimated climate sensitivity based on paleoclimate record (Sherwood et al., 2020; Zhu et al., 2020).
- Some scientists have suggested constraining the future projections based on past warming trends (Tokarska et al., 2020). However, the IPCC AR6 suggests models cannot be excluded based on currently available evidence (Intergovernmental Panel On Climate Change (IPCC), 2023).
- Other scientists have circumvented the issue of unrealistic warming by basing projections on mean global warming (e.g., global temperature patterns for 2 degrees C of global warming; NCA Atlas). Though this method is helpful for understanding projected climate impacts at these thresholds, it does not provide planners and practitioners with the ability to plan for impacts on a timeline.
- The models we identified as having a potentially unrealistic amount of warming throughout the century were CanESM5, HadGEM3-GC31-LL, and HadGEM3-GC31-MM. We determined this by using the equilibrium climate

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sensitivity threshold of 4.9C, which is the high-end of the “likely” equilibrium climate sensitivity in the paleo record (Intergovernmental Panel On Climate Change (IPCC), 2023). These three models have an equilibrium climate sensitivity at or greater than 4.9C.

CMIP5 and CMIP6 models generally agree on a variety of projections at regional and global scales.

- Similar projected regional changes in temperature under comparable climate scenarios, increased magnitude, frequency, and duration of extreme heat events, and decreased magnitude, frequency, and duration in cold spells. (Li et al., 2021)
- Increased magnitude, frequency, and duration in extreme precipitation in many regions of the world and on all continents, with less certainty about how this will contribute to regional changes in river flooding.
- Virtual certainty in large snow cover declines over the next century.
- Consistent rates of increase in sea surface temperatures for all oceanic regions except the North Atlantic.
- CMIP6 models project more warming by the end of the century than the CMIP5 models, due in part to SSP585 being a slightly higher climate scenario than RCP 8.5, and some CMIP6 models showing potentially unrealistic warming (Intergovernmental Panel On Climate Change (IPCC), 2023).

BOX 2: DOWNSCALING CLIMATE MODEL DATA

Statistical and Dynamical Downscaling

The global climate model data from both CMIP5 and CMIP6 phases is too coarse for most sub-regional research and management applications. This is mainly because global data does not capture important finer scale regional features (e.g., topography, coastline) that affect climate variations and are relevant for applied research and management. To make the data more applicable at regional and finer scales, the global climate model output can be “downscaled” to a finer spatial resolution (e.g., 1/16° x 1/16°). Several methods have been used to downscale climate data, including “statistical downscaling” which uses relationships between the simulations and observed climate data to estimate changes at a finer resolution (e.g., Localized Constructed Analogs, Multivariate Adaptive Constructed Analogs, Bias Correction and Spatial Disaggregation). Another method is “dynamical downscaling” in which a regional climate model (e.g., Weather Research and Forecasting Model) simulation uses the global climate model data to inform the smaller simulations. Efforts are underway to downscale the CMIP6 simulations both statistically and dynamically, and several are currently available. Some of these resources can be downloaded on the report website through the “Data Resource” option.

IMPLICATIONS OF THE CMIP UPDATES FOR ECOSYSTEM ASSESSMENT AND PLANNING

With each new iteration of CMIP models, natural resource managers should evaluate the benefits of incorporating updated climate projections into assessments or management plans. **The differences between CMIP6 and CMIP5 projections for the Northwest are generally small and unlikely to alter current assessments of potential impacts or**

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planned adaptation efforts. For detailed discussion of comparisons for specific climate changes, see below. However, several additional considerations are outlined below that may prompt the use of the new scenarios and projections, regardless of the small changes between model iterations.

- CMIP6 models simulated the observed historical climate more accurately compared to the CMIP5 models.
- Assessment, planning, and adaptation actions for ecosystems and species with high sensitivity to small changes in climate variables, or threshold responses, may especially benefit from the improved historical climate accuracy of the CMIP6 models.
- The change to SSPs in CMIP6 allows for the consideration of more complex social scenarios with attached narratives.
- Future scientific studies are likely to use the updated CMIP6 projections, and having consistency in management plans may simplify future integration.

The current understanding of how the CMIP6 model projections compare to the CMIP5 projections for the Northwest is incomplete. The responses to climate change are complex; it is likely that there are important differences between these CMIP phases that are not covered here. A better understanding of how sensitive ecosystems and management decisions are to change can inform how important it is to better understand the differences between the CMIP phases.

If researchers or resource managers decide to update assessments and management plans based on the new CMIP6 projections, it is important to consider how these projections are affected by the inclusion of models with a potentially unrealistic amount of warming. This is particularly important if assessments or decisions are using model maximums (rather than medians) as part of the decision-making process. **Some scientists recommend including the highly sensitive models in CMIP6 because the possibility cannot be ruled out** (Intergovernmental Panel On Climate Change (IPCC), 2023). Other scientists offer methods to avoid including potentially unrealistic warming projections (Hausfather, 2022). Though the models with potentially unrealistic warming perform worse than others in simulating recent changes in global warming, they can be used to provide insights into low-likelihood, high-impact futures that may be important to consider in management and planning. Regardless of their approach, end-users should consider how the inclusion or exclusion of these warm models may affect interpretations of projections in the context of their work.

A COMPARISON OF CMIP5 AND CMIP6 DOWNSCALED CLIMATE PROJECTIONS

We compare projections from 30 CMIP5 and 25 CMIP6 models downscaled for five climate variables throughout the Northwest region. The regional assessment area was created based on the EPA Omernik Level III ecoregions, with some modifications based on manager feedback and data coverage limitations (**Figure 1**). The comparisons include median and

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maximum projections for precipitation (cool season and late summer), temperature (summer and winter average), and growing season (average annual frost days) for all of the models. We compared both the model median and model maximum projections, since both can be important for planning and decision-making. Finally, we evaluated variability among models including the highly sensitive models for CMIP6. All comparisons are based on LOCA and LOCA2 downscaled projections and a high scenario (RCP 8.5, SSP585), for the years 2010-2039, 2040-2069, and 2070-2099. Although these comparisons are based on the entire Northwest assessment area, more specific geographic areas are referenced when describing results. Additional information for climate projections from CMIP6 downscaled data and associated trends in each ecoregion can be found in the ecoregion fact sheets, which can be downloaded on the website.

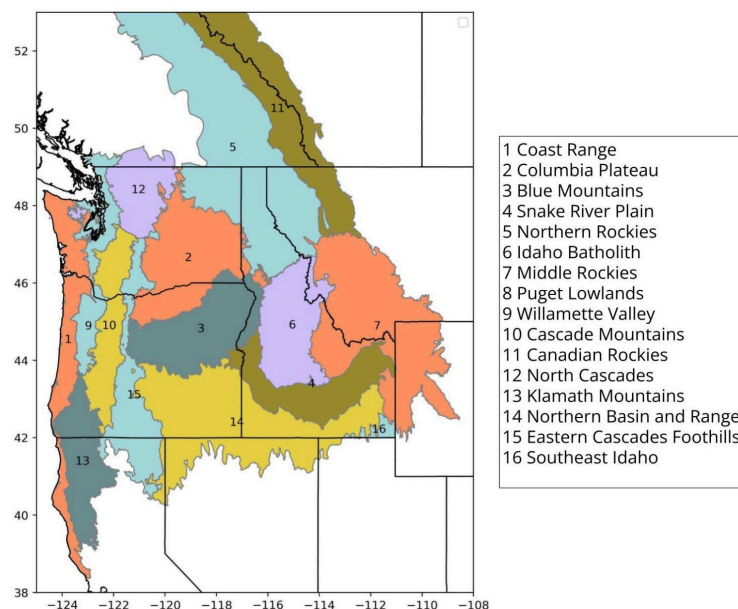


Figure 1: The 16 modified Omernik Level III ecoregions used in the assessment.

COOL SEASON PRECIPITATION

Both the CMIP5 and CMIP6 models project *increases in cool season (October – March) precipitation throughout the next century, especially east of the Cascade Mountains (Figure 2; Row 1, 2). Differences in the model median percent change in total cool season precipitation between the CMIP5 and CMIP6 models are small. CMIP6 projections are wetter by up to 10% at the end of the century, primarily east of the Cascade Mountains, but drier than CMIP5 projections in the Northern Basin and Range ecoregion (Figure 2; Row 3).*

- Model median projections for CMIP5 and CMIP6 downscaled data both project increases in precipitation and are similar in magnitude and spatial patterns throughout this century.

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- Increases are most pronounced east of the Cascade Mountains for the 2070-2099 period (Figure 2, Rows 1 and 2). However, most areas east of the Cascade Mountains have lower historical precipitation, which leads to large percent changes despite relatively small increases in total precipitation.
- For the model maximum percent change (Figure 2, Row 4), differences in the cool season precipitation can be large depending on location. The model maximum increase is smaller for the CMIP6 models than the CMIP5 models over the Cascade Mountains and southwestern Oregon for early and mid-century. For 2070-2099, the CMIP6 model maximum is also smaller than CMIP5 projections in eastern Oregon, southwest and south central Idaho, and northern Nevada. By contrast, the end-of-century model maximum increase is larger for CMIP6 in the Idaho Batholith and Middle Rockies ecoregions.

LATE SUMMER PRECIPITATION

Both the CMIP5 and CMIP6 model medians project *decreases in late summer (July – September) total precipitation* for much of the Northwest, especially west of the Cascades and in the northern US portions of the domain at the end of the century (Figure 3; Row 1, 2). *Differences between the CMIP5 and CMIP6 model projections are variable* compared to the median projected change. CMIP6 models project larger decreases in central and eastern Washington and northern Idaho during early and mid-century, but larger increases in central Oregon and southeast Idaho by end of century (Figure 3; Row 3).

- The differences between the CMIP6 and CMIP5 median projections are much smaller than the median projected change for CMIP5 in most of the region, excluding central and eastern Washington and central Oregon.
- Some aspects of the spatial distribution in the CMIP5 and CMIP6 median projections of late summer precipitation are similar (Figure 3, Rows 1 and 2), such as wetter conditions at the end of the century (2070-2099) in the Northern Basin and Range ecoregion, and drier conditions throughout the rest of the domain.
- Excluding areas in central Oregon where the CMIP6 models show a smaller decrease than the CMIP5 models, the CMIP6 models project more decrease in late summer precipitation than the CMIP5 models for 2010-2039 and 2040-2069 (Figure 3; Row 3). By 2070-2099, the CMIP6 models project a larger decrease in late summer precipitation than the CMIP5 models (Figure 3; Row 3).
- The CMIP6 model maximum projections a larger decrease in late summer precipitation than the CMIP5 model maximum projections in 2010-2039 and 2070-2099. The differences in the model maximum projections are larger than the differences in the median projections, suggesting that, in general, the model maximum projections for the CMIP6 models are more extreme than the CMIP5 projections for the early and late time period (Figure 3; Row 4).

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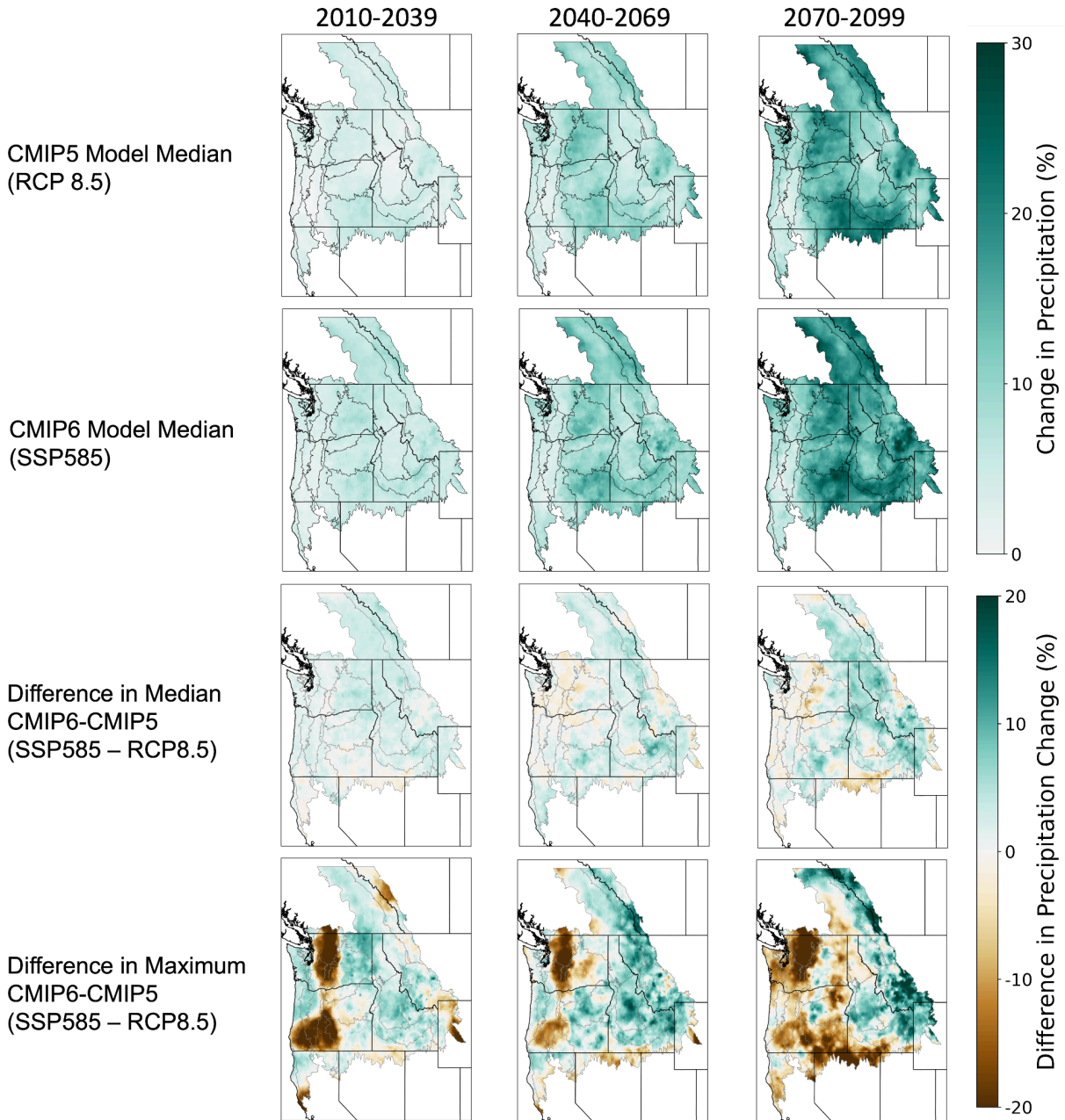


Figure 2. First Row: Model (n=30) median percent change in average total winter precipitation (Oct - Mar) for the LOCA downscaled CMIP5 data under a high greenhouse gas emission scenario (RCP 8.5) for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010. **Second Row:** Same as the first row, but for the LOCA2 downscaled CMIP6 model (n=25) data under a high greenhouse gas scenario (SSP585). **Third Row:** Difference in the model median percent change in average total winter precipitation (Oct - Mar) difference between the LOCA downscaled CMIP5 data and LOCA2 CMIP6 data under their relative high greenhouse gas emission scenarios for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010. **Fourth Row:** Difference in the model maximum percent change in average total winter precipitation (Oct - Mar) between the LOCA downscaled CMIP5 data and LOCA2 CMIP6 data under their relative high greenhouse gas emission scenarios for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010.

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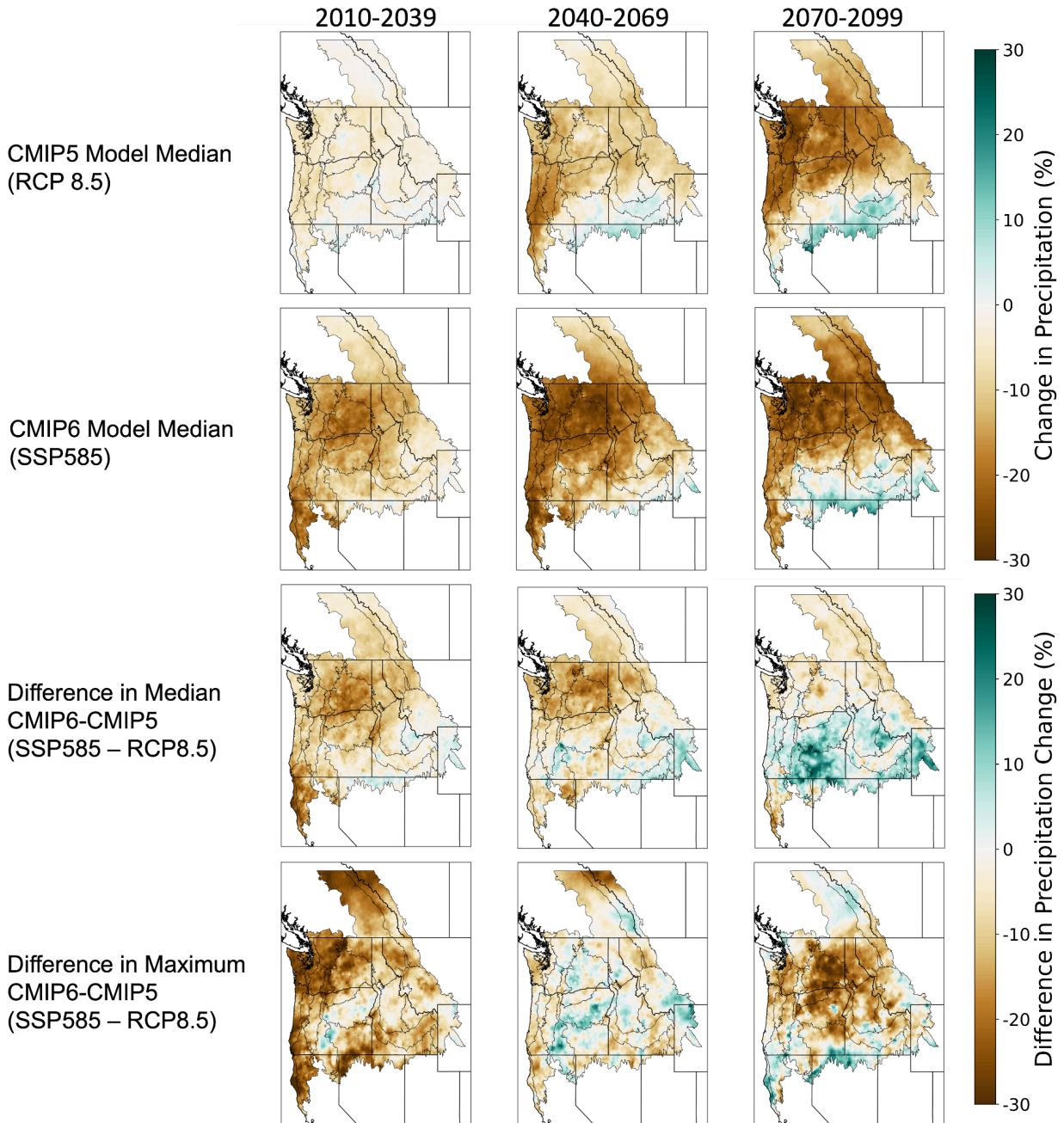


Figure 3. First Row: Model ($n=30$) median percent change in average total summer precipitation (July-September) for the LOCA downscaled CMIP5 data under a high greenhouse gas scenario (RCP 8.5) for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010. **Second Row:** Same as the first row, but for the LOCA2 downscaled CMIP6 model ($n=25$) data under a high greenhouse gas scenario (SSP585). **Third Row:** Difference in the model median percent change in average total summer precipitation (Jul-Sep) between the LOCA downscaled CMIP5 data and LOCA2 CMIP6 data under their relative high greenhouse gas emission scenarios for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010. **Fourth Row:** Difference in the model maximum percent change in average total summer precipitation (Jul-Sep) between the LOCA downscaled CMIP5 data and LOCA2 CMIP6 data under their relative high greenhouse gas emission scenarios for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010.

SUMMER AVERAGE TEMPERATURE

Both CMIP5 and CMIP6 models project increases in summer average temperature (June - August) exceeding 10°F by the end of the century, with more warming east of the Cascade Mountains relative to the coast (Figure 4; Rows 1 and 2). The CMIP6 model median projects more warming than the CMIP5 model median across all regions, with larger differences at the end of the century (Figure 4; Row 3).

- CMIP5 and CMIP6 model median projections both indicate increases in temperature, with CMIP6 projecting more warming throughout most of the region.
- There are several prominent localized differences in model median projections throughout the region and across all time periods (Fig 3, row 3) including a few areas in coastal Oregon and northern California corresponding with the southern Cascade Mountains and the Columbia River delta that show greater warming for the CMIP5 model median. Given that most of the region is quite a bit warmer in the CMIP6 models, it is unclear why these locations show less warming for CMIP6 compared to CMIP5. Further analysis is needed to understand the cause of these localized differences.
- The differences in the model maximums (Fig. 4; Row 4) are considerably larger in magnitude than the differences in the model medians. The model maximums generally show substantially greater warming for CMIP6 relative to CMIP5 in early and later time periods. As in the median projections, however, the CMIP6 maximum projection is cooler than CMIP5 for parts of the Cascade Mountains and coastal areas.

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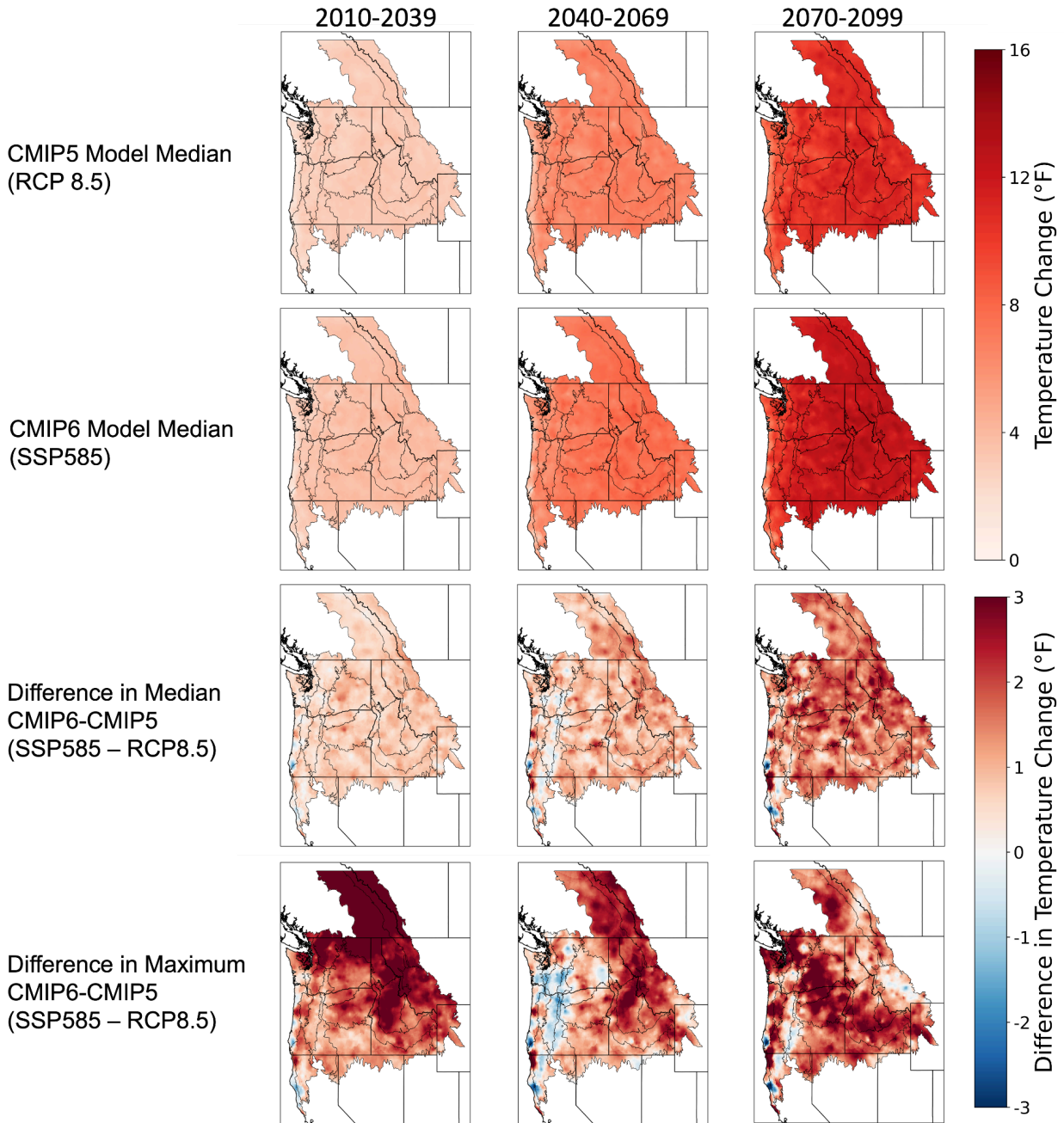


Figure 4. First Row: Model (n=30) median change in average summer temperature (June-August) for the LOCA downscaled CMIP5 data under a high greenhouse gas scenario (RCP 8.5) for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010. **Second Row:** Same as the first row, but for the LOCA2 downscaled CMIP6 model (n=25) data under a high greenhouse gas scenario (SSP585). **Third Row:** Difference in the model median change in average summer temperature (Jun-Aug) between the LOCA downscaled CMIP5 data and LOCA2 CMIP6 data under their relative high greenhouse gas emission scenarios for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010. **Fourth Row:** Difference in the model maximum change in average summer temperature (Jun-Aug) between the LOCA downscaled CMIP5 data and LOCA2 CMIP6 data under their relative high greenhouse gas emission scenarios for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010.

WINTER AVERAGE TEMPERATURE

Both CMIP5 and CMIP6 models project increases in winter average temperature exceeding 8°F by the end of the century, with more warming east of the Cascade Mountains relative to the coast (Figure 5; Rows 1 and 2). The CMIP6 model median projects more warming than the CMIP5 model median across all regions, with larger differences at the end of the century (Figure 5; Row 3). The differences between the model medians are small relative to the magnitude of changes in the model maximum (Figure 5; Row 4).

- The CMIP5 and CMIP6 model median projections show similar patterns of winter temperature change throughout the century, with the greatest warming east of the Cascade Mountains.
- The difference in the model median temperature change suggests that the CMIP6 models project more warming than the CMIP5 models for the Northern Rockies and the Cascade Mountains for the 2070-2099 period (Fig 5, Row 3).
- The model maximum projected change varies considerably throughout the region and across all time periods. The near-term differences are about 1-2°F.
- For mid-century, the CMIP6 model maximum projected change suggests less warming than the CMIP5 model maximum in the Eastern Cascades and Foothills, Columbia Plateau, Northern Basin and Range, Snake River Plain, and Canadian Rockies ecoregions.
- By the end of the century, the CMIP6 model maximum is much warmer than the CMIP5 model maximum throughout the Northwest, except the Canadian Rockies, Northern Basin and Range, and the Cascade Mountains ecoregions.

ANNUAL FROST DAYS

Both CMIP5 and CMIP6 models project decreases in the number of frost days throughout the century (Figure 6; Rows 1 and 2). Substantial decreases in frost days become more pronounced in areas that have historically experienced more frost days (e.g., high elevation areas), with many mountainous areas projected to experience a decrease of up to 100 frost days. The CMIP5 and CMIP6 model median projections of frost days are similar across the region. Differences in maximum number of frost days between the two CMIP model ensembles are up to about 40 days.

- Throughout the century, frost days are projected to decrease most to the east of the Cascade Mountains, in part because coastal areas already experience few frost days.
- Model median differences show that the CMIP6 models are generally warmer than the CMIP5 models and have fewer frost days, particularly at the end of the century. One exception is the Columbia Plateau, where the CMIP5 model median projects modestly fewer frost days than the CMIP6 model median. Maximum change in the CMIP6 models show up to 40 fewer annual frost days at the end of the century.

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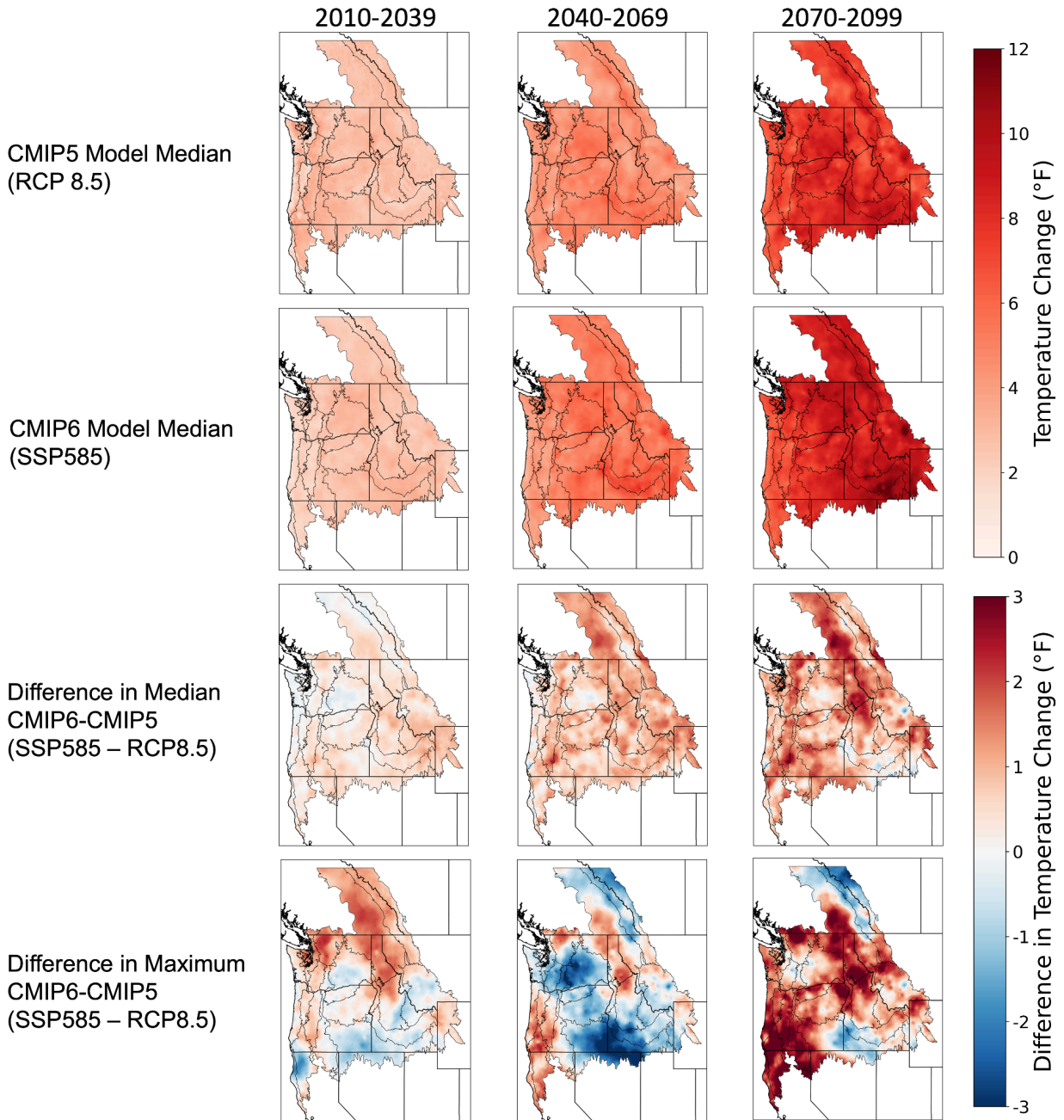


Figure 5. First Row: Model (n=30) median change in average winter temperature (December-February) for the LOCA downscaled CMIP5 data under a high greenhouse gas scenario (RCP 8.5) for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010. **Second Row:** Same as the first row, but for the LOCA2 downscaled CMIP6 model (n=25) data under a high greenhouse gas scenario (SSP585). **Third Row:** Difference in the model median change in average winter temperature (Dec-Feb) between the LOCA downscaled CMIP5 data and LOCA2 CMIP6 data under their relative high greenhouse gas emission scenarios for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010. **Fourth Row:** Difference in the model maximum change in average winter temperature (Dec-Feb) between the LOCA downscaled CMIP5 data and LOCA2 CMIP6 data under their relative high greenhouse gas emission scenarios for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010.

CLIMATE PROJECTIONS OVERVIEW

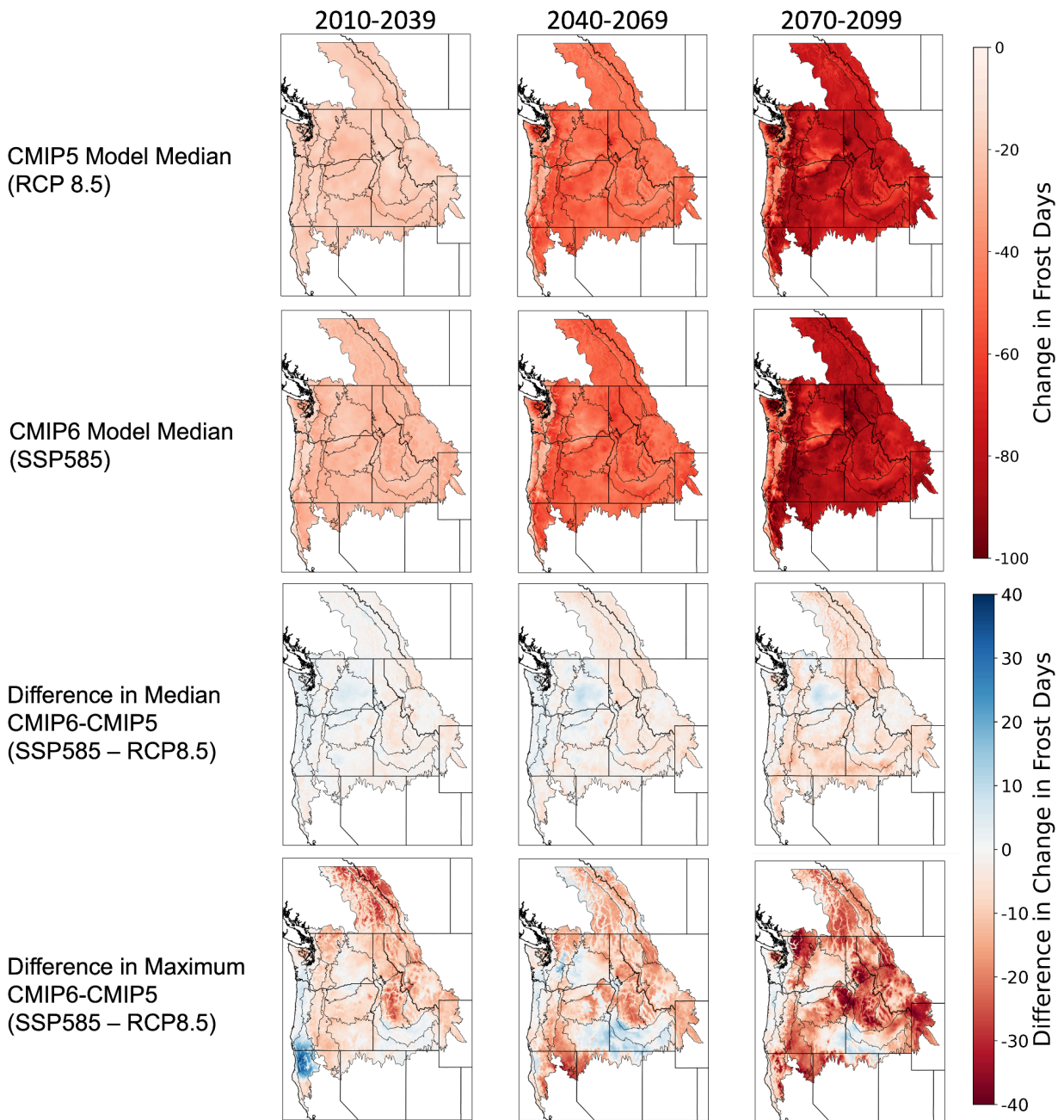


Figure 6. First Row: Model (n=30) median change in mean annual number of frost days for the LOCA downscaled CMIP5 data under a high greenhouse gas scenario (RCP 8.5) for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010. **Second Row:** Same as the first row, but for the LOCA2 downscaled CMIP6 model (n=25) data under a high greenhouse gas scenario (SSP585). **Third Row:** Difference in the model median change in mean annual number of frost days between the LOCA downscaled CMIP5 data and LOCA2 CMIP6 data under their relative high greenhouse gas emission scenarios for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010. **Fourth Row:** Difference in the model maximum change in mean annual number of frost days between the LOCA downscaled CMIP5 data and LOCA2 CMIP6 data under their relative high greenhouse gas emission scenarios for 2010-2039, 2040-2069, and 2070-2099 relative to 1950-2010.

IMPLICATIONS OF THE HIGHLY SENSITIVE CMIP6 MODELS

Three of the new CMIP6 models project excessive warming – above the maximum of the very likely range in climate sensitivity (Intergovernmental Panel On Climate Change (IPCC), 2023) (*CanESM5*, *HadGEM3-GC31-LL*, *HadGEM3-GC31-MM*). We analyzed the effect of these highly sensitive models on both the median and maximum model projections for each of the above discussed metrics to determine how they might influence regional climate projections. We averaged the projected changes for the full CMIP6 LOCA2 ensemble and the CMIP6 LOCA2 ensemble with the three highly sensitive models removed for each ecoregion (Figure1) and each metric.

Maximum temperature values are highly affected by the decision to include or exclude the highly sensitive models in the ensemble. In contrast, median temperature and precipitation values are relatively unaffected by the 3 highly sensitive models. Therefore, the decision to include or exclude the highly sensitive models is more important when considering the model maximum change and temperature.

Model maximum projections with and without the highly sensitive CMIP6 models vary considerably for temperature and less for precipitation.

- The maximum CMIP6 projection for the full model ensemble is warmer everywhere, for both summer and winter temperature.
- The model maximum summer maximum temperature is about 5°F warmer in the full ensemble for the Northern Rockies for the same time period and scenario.
- The largest difference in model maximum percent change in winter precipitation is about 13% for the Canadian Rockies for the 2070-2099 time period under a high scenario (ssp585), with the full ensemble showing larger increases.
- The maximum difference in percent change in summer precipitation is about 18% for the Eastern Cascades Foothills for the 2070-2099 time period under a high scenario (ssp585); the full ensemble model maximum shows a smaller decrease in precipitation.

Model median projections are generally similar with and without the highly sensitive CMIP6 models for all temperature and precipitation variables.

- The largest differences, for 2070-2099 and the high scenario (SSP585), show the full ensemble projection is 3% wetter for cool season precipitation in southeast Idaho and 7% wetter in the Klamath Mountains.
- The maximum difference for any temperature variable is about 0.6°F, regardless of time period or scenario.

Blue Mountains Climate Projections

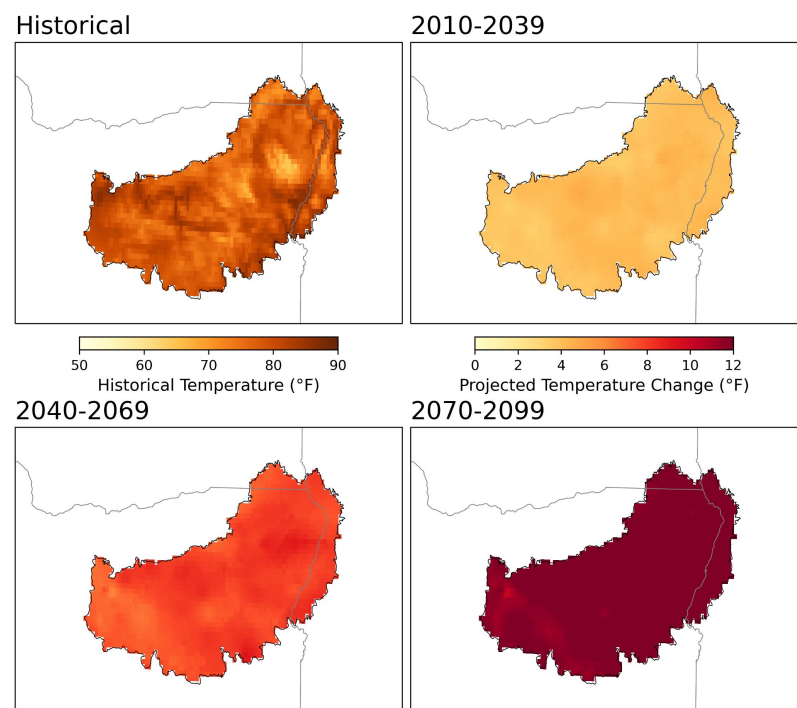


Climate Overview

The Blue Mountains are generally not as high in elevation nor as dense with peaks as the neighboring mountainous regions like the Cascades. The climate has both continental and Mediterranean influences, with warm, dry summers and cold winters. Mean annual temperature and precipitation vary widely depending upon elevation.

Climate Projections

The median temperature change for 25 CMIP6 model projections for this region is spatially uniform except for the southwestern Blue Mountains, where there is slightly less warming. Winters in the Blue Mountains are projected to become warmer, and summers drier. The CMIP6 projections suggest more warming than the CMIP5 projections at the end of the century and less of a decrease in late summer precipitation. The CMIP6 models also project more of an increase in cool season precipitation than the CMIP5 models, especially in the southwestern Blue Mountains.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2069-2099) for a high (SSP585) scenario. Future projections show increasing temperatures over the century, with slightly less warming in the southwestern Blue Mountains. Data Source: Localised Constructed Analogs v.2 [LOCA2](#). Resolution: 6km

CMIP 6 (LOCA2) Temperature Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	60.2 (±1.8)	+3.4 (2.2 to 6.4)	+3.9 (2.1 to 6.9)	+5.5 (3.1 to 9.3)	+7.5 (4.9 to 11.2)	+7.0 (4.3 to 10.2)	+12.3 (7.6 to 18.1)
Summer Tmax (°F)	78.2 (±2.6)	+3.8 (1.9 to 7.3)	+4.1 (2.0 to 8.0)	+5.8 (3.3 to 11.3)	+8.3 (5.2 to 14.2)	+7.5 (4.1 to 14.0)	+13.3 (7.1 to 22.1)
Winter Tavg (°F)	26.5 (±1.2)	+2.5 (0.6 to 3.6)	+2.5 (1.0 to 4.1)	+4.4 (2.1 to 7.0)	+5.4 (3.2 to 8.8)	+5.6 (3.1 to 9.1)	+8.4 (5.1 to 13.0)
Winter Tmax (°F)	35.9 (±1.4)	+2.4 (0.4 to 3.4)	+2.3 (0.7 to 4.2)	+4.3 (1.7 to 6.3)	+5.5 (2.7 to 7.9)	+5.6 (2.7 to 8.3)	+8.9 (4.5 to 12.8)
Winter Tmin (°F)	17.1 (±1.3)	+2.8 (0.8 to 4.1)	+2.8 (1.2 to 5.5)	+4.5 (2.4 to 8.3)	+5.5 (3.5 to 9.8)	+6.1 (3.5 to 11.0)	+9.4 (5.5 to 15.5)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative to the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP)245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Blue Mountains Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the Blue Mountains, with the largest increases projected in the summer. Summer average temperature is projected to increase by as much as 8°F for the 2040-2069 period, and as much as 12°F by the end of the century under a high (SSP585) scenario.



Precipitation

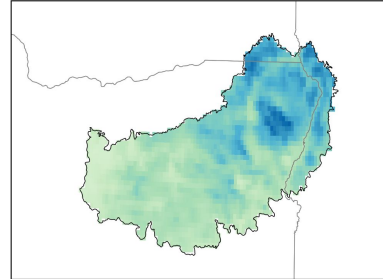
Late summer total precipitation is projected to *decrease by* as much as 12% for the 2069-2099 period. Cool season precipitation projections show an *increase* in precipitation of 16%, with more of it falling as rain. Confidence in projected late summer precipitation change is lower than cool season precipitation.



Growing Season

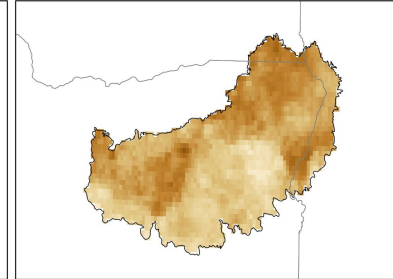
Growing degree days are projected to more than double by the 2069-2099 period under the high (SSP585) scenario. Frost days are projected to decrease from 210 per year to fewer than 150 per year, on average by the end of the century.

Historical



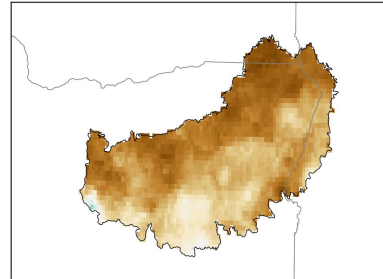
0 1 2 3 4 5
Historical Precipitation (in)

2010-2039

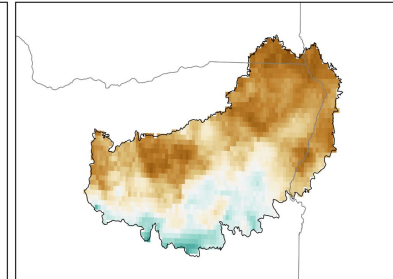


-30 -20 -10 0 10 20 30
Projected Precipitation Change (%)

2040-2069



2070-2099



Total Late Summer Precipitation. Model median historical (1950-2010; Jul-Sept) and percent change for three future periods (2010-2039, 2040-2069, 2069-2099) under a high (SSP585) scenario. Future projections show decreasing late summer precipitation across the northern Blue Mountains throughout the century, and a slight increase for the southernmost Blue Mountains in the 2069-2099 time period. Confidence is low in projected changes in late summer precipitation after the 2010-2039 period due to variability among model. Data Source: [LOCA2](https://loca.ucsd.edu/). Resolution: 6km

CMIP6 (LOCA2) Growing Season Projections [median (range)]

	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	2.2 in (±1.3)	-13% (-34 to 18)	-13% (-34 to 89)	-12% (-36 to 25)	-17% (-40 to 21)	-8% (-38 to 47)	-12% (-61 to 80)
Cool Season Precipitation	13.1in (±3.0)	+4% (-1 to 13)	+5% (-4 to 16)	+10% (1 to 18)	+9% (-4 to 26)	+9% (0 to 27)	+16% (1 to 30)
GDD (deg-days)	1286 (±758)	+426 (311 to 838)	+559 (291 to 869)	+734 (464 to 1281)	+1242 (701 to 1558)	+972 (608 to 1553)	+2173 (1146 to 2953)
Frost Days	210 (±14)	-23 (-37 to -14)	-24 (-42 to -16)	-40 (-69 to -28)	-52 (-85 to -38)	-48 (-92 to -37)	-82 (-131 to -63)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loca.ucsd.edu/>

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative to the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP) 245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Canadian Rockies Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the Canadian Rockies ecoregion, with the largest increases projected for the summer. Summer average temperature is projected to increase by as much as 8°F for the 2040-2069 period, and as much as 12°F for the 2070-2099 period.



Precipitation

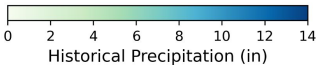
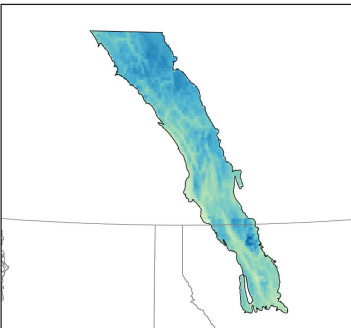
Late summer precipitation is projected to *decrease* by as much as 20% by the end of the century. Cool season precipitation is projected to *increase* by 20%. Consistency among models indicates high confidence in the direction of change in precipitation, but confidence in the magnitude of change is lower due to the range among models.



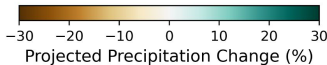
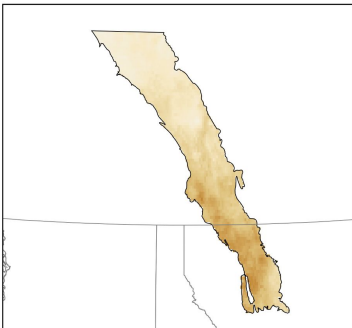
Growing Season

Growing degree days are projected to more than double by the 2070-2099 period under the high scenario (SSP585). Frost days are projected to decrease from 269 days to fewer than 200 per year, on average, for the 2070-2099 period.

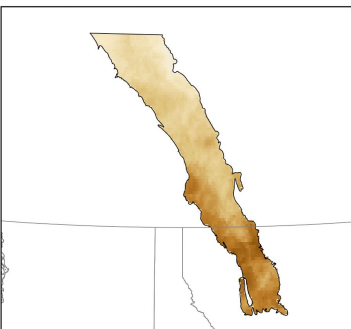
Historical



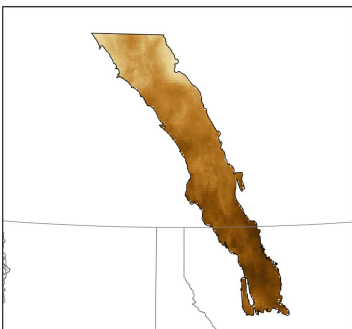
2010-2039



2040-2069



2070-2099



Total Late Summer (Jul-Sept) Precipitation. Model median historical (1950-2010) and percent change for three future periods (2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Future projections show decreasing late summer precipitation across the ecoregion, with a larger decrease in the southern portion. Confidence is low in projected changes in late summer precipitation after the 2010-2039 period. Data Source: [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]

	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	7.5in (±2.6)	-6% (-30 to 4)	-7% (-31 to 4)	-9% (-24 to 5)	-12% (-34 to 10)	-11% (-35 to 6)	-21% (-41 to 9)
Cool Season Precipitation	19.2in (±4.3)	+5% (-2 to 15)	+7% (-1 to 12)	+9% (2 to 30)	+11% (-1 to 33)	+13% (1 to 37)	+20% (5 to 53)
GDD (deg-days)	368 (±514)	+239 (136 to 639)	+266 (142 to 697)	+412 (263 to 952)	+652 (405 to 1254)	+597 (325 to 1078)	+1212 (624 to 2095)
Frost Days	269 (263 to 278)	-21 (-44 to -14)	-24 (-47 to -15)	-39 (-65 to -24)	-50 (-78 to -37)	-48 (-76 to -36)	-78 (-121 to -61)

Historical precipitation (inches) and future changes in percent change relative to the historical values. The range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Standard deviations may be greater than the average when the distribution is skewed. Data Source: <https://loca.ucsd.edu/>

Cascades Climate Projections

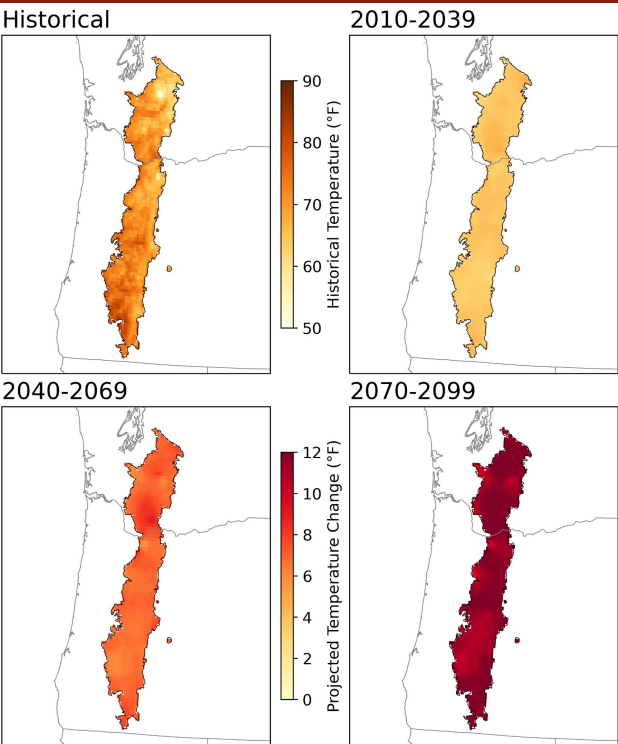


Climate Overview

The Cascade ecoregion is characterized by steep ridges and river valleys to the west and a high plateau to the east. The region has a mild to severe mid-latitude climate with dry, warm summers and mild or cool, very wet winters. The climate varies by latitude and elevation, especially near the volcanoes within this ecoregion.

Climate Projections

The projected median temperature change for 25 CMIP6 models for the Cascade ecoregion is spatially uniform, and tends to be warmer than the CMIP5 projections at the end of the century. The median for the CMIP6 models suggests less decrease in summer precipitation for 2010-2039, but change similar to the CMIP5 model median at the end of the century. Less precipitation will fall as snow in Cascades in the future, leading to even wetter winters and drier summers.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) for a high (SSP585) scenario. Future projections show increasing temperatures, with slightly less warming in the southwest. Data Source: Localised Constructed Analogs v.2 [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP 6 (LOCA2) Temperature Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	56.6 (±1.5)	+3.0 (2.0 to 5.3)	+3.4 (1.9 to 5.7)	+4.8 (3.5 to 8.0)	+6.5 (5.0 to 9.5)	+6.5 (4.1 to 9.4)	+11.1 (7.5 to 16.2)
Summer Tmax (°F)	70.9 (±2.5)	+3.4 (1.9 to 6.5)	+3.8 (2.2 to 7.0)	+5.4 (3.6 to 10.0)	+7.0 (5.1 to 12.7)	+6.9 (3.9 to 12.4)	+12.0 (7.1 to 20.5)
Winter Tavg (°F)	31.1 (±1.0)	+1.8 (0.5 to 3.3)	+2.1 (0.9 to 3.6)	+3.3 (1.9 to 5.6)	+4.3 (3.0 to 7.4)	+4.9 (2.7 to 7.8)	+7.2 (4.7 to 10.4)
Winter Tmax (°F)	38.1 (±1.3)	+2.0 (0.4 to 3.5)	+1.9 (0.6 to 3.8)	+3.3 (1.6 to 5.7)	+4.5 (2.6 to 7.3)	+5.0 (2.4 to 7.8)	+7.7 (4.4 to 11.0)
Winter Tmin (°F)	24.2 (±1.0)	+1.8 (0.6 to 3.6)	+2.0 (1.0 to 4.0)	+3.3 (2.2 to 6.1)	+4.3 (3.1 to 7.6)	+4.7 (2.9 to 7.9)	+7.1 (5.0 to 11.2)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative to the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP) 245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Cascades Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the Cascades ecoregion, with the largest increases projected for summer. Summer average temperature is projected to increase by as much as 7°F for the 2040-2069 period and as much as 11°F for the 2070-2099 period.



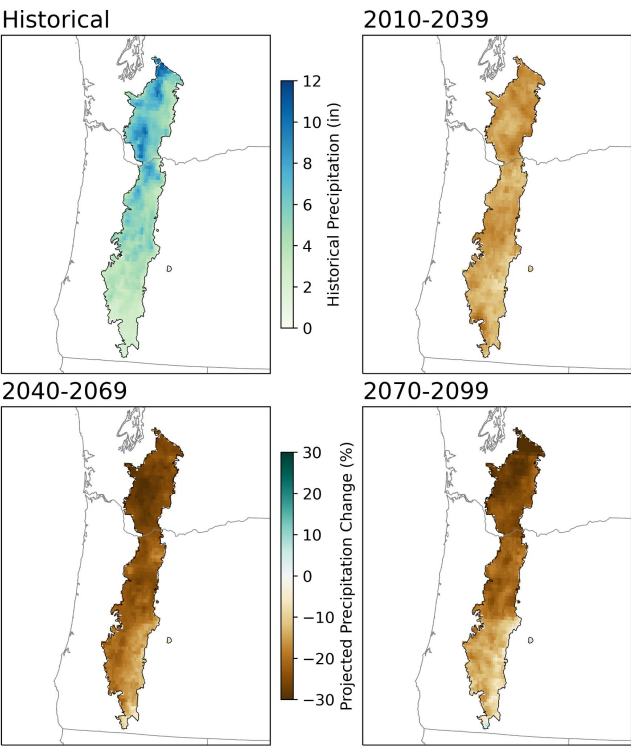
Precipitation

Late summer precipitation is projected to *decrease* by as much as 19% by the 2070-2099 period, and cool season precipitation is projected to *increase* by 6%. Due to the large model range, confidence in cool season projections is lower than for the summer projections, especially for the high (SSP585) scenario .



Growing Season

Growing degree days are projected to more than double by the 2070-2099 period for this ecoregion under a high (SSP585) scenario. Frost days are projected to decrease from 171 per year until there are fewer than 100 per year, on average, under the high (SSP585) scenario.



Total Late Summer (Jul-Sept) Precipitation. Model median historical (1950-2010) and percent change. Future projections (2010-2039, 2040-2069, 2070-2099) for a high (SSP585) scenario show decreasing late summer precipitation across the region with a greater decrease in the north. Confidence is low in projected changes after 2010-2039. Data Source: Localised Constructed Analogs v.2 [LOCA2](#). Resolution: 6km.

	CMIP6 (LOCA2) Growing Season Projections [median (range)]						
	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	5.0in (±2.8)	-18 (-32 to 11)	-17% (-39 to 7)	-17 (-35 to 14)	-22% (-43 to 2)	-19 (-43 to 15)	-16% (-63 to 29)
Cool Season Precipitation	56.8in (±11.7)	+2% (-6 to 10)	+2% (-5 to 13)	+4% (-3 to 14)	+4% (-12 to 17)	+5% (-3 to 17)	+6% (-13 to 22)
GDD (deg-days)	951 (±658)	+347 (264 to 683)	+414 (256 to 701)	+621 (447 to 1085)	+904 (624 to 1288)	+855 (534 to 1295)	+1580 (1044 to 2459)
Frost Days	171 (±15)	-22 (-39 to -13)	-24 (-42 to -18)	-43 (-68 to -29)	-53 (-80 to -42)	-53 (-88 to -38)	-88 (-120 to -66)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loca.ucsd.edu/>

Coast Range Climate Projections

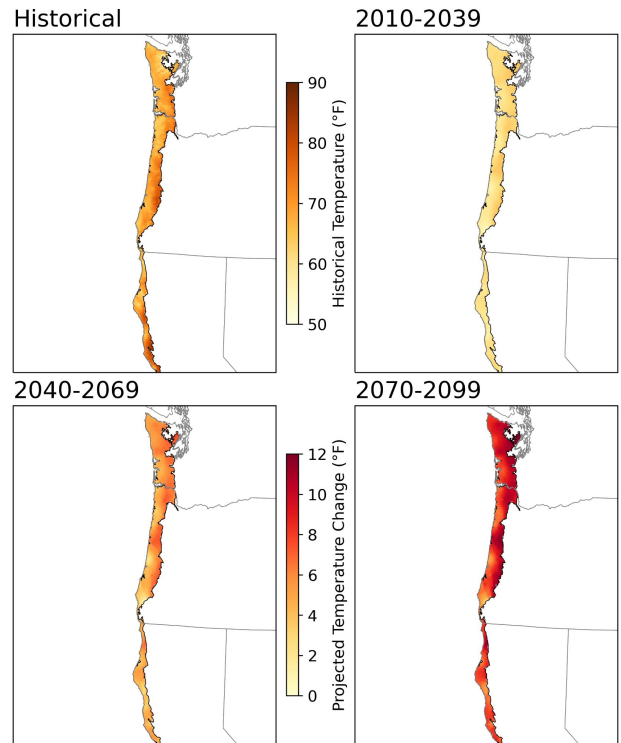


Climate Overview

The Coast Range terrain is varied, with steeply sloping dissected mountains, some hills, sand dunes, and beaches. The climate is maritime with warm, dry summers and mild, but very wet winters. Mean annual temperature and precipitation vary considerably due to the large variation in latitudes and elevations.

Climate Projections

The model median temperature change for 25 CMIP6 models for the Coast Range shows greater increases from the coast moving inland. Projected warming is greater for CMIP6 compared to CMIP5 projections at the end of the century. The median of the CMIP6 models also shows a larger decrease in summer precipitation through the century compared to the CMIP5 models. The CMIP5 and CMIP6 models project similar changes in cool season precipitation. Winters in the Coast Range are projected to be wetter, and summers are projected to be drier in the future.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) for the high scenario (SSP585). Future projections show increasing temperatures through the century, with less warming in areas adjacent to the Pacific Ocean. Data Source: Localised Constructed Analogs v.2 [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP 6 (LOCA2) Temperature Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	58.4 (±1.3)	+2.1 (1.6 to 3.3)	+2.4 (1.4 to 3.9)	+3.8 (2.8 to 6.1)	+5.1 (4.0 to 7.8)	+4.9 (3.9 to 8.1)	+8.3 (6.7 to 13.8)
Summer Tmax (°F)	69.5 (±1.8)	+2.3 (1.6 to 3.8)	+2.7 (1.5 to 4.4)	+3.9 (2.8 to 6.9)	+5.4 (4.0 to 8.6)	+5.1 (3.6 to 8.9)	+8.8 (6.4 to 15.0)
Winter Tavg (°F)	40.3 (±1.1)	+1.6 (0.6 to 3.1)	+1.8 (0.9 to 4.0)	+3.1 (2.0 to 5.0)	+3.7 (3.0 to 8.1)	+4.2 (2.6 to 6.8)	+6.4 (4.7 to 12.1)
Winter Tmax (°F)	47.3 (±1.2)	+1.7 (0.5 to 2.8)	+1.9 (0.7 to 3.5)	+3.0 (1.7 to 5.3)	+3.8 (2.8 to 6.0)	+4.3 (2.4 to 7.0)	+6.3 (4.4 to 10.4)
Winter Tmin (°F)	33.3 (±1.3)	+1.6 (0.6 to 3.3)	+1.8 (1.0 to 3.6)	+3.2 (2.3 to 5.5)	+3.8 (2.8 to 6.7)	+4.4 (2.9 to 7.3)	+6.7 (5.0 to 10.7)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative the the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP)245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Coast Range Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the Coast Range ecoregion, with the largest increases projected for the summer. For a high (SSP585), summer average temperature is projected to increase by as much as 5°F for the 2040-2069 period and by as much as 8°F by the end of the century.



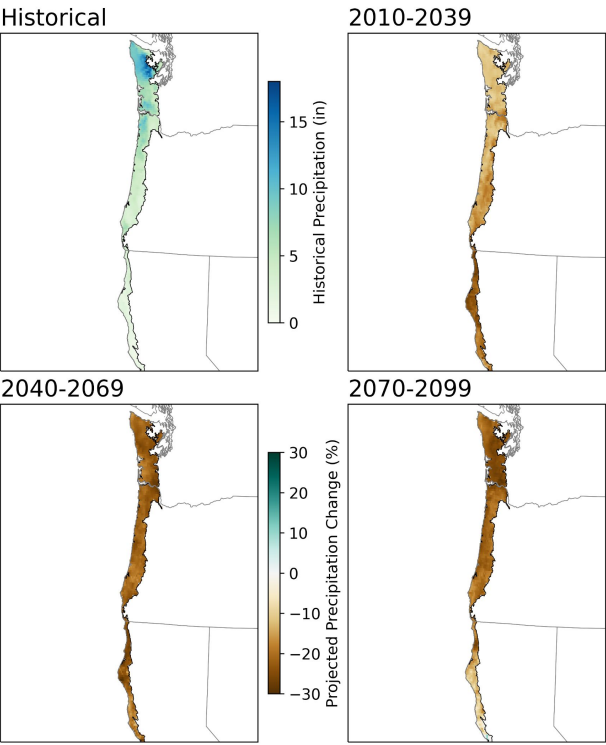
Precipitation

In late summer, total precipitation is projected to *decrease* by as much as 20% by the end of the century. For the cool season, the projections show an *increase* in precipitation of 9%. The confidence in changes in cool season precipitation is greater than in late summer precipitation.



Growing Season

For a high (SSP585) scenario, growing degree days are projected to double by the end of the century. Frost days are projected to decrease from an average of 63 per year to about 15–30 per year, on average, for the 2070-2099 period.



Total Late Summer (Jul-Sept) Precipitation. Model median historical (1950-2010) and projected percent change. Future projections (2010-2039, 2040-2069, 2070-2099) for a high (SSP585) scenario show decreasing late summer precipitation, with a greater decrease projected for the northern part of the ecoregion for the 2070-2099 period. Data Source: Localised Constructed Analogs v.2 [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]							
Variable	1950-2010	2010-2039		2040-2069		2070-2099	
	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	5.1in (±2.9)	-14% (-34 to 18)	-15% (-47 to 15)	-15% (-39 to 17)	-23% (-43 to 0)	-20% (-47 to 19)	-17% (-56 to 33)
Cool Season Precipitation	70.1in (±14.7)	+1% (-4 to 9)	+3% (-5 to 12)	+6% (-4 to 16)	+6% (-12 to 16)	+5% (-3 to 17)	+9% (-4 to 21)
GDD (deg-days)	+1249 (±747)	+375 (287 to 623)	+441 (266 to 796)	+710 (469 to 1177)	+958 (709 to 1399)	+937 (685 to 1625)	+1694 (1297 to 2379)
Frost Days	63 (±18)	-14 (-26 to -7)	-16 (-28 to -17)	-27 (-41 to -19)	-31 (-48 to -38)	-35 (-49 to -25)	-47 (-58 to -61)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loca.ucsd.edu/>

Columbia Plateau Climate Projections

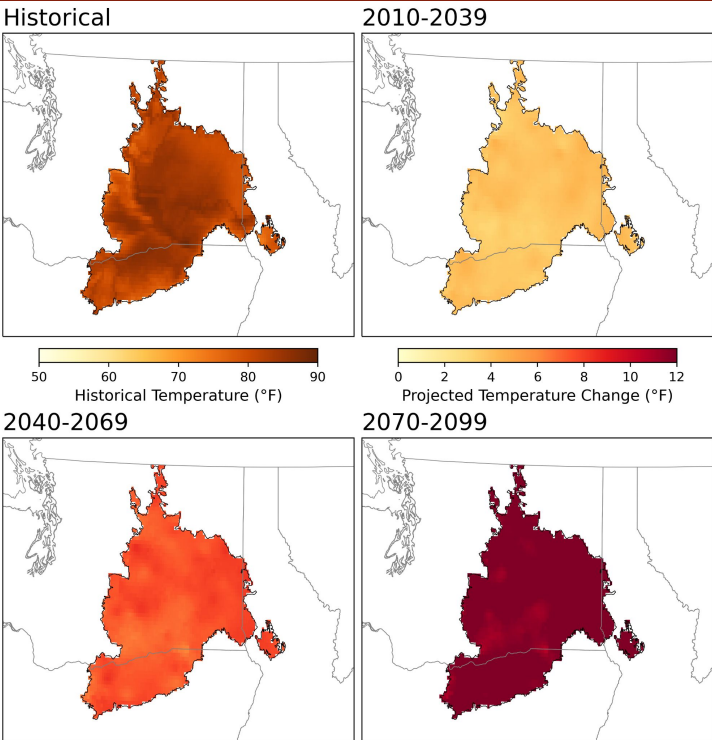


Climate Overview

The Columbia Plateau ecoregion consists of irregular plains and hills. The climate is dry and desert-like with hot, dry summers and cold winters. Mean annual precipitation is low, especially in the western area of the ecoregion due to the rain-shadow effect of the Cascade Range. Most summer precipitation evaporates quickly leaving little water for streams and reservoirs.

Climate Projections

The median temperature change for 25 CMIP6 model projections for the Columbia Plateau ecoregion is spatially uniform, and tends to be warmer than for the CMIP5 model projections at the end of the century. The CMIP6 models also suggest a greater decrease in late summer precipitation than the CMIP5 models for the Columbia Plateau through the next century. Summer in the Columbia Plateau is expected to become more hot and dry.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) for a high (SSP585) scenario. Future projections show increasing temperatures over the next century that is spatially uniform over the Columbia Plateau. Data Source: Localised Constructed Analogs v.2^{[LOCA2](https://loca.ucsd.edu/)}. Resolution: 6km.

Climate Variable	CMIP 6 (LOCA2) Temperature Projections [median (range)]						
	1950-2010	2010-2039		2040-2069		2070-2099	
	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	67.0 (±1.7)	+3.4 (2.2 to 5.7)	+3.8 (2.1 to 6.2)	+5.3 (3.5 to 8.5)	+7.2 (5.2 to 10.5)	+7.0 (4.2 to 10.2)	+12.0 (7.5 to 18.7)
Summer Tmax (°F)	82.4 (±2.4)	+3.7 (2.2 to 7.0)	+3.9 (2.4 to 7.9)	+5.6 (3.9 to 11.2)	+7.5 (5.3 to 14.5)	+7.3 (4.1 to 14.1)	+12.4 (7.1 to 22.5)
Winter Tavg (°F)	31.2 (±1.2)	+2.4 (0.7 to 4.4)	+2.9 (0.8 to 4.8)	+4.7 (2.3 to 7.1)	+5.7 (3.4 to 9.4)	+5.9 (3.3 to 9.7)	+8.9 (5.8 to 13.0)
Winter Tmax (°F)	38.5 (±1.4)	+2.3 (0.6 to 4.2)	+2.7 (0.7 to 4.8)	+4.7 (1.9 to 6.9)	+5.7 (2.9 to 9.0)	+6.0 (2.9 to 9.5)	+8.9 (5.1 to 13.6)
Winter Tmin (°F)	24.0 (±1.3)	+2.5 (0.5 to 4.6)	+3.2 (1.0 to 6.0)	+4.5 (2.6 to 8.9)	+5.7 (3.8 to 10.1)	+5.9 (3.6 to 11.6)	+8.7 (6.3 to 15.7)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative to the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP) 245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Columbia Plateau Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the region, with the largest increases projected in summer. Summer average temperature is projected to increase by as much as 7°F for the 2040-2069 period, and as much as 12°F for the 2070-2099 period under a high (SSP585) scenario.



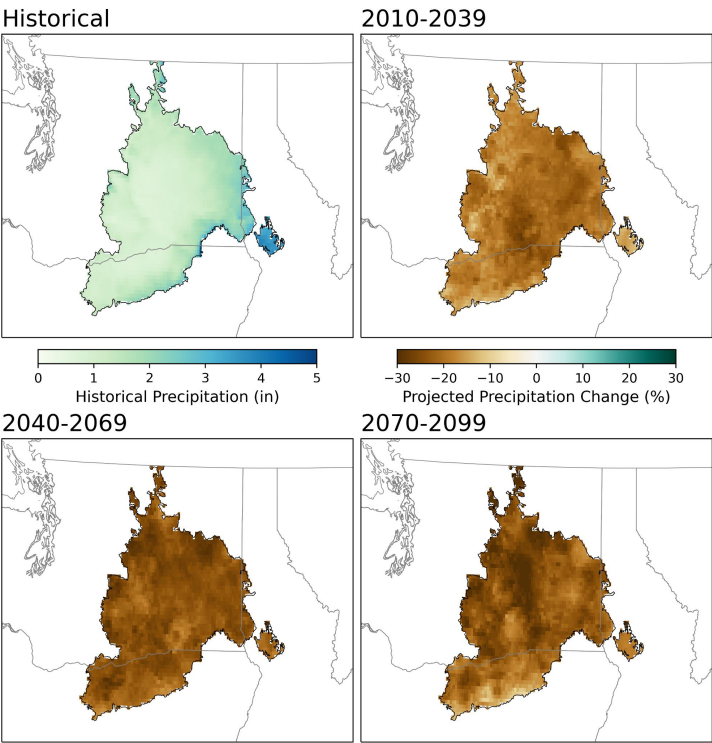
Precipitation

Late summer precipitation is projected to *decrease* as much as 24% for a high (SSP585) scenario in the 2070-2099 period. Cool season precipitation projections show an *increase* in precipitation of as much as 16% for the 2070-2099 period. Compared to other ecoregions, confidence is high these projected precipitation changes.



Growing Season

Growing degree days are projected to double by the 2070-2099 period under a high future scenario. Frost days are projected to decrease from 125 per year until there are fewer than 60, on average, under the high scenario (SSP585).



Total Late Summer (Jul-Sept) Precipitation. Model median historical (1950-2010) and percent change in total late summer precipitation for three future periods (2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Future projections show decreasing late summer precipitation across all of the Columbia Plateau ecoregion, with slightly greater decrease projected for the northern plateau. Data Source: [LOCA2](#). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]

	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	1.4in (±0.9)	-21% (-33 to 8)	-22% (-42 to 18)	-19% (-39 to 18)	-23% (-47 to 4)	-21 (-48 to 24)	-24% (-65 to 59)
Cool Season Precipitation	8.5in (±2.1)	+4% (-4 to 13)	+6% (-2 to 15)	+8% (2 to 23)	+11% (-8 to 24)	+10% (-1 to 30)	+16% (-2 to 30)
GDD (deg-days)	2247 (±895)	+505 (368 to 956)	+559 (360 to 796)	+881 (624 to 1525)	+1242 (865 to 1399)	+1204 (812 to 1958)	+2173 (1468 to 2379)
Frost Days	125 (±15)	-19 (-34 to -12)	-21 (-38 to -14)	-35 (-57 to -25)	-45 (-71 to -33)	-47 (-72 to -33)	-70 (-94 to -54)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Eastern Cascades Foothills Climate Projections

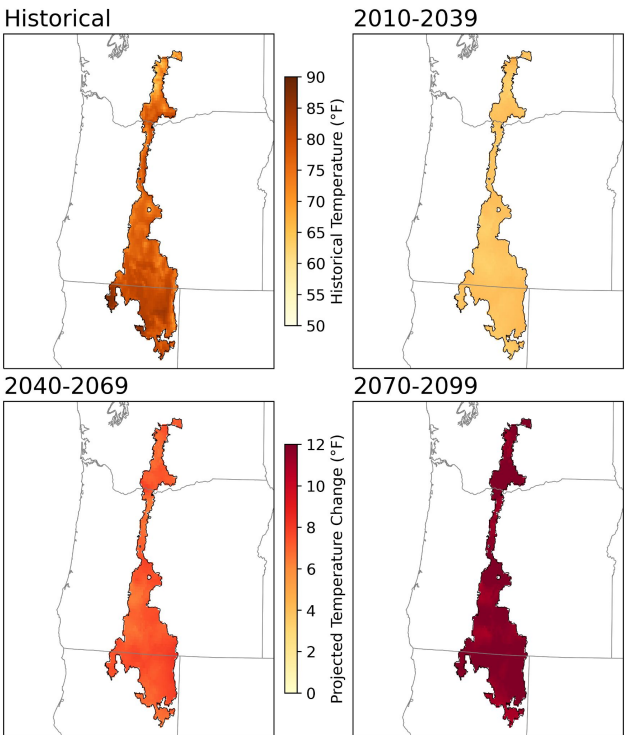


Climate Overview

The Eastern Cascades Foothills terrain includes sloping mountains and high plateaus. The climate is more continental with greater temperature extremes than a maritime climate and less precipitation. Summers are warm and dry; winters are cold. The frost-free period is typically short, especially on the high peaks, and the mean annual precipitation varies considerably with elevation.

Climate Projections

The median temperature change for 25 CMIP6 model projections for the Eastern Cascades Foothills is spatially uniform, and tends to be warmer than the CMIP5 projections for the 2070-2099 period. The CMIP6 model median also projects a greater decrease in summer precipitation for 2010-2039 and 2040-2069 periods, but less of a decrease in the 2070-2099 period compared to the CMIP5 models, especially in the south. With increased temperatures, the frost-free period in the Eastern Cascades Foothills will lengthen.



Summer Maximum Temperature. Model median historical (1950-2010) and change under a high (SSP585) scenario. Future projections show increasing temperatures over the next century, with slightly less warming in the western section of the region with higher elevation. Data Source: Localised Constructed Analogs v.2 [LOCA2](#). Resolution: 6km.

CMIP 6 (LOCA2) Temperature Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	60.0 (±1.7)	+3.1 (2.1 to 5.3)	+3.7 (2.1 to 5.8)	+5.0 (3.5 to 8.1)	+7.2 (4.9 to 9.7)	+6.8 (3.9 to 9.7)	+11.8 (7.2 to 16.3)
Summer Tmax (°F)	77.8 (±2.5)	+3.6 (1.9 to 6.5)	+3.8 (2.1 to 6.7)	+5.4 (3.7 to 9.7)	+7.5 (5.0 to 12.1)	+7.1 (3.7 to 12.1)	+12.0 (6.9 to 19.2)
Winter Tavg (°F)	29.0 (±1.1)	+2.2 (0.6 to 3.5)	+2.6 (1.0 to 3.8)	+4.0 (2.2 to 6.3)	+4.9 (3.2 to 8.2)	+5.3 (3.1 to 8.4)	+7.8 (5.3 to 12.1)
Winter Tmax (°F)	38.7 (±1.4)	+2.2 (0.4 to 3.4)	+2.4 (0.5 to 4.0)	+4.1 (1.8 to 6.1)	+5.1 (2.5 to 8.0)	+5.3 (2.5 to 8.4)	+8.7 (4.5 to 12.5)
Winter Tmin (°F)	19.1 (±1.3)	+2.5 (0.9 to 4.0)	+2.7 (1.3 to 5.3)	+4.0 (2.6 to 8.0)	+5.1 (3.7 to 9.2)	+5.7 (3.6 to 10.0)	+8.2 (5.8 to 13.7)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative the the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP)245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Eastern Cascades Foothills Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the Eastern Cascades Foothills, with the greatest increases projected for the summer. Summer average temperature is projected to increase by as much as 7°F for the 2040-2069 period, and as much as 12°F for the 2070-2099 period under a high (SSP585) scenario.



Precipitation

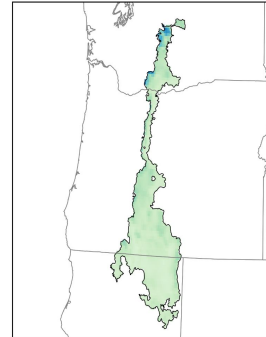
Late summer total precipitation is projected to *decrease* in the north and *increase* in the south of the ecoregion. Projections of cool season precipitation show an *increase* of as much as +9% under a high (SSP585) scenario for the 2070-2099 period. Confidence is low in the projected changes in summer precipitation.



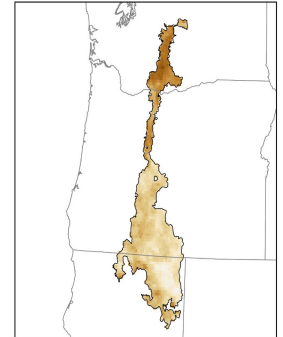
Growing Season

Under a high (SSP585) scenario, growing degree days are projected to double by the 2070-2099 period and frost days are projected to decrease from over 200 per year until there are 120 per year, on average, by the end of the century.

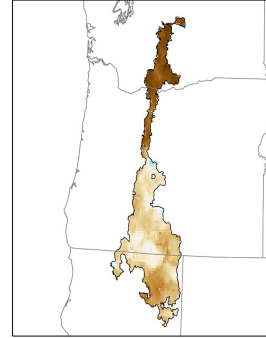
Historical



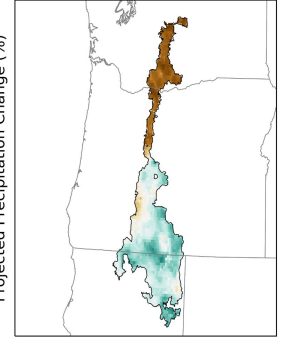
2010-2039



2040-2069



2070-2099



Total Late Summer Precipitation. Model median historical (1950-2010; Jul-Sept) and percent change in for three future periods (2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Future projections show decreasing late summer precipitation across the northern Foothills through the century and an increase for the southernmost Foothills for the end of the century. Confidence is low in projected changes in late summer precipitation after the 2010-2039 period. Data Source: Localised Constructed Analogs v.2 [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]

	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	1.6in (±1.2)	-12% (-34 to 28)	-8% (-34 to 12)	-12% (-39 to 48)	-12% (-40 to 56)	-5% (-31 to 37)	10% (-59 to 114)
Cool Season Precipitation	16.6in (±5.2)	+3% (-5 to 12)	+3% (-4 to 15)	+6% (0 to 14)	+5% (-9 to 22)	+9% (-9 to 19)	+9% (-3 to 25)
GDD (deg-days)	1281 (±733)	+412 (304 to 724)	+491 (297 to 758)	+746 (526 to 1152)	+1028 (714 to 1427)	+968 (574 to 1462)	+1767 (1119 to 2703)
Frost Days	204 (±15)	-23 (-38 to -13)	-25 (-42 to -17)	-42 (-69 to -28)	-54 (-87 to -41)	-53 (-90 to -37)	-86 (129 to -65)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loca.ucsd.edu/>

Idaho Batholith Climate Projections

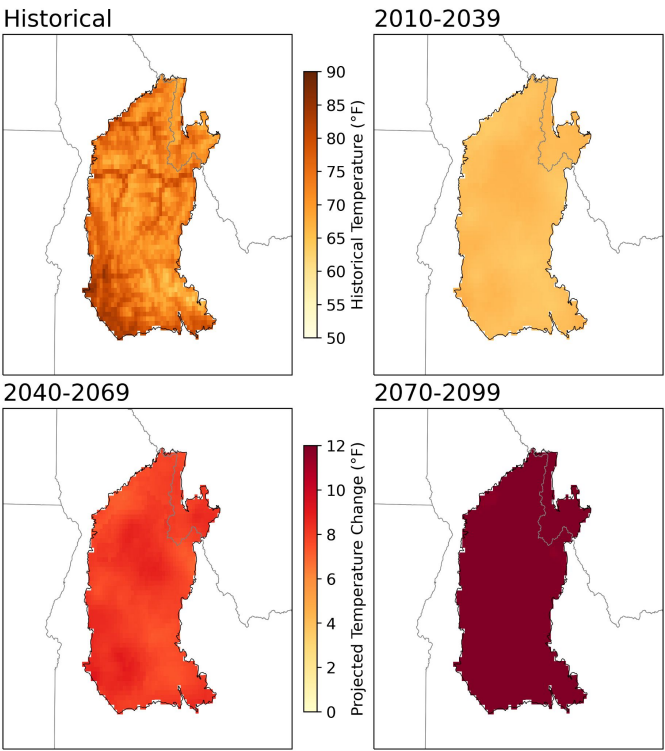


Climate Overview

The Idaho Batholith ecoregion is a mountain plateau with perennial snowfields and several canyons. The climate is severe, mid-latitude, and slightly continental. Summers are typically warm and dry; winters are cold. Maritime influences lessen in the southern end of the ecoregion leading to less precipitation than in the north.

Climate Projections

The median temperature change for 25 CMIP6 models is spatially uniform for the Idaho Batholith and tends to be warmer than for the CMIP5 model projections in the 2070-2099 period. The CMIP6 model median shows less summer precipitation for 2010-2039 compared to the CMIP5 projections, but changes are similar to the CMIP5 projections for the 2070-2099 period. With warming, perennial snowfields are expected to recede and summers are expected to become warmer and drier. Cool season precipitation is projected to increase slightly throughout the next century, falling more as rain in lower and mid-elevations.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) for a high (SSP585) scenario. Future projections show increasing temperatures through the century that are spatially uniform over the Idaho Batholith ecoregion: Localised Constructed Analogs v.2 [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP 6 (LOCA2) Temperature Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	55.0 (±1.8)	+3.6 (2.4 to 7.0)	+3.9 (2.3 to 7.5)	+5.8 (3.2 to 10.1)	+7.9 (5.1 to 12.1)	+7.2 (4.2 to 11.0)	+12.7 (7.6 to 17.7)
Summer Tmax (°F)	73.4 (±2.5)	+3.9 (2.2 to 7.2)	+4.1 (2.1 to 7.9)	+5.9 (3.3 to 11.4)	+8.1 (5.3 to 13.9)	+7.8 (4.0 to 14.2)	+13.4 (7.3 to 22.5)
Winter Tavg (°F)	17.3 (±1.3)	+2.4 (0.9 to 4.2)	+2.8 (1.3 to 3.9)	+4.6 (2.3 to 6.7)	+5.6 (3.6 to 9.0)	+6.1 (3.6 to 8.9)	+8.7 (6.4 to 13.5)
Winter Tmax (°F)	27.7 (±1.3)	+2.1 (0.5 to 3.6)	+2.3 (0.8 to 3.8)	+3.9 (1.7 to 5.7)	+5.0 (2.8 to 7.6)	+5.3 (2.8 to 7.7)	+8.2 (4.7 to 12.1)
Winter Tmin (°F)	6.8 (±1.5)	+3.2 (1.3 to 5.3)	+3.3 (1.7 to 4.8)	+5.2 (3.0 to 7.8)	+6.7 (3.8 to 10.3)	+7.1 (3.9 to 10.7)	+10.8 (7.5 to 17.1)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative to the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP) 245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Klamath Mountains Climate Projections

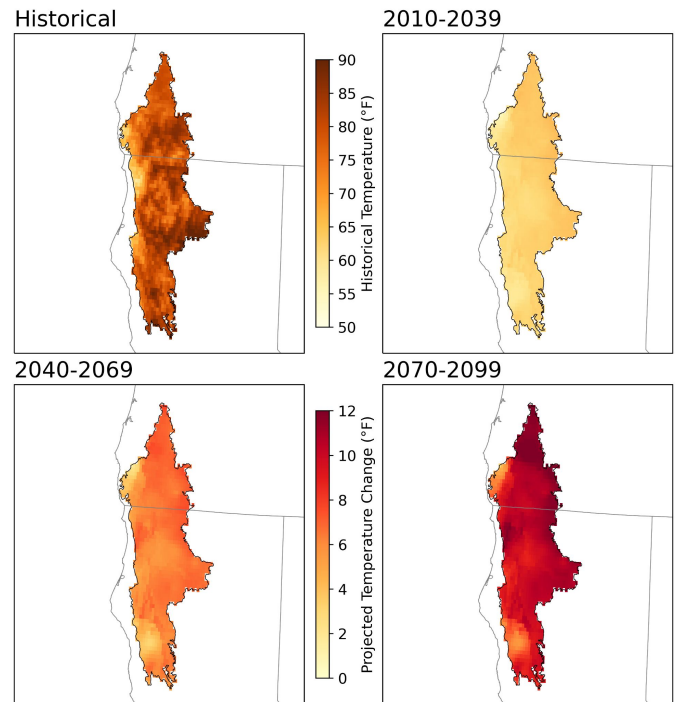


Climate Overview

The Klamath Mountain region includes mountainous terrain and steep slopes, foothills terraces, and floodplains. The climate is mild and Mediterranean with warm summers that typically have a long dry period and mild winters. Mean annual precipitation varies greatly between the low dry areas to the wetter high mountains. Mean annual temperature and number of frost-free days vary considerably with elevation.

Climate Projections

The median temperature change for 25 CMIP6 models for the Klamath Mountains ecoregion generally shows more of increase to the north and east and tends to be warmer than the CMIP5 projections at the end of the century. The CMIP6 model median suggests less summer precipitation for 2010-2039 compared to CMIP5 projections, but similar summer precipitation projections for the model median for the 2070-2099 period. Summers are projected to be warmer and drier, which is expected to lead to longer drought periods.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Future projections show increasing temperatures through the century, with slightly less warming in areas of the ecoregion that are closer to the coast. Data Source: Localised Constructed Analogs v.2 [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP 6 (LOCA2) Temperature Projections [median (range)]

	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	62.1 (±1.5)	+2.5 (1.8 to 4.4)	+3.1 (2.0 to 4.9)	+4.5 (3.2 to 7.1)	+6.2 (4.5 to 8.5)	+6.1 (3.9 to 9.1)	+9.9 (7.4 to 14.4)
Summer Tmax (°F)	79.4 (±2.3)	+3.0 (1.6 to 5.4)	+3.3 (1.9 to 5.8)	+4.7 (3.4 to 8.6)	+6.4 (4.3 to 10.8)	+6.0 (3.4 to 10.7)	+10.1 (6.8 to 17.3)
Winter Tavg (°F)	36.0 (±1.0)	+1.8 (0.7 to 3.4)	+2.0 (1.0 to 3.3)	+3.2 (2.0 to 5.4)	+4.2 (3.1 to 7.0)	+4.6 (2.7 to 7.3)	+6.7 (4.8 to 10.8)
Winter Tmax (°F)	44.9 (±1.3)	+1.8 (0.4 to 3.4)	+2.0 (0.5 to 3.6)	+3.3 (1.7 to 5.4)	+4.2 (2.4 to 6.6)	+4.7 (2.3 to 7.0)	+7.3 (4.3 to 10.4)
Winter Tmin (°F)	27.0 (±1.2)	+1.7 (0.8 to 3.5)	+2.0 (1.3 to 3.9)	+3.2 (2.3 to 5.8)	+4.3 (3.1 to 7.5)	+4.5 (3.0 to 7.7)	+7.2 (5.1 to 11.2)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative to the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP) 245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Klamath Mountains Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the Klamath Mountains ecoregion, with the largest increases projected in the summer. Summer average temperature is projected to increase by as much as 6°F for the 2040-2069 period, and as much as 10°F for the 2070-2099 period under a high (SSP585) scenario.



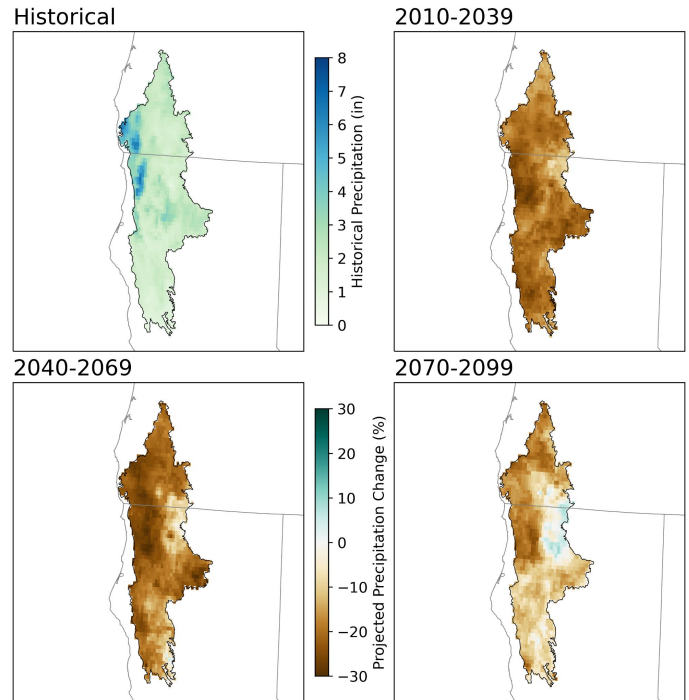
Precipitation

Late summer total precipitation is projected to *decrease* as much as 15%, and cool season precipitation projections show an *increase* of 7% (2070-2099) period. Both projections show low confidence in their results.



Growing Season

Growing degree days are projected to double for the 2070-2099 period under a high (SSP585) scenario. Frost days are projected to decrease from 138 per year on average until there are between 30-80 per year, on average, for the 2070-2099 period under a high (SSP585) scenario.



Total Late Summer (Jul-Sept) Precipitation. Model median historical and percent change for three future periods (2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Future projections show decreasing late summer precipitation across the western Klamath Mountains ecoregion through the century and a slight increase for the eastern Klamath Mountains in the 2070-2099 time period. Confidence is low in projected changes in late summer precipitation due to high model variability. Data Source: [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]

	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	2.2in (±2.0)	-21% (-47 to 33)	-22% (-58 to 19)	-15% (-50 to 58)	-17% (-58 to 49)	-15% (-41 to 54)	-12% (-62 to 86)
Cool Season Precipitation	48.5in (±13.8)	+2% (-11 to 14)	+2% (-7 to 14)	+5% (-8 to 15)	+6% (-15 to 21)	+5% (-10 to 20)	+7% (-11 to 25)
GDD (deg-days)	1673 (±757)	+420 (306 to 693)	+479 (311 to 724)	+781 (531 to 1200)	+1049 (721 to 1537)	+1043 (702 to 1601)	+1812 (1342 to 2826)
Frost Days	138 (±19)	-21 (-35 to -13)	-24 (-38 to -18)	-40% (-61 to -28)	-50 (-74 to -40)	-51 (-77 to -36)	-78 (-102 to -61)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loca.ucsd.edu/>

Middle Rockies

Climate Projections

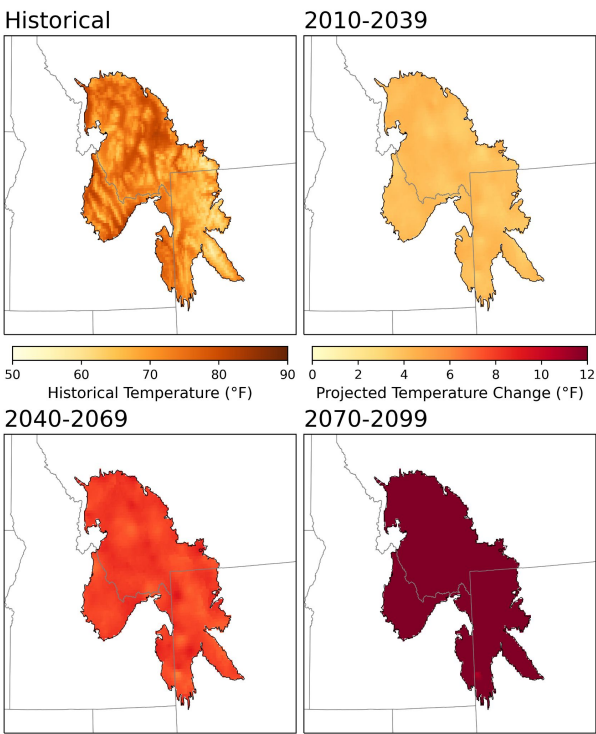


Climate Overview

The Middle Rockies ecoregion consists of high alpine mountains with steep slopes, perennial snowfields, glaciers, plateaus, and glacial basins. The climate is humid and continental, with warm to cool summers and cold winters. The mean annual temperature and precipitation vary considerably by elevation due to the topographic complexity.

Climate Projections

The median temperature change for 25 CMIP6 models for the Middle Rockies ecoregion is mostly uniform across the ecoregion and tends to be warmer than the CMIP5 model projections for the 2070-2099 period. The CMIP6 model median shows a greater contrast in summer precipitation changes across the Middle Rockies than the CMIP5 models, with a larger decrease in the north and more of an increase in the south. With increasing temperatures, winters will warm and more precipitation will fall as rain in winter at low and mid-elevations, leading to glacial and perennial snowfield recession.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) for a high (SSP585) scenario. Projections show increasing temperatures through the century for all of the Middle Rockies ecoregion. Data Source: Localised Constructed Analogs [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

	CMIP 6 (LOCA2) Temperature Projections [median (range)]						
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	54.9 (±1.8)	+3.4 (2.3 to 6.3)	+3.9 (2.2 to 6.7)	+5.8 (3.0 to 9.1)	+7.8 (5.1 to 11.1)	+6.9 (4.2 to 10.2)	+12.3 (7.6 to 16.8)
Summer Tmax (°F)	72.1 (±2.4)	+3.9 (2.2 to 7.3)	+4.0 (2.1 to 7.6)	+6.2 (2.9 to 10.6)	+7.9 (5.2 to 13.1)	+7.5 (4.2 to 13.1)	+13.4 (7.4 to 21.4)
Winter Tavg (°F)	15.5 (±1.4)	+2.3 (1.0 to 3.8)	+2.7 (1.3 to 4.0)	+4.3 (2.2 to 6.6)	+5.9 (3.5 to 8.8)	+5.9 (3.5 to 8.8)	+9.3 (6.3 to 13.5)
Winter Tmax (°F)	26.8 (±1.4)	+2.0 (0.7 to 4.1)	+2.1 (1.0 to 4.3)	+3.6 (1.7 to 6.3)	+4.9 (2.7 to 7.6)	+4.7 (3.2 to 7.9)	+8.2 (4.7 to 11.7)
Winter Tmin (°F)	4.2 (±1.6)	+2.8 (1.4 to 3.9)	+3.0 (1.5 to 4.6)	+5.2 (2.6 to 7.9)	+7.0 (3.8 to 10.5)	+7.1 (3.8 to 10.4)	+11.4 (7.6 to 16.5)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative to the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP) 245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Middle Rockies

Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the region, with the largest increases projected in summer. Summer average temperature is projected to increase by as much as 8°F for the 2040-2069 period and as much as 12°F for the 2070-2099 period under the high (SSP585) scenario.



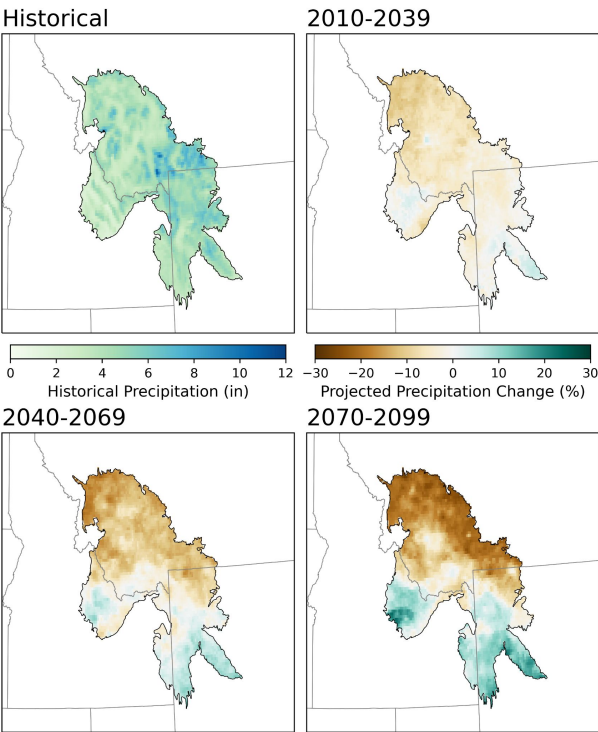
Precipitation

Late summer total precipitation is projected to *decrease* as much as 5% for the 2070-2099 period under a high (SSP585) scenario. Cool season precipitation projections show an *increase* in precipitation of 17%. Late summer precipitation projections have lower confidence than cool season projections.



Growing Season

For the 2070-2099 period under a high (SSP585) scenario, growing degree days are projected to triple, and frost days are projected to decrease from 258 days per year on average until there are fewer than 200 frost days per year on average



Total Late Summer (Jul-Sept) Precipitation. Model median historical (1950-2010) and percent change for three future periods (2010-2039, 2040-2069, 2070-2099) for the high (SSP585) scenario. In the Middle Rockies ecoregion, future projections show late summer precipitation decreasing in the north and increasing in the south throughout the century. Confidence is low in projected changes in late summer precipitation due to the large model range. Data Source: [LOCA2](#). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	4.3in (±1.9)	0% (-28 to 11)	-1% (-23 to 18)	-7% (-30 to 40)	-5% (-35 to 34)	0% (-32 to 37)	-5% (-45 to 75)
Cool Season Precipitation	11.3mm (±2.6)	+5% (0 to 13)	+5% (-4 to 15)	+8% (2 to 20)	+9% (2 to 29)	+10% (0 to 24)	+17% (5 to 39)
GDD (deg-days)	715 (±643)	+343 (245 to 674)	+407 (236 to 712)	+638 (298 to 1067)	+897 (546 to 1346)	+790 (465 to 1235)	+1503 (933 to 2508)
Frost Days	258 (±13)	-23 (-36 to -16)	-24 (-39 to -16)	-38 (-58 to -26)	-49 (-77 to -37)	-50 (-77 to -36)	-76 (-118 to -60)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loca.ucsd.edu/>

North Cascades Climate Projections

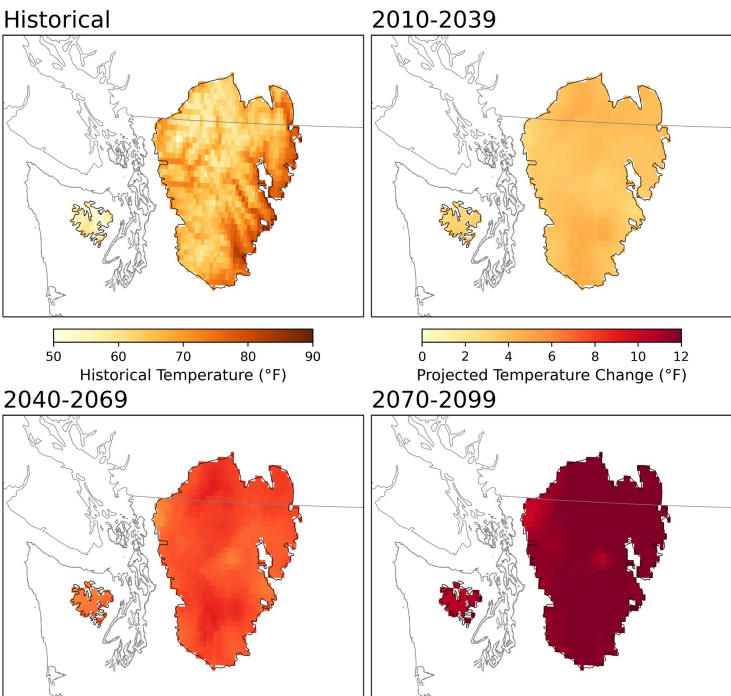


Climate Overview

The North Cascades ecoregion terrain consists of high mountains and glaciated peaks. It includes a variety of climatic zones, with a dry continental climate in the east and mild maritime conditions in the west. Summers are warm and dry; winters are cold and wet. High elevations receive abundant snowfall that feeds a high density of streams during the spring and early summer.

Climate Projections

The median temperature change for 25 CMIP6 model projections for the North Cascades ecoregion are spatially uniform and tend to be warmer than the CMIP5 projections at the end of the century. The CMIP6 model median also shows considerably less late summer precipitation than the CMIP5 models, especially late in the century. With warming temperatures, more winter precipitation will fall as rain in the future.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Future projections show increasing temperatures over the next century throughout the North Cascades. Data Source: Localised Constructed Analogs v.2 [LOCA2](#). Resolution: 6km.

CMIP 6 (LOCA2) Temperature Projections [median (range)]							
Climate Variable	1950-2010	2010-2039		2040-2069		2070-2099	
	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	53.5 (±1.6)	+3.1 (2.0 to 6.7)	+3.5 (1.9 to 7.3)	+5.1 (3.6 to 9.5)	+7.2 (5.3 to 11.3)	+6.7 (4.2 to 10.5)	+11.7 (7.3 to 18.6)
Summer Tmax (°F)	66.4 (±2.4)	+3.5 (1.9 to 7.7)	+4.1 (2.2 to 8.4)	+5.6 (3.8 to 11.4)	+7.6 (5.4 to 14.8)	+7.2 (4.0 to 14.1)	+12.3 (7.0 to 23.3)
Winter Tavg (°F)	22.0 (±1.2)	+2.2 (0.9 to 4.1)	+2.7 (1.0 to 4.0)	+4.5 (2.7 to 6.3)	+5.3 (4.0 to 8.1)	+5.7 (3.5 to 8.4)	+8.6 (6.3 to 12.1)
Winter Tmax (°F)	28.2 (±1.3)	+2.0 (0.8 to 3.7)	+2.4 (0.7 to 4.1)	+4.1 (2.2 to 6.0)	+5.0 (3.3 to 7.7)	+5.4 (3.0 to 8.0)	+8.2 (5.5 to 12.5)
Winter Tmin (°F)	15.7 (±1.2)	+2.5 (0.7 to 4.9)	+2.9 (1.2 to 4.9)	+4.8 (3.1 to 7.3)	+5.5 (4.5 to 9.0)	+6.3 (3.9 to 10.2)	+9.3 (7.2 to 15.6)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative the the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP)245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

North Cascades Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the North Cascades ecoregion, with the largest increases projected for the summer. Summer average temperature is projected to increase by as much as 7°F for the 2040-2069 period and as much as 12°F for the 2070-2099 period under a high (SSP585) scenario.



Precipitation

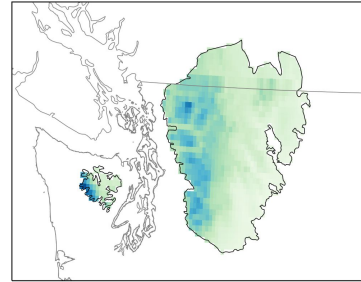
Late summer total precipitation is projected to *decrease* as much as 28% for the 2070-2099 period. Cool season precipitation projections show an *increase* in by as much as 10%. Both late summer and cool season precipitation projections show confidence in their results.



Growing Season

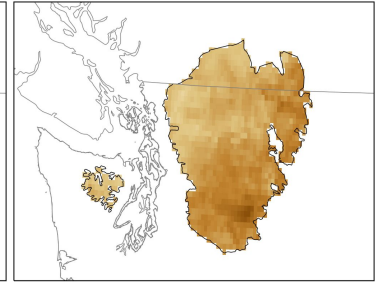
Under a high (SSP585) scenario, growing degree days are projected to triple. Frost days are projected to decrease from over 200 per year until there are fewer than 150 per year, on average, by the end of the century.

Historical



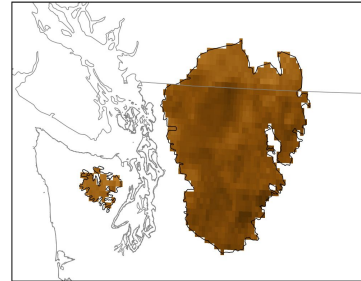
0 5 10 15 20
Historical Precipitation (in)

2010-2039

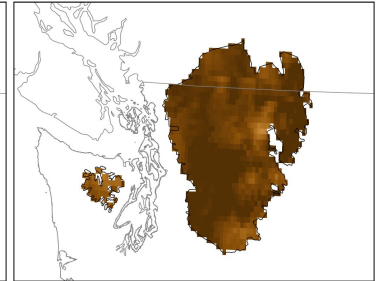


-30 -20 -10 0 10 20 30
Projected Precipitation Change (%)

2040-2069



2070-2099



Total Late Summer Precipitation. Model median historical (1950-2010; Jul-Sept) and percent change in for three future periods (2010-2039, 2040-2069, 2070-2099) for a high (SSP585) scenario. Future projections show decreasing late summer precipitation across the entirety of the North Cascades ecoregion, with the largest magnitude decrease for the 2070-2099 period. Confidence is high for both late summer and cool season precipitation projections due to model agreement Data Source: [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]

	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	6.6in (±3.1)	-17% (-37 to 21)	-16% (-47 to 15)	-19% (-43 to 14)	-25% (-46 to 0)	-23% (-52 to 18)	-28% (-53 to 33)
Cool Season Precipitation	49.2in (±9.6)	+2% (-4 to 12)	+4% (-4 to 15)	+7% (-1 to 14)	+7% (-7 to 18)	+10% (2 to 21)	+11% (4 to 26)
GDD (deg-days)	613 (±585)	+285 (194 to 776)	+331 (188 to 796)	+495 (338 to 1148)	+764 (520 to 1399)	+705 (420 to 1288)	+1360 (808 to 2379)
Frost Days	219 (±13)	-21 (-43 to -13)	-24 (-44 to -17)	-38 (-70 to -26)	-51 (-82 to -38)	-50 (-90 to -37)	-82 (-135 to -61)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loca.ucsd.edu/>

Northern Basin and Range Climate Projections

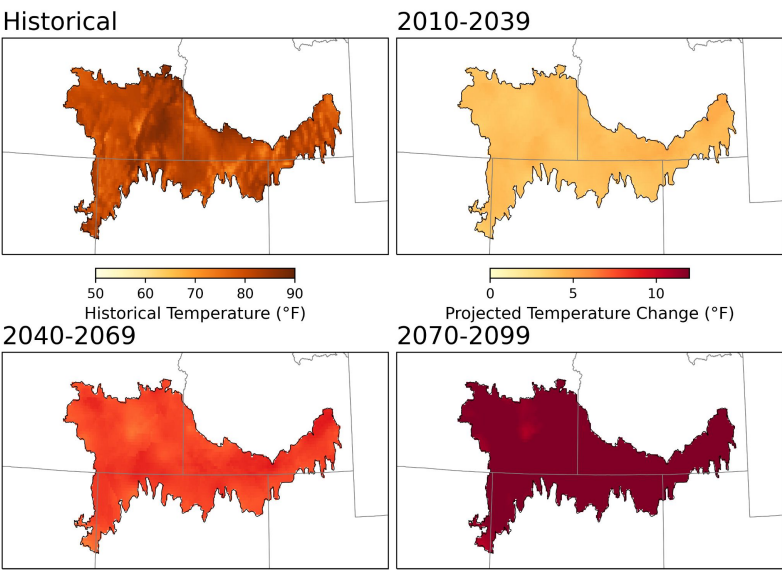


Climate Overview

The Northern Basin and Range terrain consists of tablelands, basins, plains, some mountains, and valleys. The climate is arid with both steppe and desert climates, hot summers, and cold winters. Mean annual precipitation varies from minimal in the low areas to considerable in the higher mountainous areas.

Climate Projections

The median temperature change for 25 CMIP6 model projections for the Northern Basin and Range ecoregion is spatially uniform and tends to be warmer than for the CMIP5 model projections for the 2070-2099 period. The CMIP6 model median is generally wetter and warmer than the CMIP5 model median, regardless of season. Increasing temperatures will lead to hotter summers, warmer winters, and more precipitation falling as rain in the winter in the higher elevation areas.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Future projections show increasing temperatures through the century for the entire Northern Basin and Range ecoregion. Data Source: Localised Constructed Analogs [LOCA2](#). Resolution: 6km.

CMIP 6 (LOCA2) Temperature Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	62.8 (±1.8)	+3.5 (2.3 to 5.3)	+3.9 (2.4 to 5.8)	+5.6 (3.2 to 8.5)	+7.7 (5.1 to 10.6)	+6.9 (4.1 to 10.4)	+12.2 (7.6 to 16.7)
Summer Tmax (°F)	81.0 (±2.5)	+4.0 (2.1 to 6.7)	+4.2 (2.2 to 7.1)	+6.1 (3.3 to 9.7)	+8.2 (5.2 to 12.0)	+7.6 (4.0 to 11.9)	+12.9 (7.3 to 19.2)
Winter Tavg (°F)	26.9 (±1.3)	+2.7 (0.9 to 4.6)	+3.0 (0.4 to 5.1)	+4.5 (2.2 to 7.2)	+6.3 (3.5 to 9.6)	+6.2 (3.4 to 9.7)	+9.3 (5.5 to 14.3)
Winter Tmax (°F)	37.5 (±1.4)	+2.4 (0.6 to 4.2)	+2.6 (0.8 to 4.8)	+4.4 (1.8 to 6.8)	+6.3 (2.7 to 8.4)	+5.6 (2.8 to 8.9)	+9.3 (4.5 to 14.3)
Winter Tmin (°F)	16.2 (±1.6)	+3.3 (1.2 to 4.9)	+3.3 (0.0 to 5.5)	+5.3 (2.6 to 8.6)	+7.3 (4.0 to 11.2)	+7.0 (4.0 to 11.1)	+10.3 (6.0 to 17.4)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative to the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP) 245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Northern Basin and Range Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the ecoregion, with the largest increases projected in summer. Summer average temperature is projected to increase by as much as 8°F for the 2040-2069 period and as much as 12°F for the 2070-2099 period under the high (SSP585) scenario.



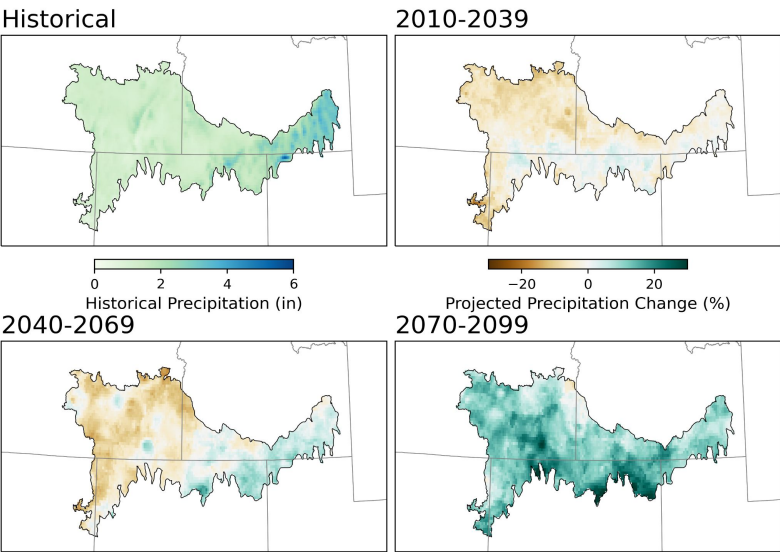
Precipitation

Late summer total precipitation is projected to *increase* or *decrease* depending on time period and scenario. Cool season precipitation projections show an *increase* in precipitation of as much as 19% for the 2070-2099 period. Confidence is low in the late summer projections due to the large model range.



Growing Season

Growing degree days are projected to double by the 2070-2099 period for the Northern Basin and Range under a high scenario (SSP585). Frost days are projected to decrease from 200 until there are fewer than 150 per year, on average, under the high scenario (SSP585).



Total Late Summer (Jul-Sept) Precipitation. Model median historical (1950-2010) and percent change for three future periods (2010-2039, 2040-2069, 2070-2099) for a high (SSP585) scenario. Future projections show varied changes in late summer precipitation across the Northern Basin and Range ecoregion through the next century. For the 2070-2099 period, projections show an increase in precipitation for the southern are of the Northern Basin and Range ecoregion. Confidence is low in projected changes in late summer precipitation due to a large model range. Data Source: [LOCA2](#). Resolution: 6km

Variable	CMIP6 (LOCA2) Growing Season Projections [median (range)]						
	1950-2010	2010-2039		2040-2069		2070-2099	
	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	1.6in (±0.1)	-2% (-35 to 32)	-1% (-45 to 43)	-9% (-36 to 85)	-2% (-34 to 91)	1% (-27 to 68)	12% (-39 to 163)
Cool Season Precipitation	7.5in (±2.1)	+4% (-5 to 14)	+7% (-6 to 16)	+11% (3 to 18)	+11% (1 to 29)	+11% (-4 to 24)	+19% (4 to 32)
GDD (deg-days)	1584 (±817)	+484 (343 to 790)	+551 (339 to 836)	+879 (505 to 1315)	+1153 (801 to 1731)	+1055 (657 to 1742)	+1888 (1271 to 3215)
Frost Days	201 (±15)	-21 (-34 to -12)	-24 (-36 to -13)	-38 (-62 to -25)	-47 (-83 to -34)	-49 (-85 to -33)	-78 (-124 to -59)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loca.ucsd.edu/>

Northern Rockies

Climate Projections

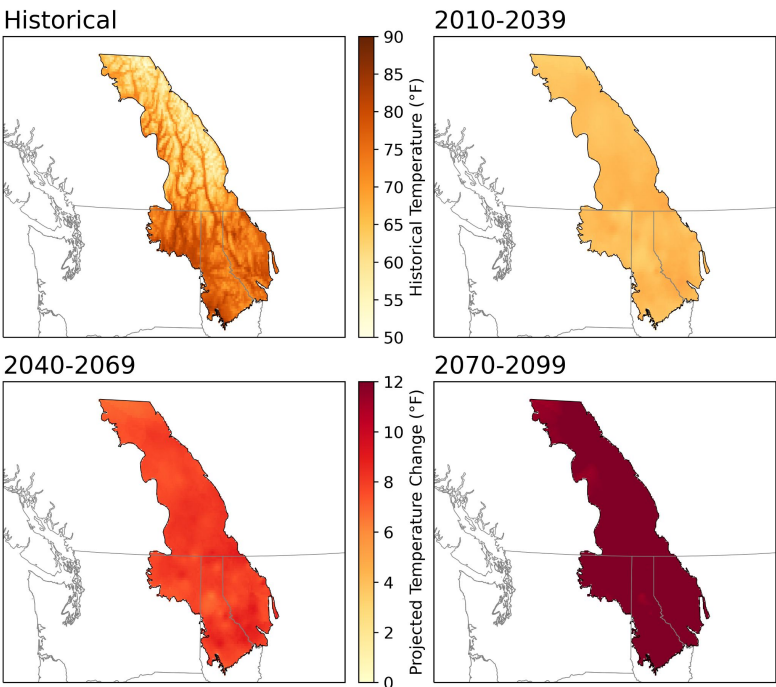


Climate Overview

The Northern Rockies terrain is rugged, with high and low mountains, narrow valleys, and deep canyons. The climate is relatively dry and warm in the summer with cold, snowy winters. Mean winter temperature is below freezing, and the frost-free period in the high elevations can be a matter of only weeks. High elevations experience more precipitation than lower elevations.

Climate Projections

The median temperature change for 25 CMIP6 model projections for the Northern Rockies is spatially uniform and tends to be warmer than the CMIP5 projections for the 2070-2099 period. Compared to the CMIP5 model median, the CMIP6 model median shows more cool season precipitation and less late summer precipitation, especially for the southernmost sections of the ecoregion. Frost days are expected to decrease and more cool season precipitation will fall as rain.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) for the high (SSP585) scenario. Future projections show spatially uniform increasing temperatures over the century for the Northern Rockies. Data Source: Localised Constructed Analogs v.2 [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

	CMIP 6 (LOCA2) Temperature Projections [median (range)]						
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	55.6 (±1.7)	+3.6 (1.9 to 7.5)	+3.7 (1.9 to 8.2)	+5.5 (3.6 to 10.3)	+7.6 (5.3 to 12.6)	+7.2 (4.1 to 11.5)	+12.4 (7.2 to 18.8)
Summer Tmax (°F)	70.4 (±2.6)	+3.9 (2.0 to 8.0)	+4.2 (2.1 to 8.9)	+5.9 (3.8 to 11.9)	+7.9 (5.5 to 15.3)	+7.6 (4.0 to 14.8)	+12.8 (6.8 to 24.4)
Winter Tavg (°F)	18.8 (±1.4)	+2.1 (0.7 to 5.4)	+2.6 (0.9 to 4.9)	+4.4 (2.6 to 7.1)	+5.5 (3.9 to 9.0)	+5.9 (3.6 to 8.7)	+9.0 (6.8 to 13.2)
Winter Tmax (°F)	25.4 (±1.5)	+1.9 (0.7 to 4.3)	+2.3 (0.7 to 4.1)	+3.6 (1.9 to 5.9)	+5.0 (3.1 to 7.8)	+4.9 (3.0 to 8.1)	+7.9 (5.4 to 11.8)
Winter Tmin (°F)	12.1 (±1.6)	+2.3 (0.8 to 6.4)	+2.9 (1.1 to 5.7)	+4.9 (3.2 to 8.3)	+6.1 (4.5 to 10.6)	+6.9 (4.2 to 10.8)	+10.3 (8.0 to 16.8)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative the the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP)245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Northern Rockies

Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the ecoregion, with the largest increases projected for summer. Summer average temperature is projected to increase by as much as 8°F for the 2040-2069 period and as much as 12°F by the end of the century for a high (SSP585) scenario.



Precipitation

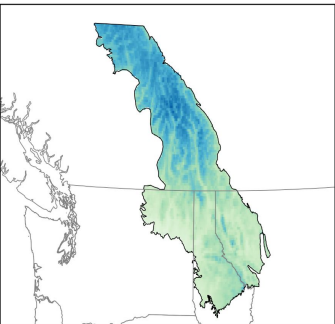
For the 2070-2099 period, late summer total precipitation is projected to *decrease* as much as 19%, and cool season precipitation projections show an *increase* in precipitation of 17%. Both the late summer and cool season projections have confidence in their results.



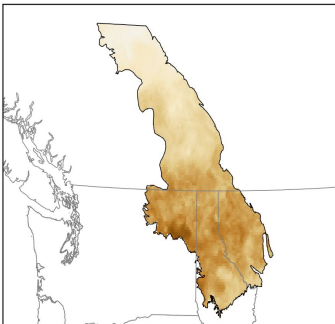
Growing Season

Growing degree days are projected to nearly triple by the 2070-2099 period for the Northern Rockies under a high (SSP585) scenario. Frost days are projected to decrease from 226 per year until there are fewer than 150 per year, on average, by the end of the century for a high scenario.

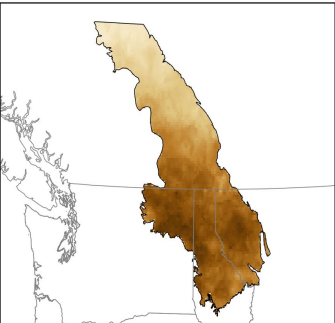
Historical



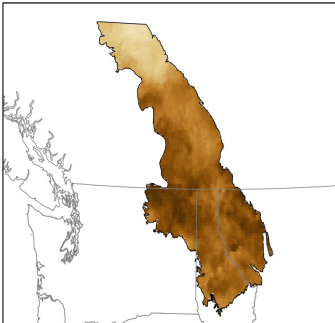
2010-2039



2040-2069



2070-2099



Total Late Summer Precipitation. Model median historical (1950-2010; Jul-Sept) and change for three future periods (2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Future projections show decreasing late summer precipitation across much of the Northern Rockies throughout the century, with more of a decrease projected for the south. Confidence is generally high in projected changes in late summer precipitation due to model agreement. Data Source: [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]

	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	5.7in (±2.2)	-12% (-28 to 3)	-13% (-33 to 9)	-10% (-28 to 5)	-19% (-41 to 0)	-12% (-40 to 8)	-19% (-47 to 24)
Cool Season Precipitation	21.2in (±4.3)	+5% (-2 to 14)	+6% (-2 to 15)	+7% (1 to 22)	+8% (-4 to 25)	+13% (1 to 26)	+17% (4 to 31)
GDD (deg-days)	799 (±651)	+342 (224 to 879)	+378 (202 to 926)	+583 (400 to 1281)	+884 (593 to 1580)	+811 (474 to 1414)	+1561 (888 to 2640)
Frost Days	226 (±15)	-22 (-45 to -13)	-23 (-45 to -16)	-42 (-68 to -25)	-51 (-80 to -36)	-51 (-83 to -40)	-82 (-128 to -63)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Standard deviations may be greater than the average when the distribution is skewed. Data Source: <https://loca.ucsd.edu/>

Puget Lowlands Climate Projections

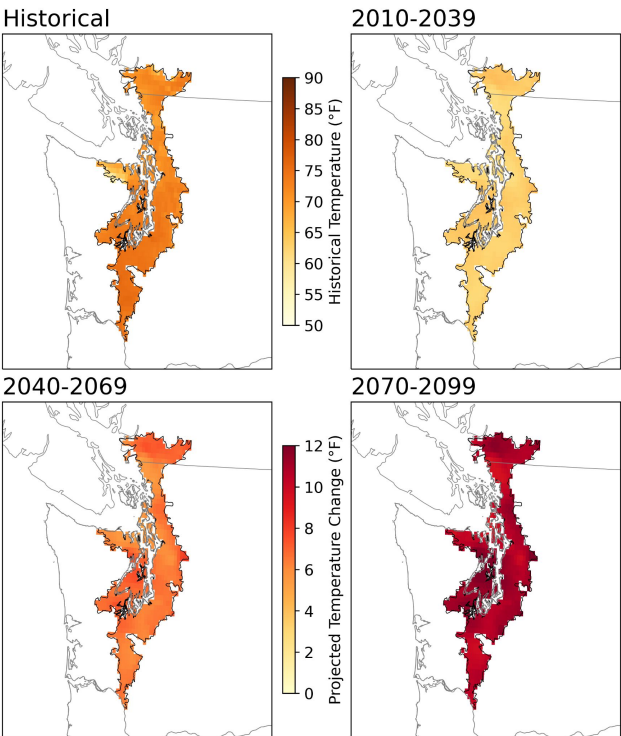


Climate Overview

The Puget Lowlands ecoregion is mostly low elevation and consists of many islands, peninsulas, and bays. The climate is mild and maritime with warm, dry summers and mild, wet winters. Frosts may occur, but snow is not common. Mean annual precipitation varies considerably and increases with elevation.

Climate Projections

The median temperature change for 25 CMIP6 model projections for the Puget Lowlands is spatially uniform and tends to be warmer than the CMIP5 projections for the 2070-2099 period. Model median winter precipitation projections are similar but the CMIP6 model median projects a larger decrease in summer precipitation than the CMIP5 models for the 2070-2099 period. With increasing temperatures, more total precipitation is expected in the winters and frosts are expected to become even less frequent.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) for the high (SSP585) scenario. Future projections show increasing temperatures throughout the region. Data Source: Localised Constructed Analogs v.2 [LOCA2](#). Resolution: 6km

CMIP 6 (LOCA2) Temperature Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	61.4 (±1.2)	+2.6 (1.8 to 5.6)	+3.0 (1.6 to 6.0)	+4.6 (3.2 to 8.2)	+6.3 (4.7 to 9.7)	+5.8 (4.1 to 9.4)	+10.1 (7.0 to 16.5)
Summer Tmax (°F)	72.4 (±1.9)	+3.0 (1.6 to 6.3)	+3.4 (1.9 to 7.0)	+4.8 (3.4 to 9.4)	+6.4 (4.9 to 12.2)	+6.3 (3.8 to 11.8)	+11.2 (6.5 to 20.2)
Winter Tavg (°F)	39.1 (±1.0)	+2.1 (0.6 to 3.9)	+2.4 (0.9 to 3.7)	+4.1 (2.4 to 6.0)	+5.0 (3.5 to 7.8)	+5.4 (3.0 to 8.0)	+8.1 (5.8 to 11.3)
Winter Tmax (°F)	45.1 (±1.2)	+2.0 (0.7 to 3.6)	+2.3 (0.7 to 4.0)	+3.8 (2.0 to 6.0)	+4.8 (3.2 to 7.2)	+5.4 (2.8 to 8.3)	+8.2 (5.4 to 12.5)
Winter Tmin (°F)	33.0 (±1.1)	+2.1 (0.5 to 4.8)	+2.4 (1.0 to 4.6)	+4.2 (2.5 to 7.1)	+5.0 (3.8 to 8.9)	+5.4 (3.2 to 9.7)	+8.2 (6.3 to 14.1)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative the the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP)245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

A map of the state of Georgia with its county boundaries outlined. The northwestern portion of the state is shaded in black, indicating the study area. The map shows the state's irregular shape, including the Florida panhandle to the west and the Atlantic coast to the east.



Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loda.ucsd.edu/>

Snake River Plain Climate Projections

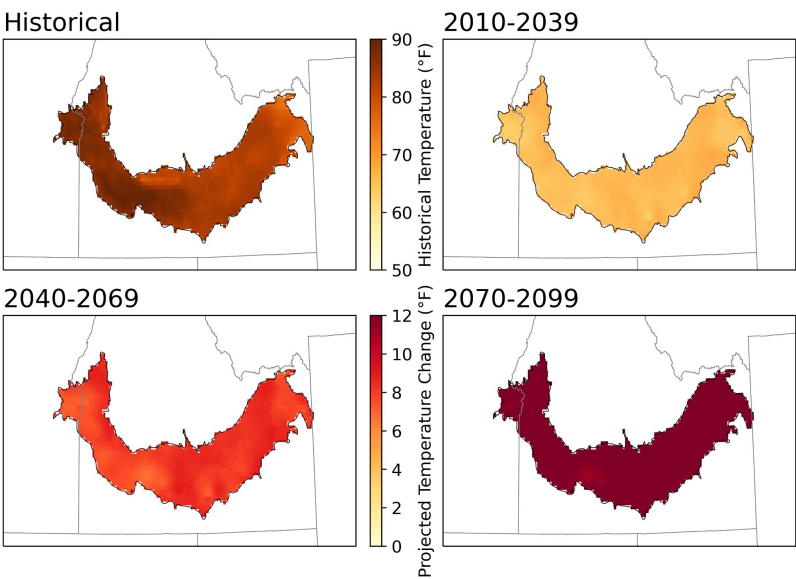


Climate Overview

The Snake River Plain is low and gently-sloping, consisting of valleys, plains, and low hills. The climate is arid with steppe and desert climates, hot summers, and cold winters. The mean annual temperature is cooler in the eastern part of the region, partially due to elevation. The mean annual precipitation is low compared to surrounding regions because of its relatively low elevation.

Climate Projections

The projected median temperature change for 25 CMIP6 models for the Snake River Plain is spatially uniform. End of the century projections tend to be warmer than the CMIP5 projections. The CMIP6 model median suggests a larger decrease in late summer precipitation for the 2040-2069 period, but changes are similar to the CMIP5 model for the 2070-2099 period under the high scenario (SSP585). Warmer temperatures are expected to increase aridity in the region.



Summer Maximum Temperature. Model median historical (1950-2010) and projected change (2010-2039, 2040-2069, 2070-2099) for a high (SSP585) scenario. Future projections show spatially uniform increasing temperatures for the Snake River Plain through the century. Data Source: Localised Constructed Analogs v.2 [LOCA2](https://loca.ucsd.edu/). Resolution: 6km.

CMIP 6 (LOCA2) Temperature Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	66.8 (±1.9)	+3.7 (2.3 to 6.1)	+4.0 (2.4 to 6.6)	+5.9 (2.8 to 9.0)	+7.9 (5.1 to 11.1)	+7.3 (3.9 to 11.0)	+12.4 (7.8 to 17.5)
Summer Tmax (°F)	84.1 (±2.4)	+4.2 (2.1 to 7.0)	+4.1 (2.3 to 7.4)	+6.3 (3.0 to 10.4)	+8.3 (5.3 to 12.7)	+7.9 (4.2 to 12.8)	+13.3 (7.8 to 20.4)
Winter Tavg (°F)	25.9 (±1.4)	+2.9 (1.4 to 4.5)	+3.2 (1.5 to 4.8)	+5.0 (2.7 to 7.5)	+6.8 (4.1 to 9.8)	+6.6 (4.2 to 9.7)	+10.7 (6.4 to 14.8)
Winter Tmax (°F)	35.5 (±1.4)	+2.6 (0.8 to 4.4)	+3.0 (1.0 to 4.3)	+4.5 (2.1 to 7.2)	+6.5 (3.4 to 9.2)	+5.7 (3.4 to 9.4)	+10.3 (5.5 to 15.7)
Winter Tmin (°F)	16.3 (±1.6)	+3.3 (1.5 to 4.7)	+3.7 (1.3 to 5.4)	+5.8 (3.3 to 8.8)	+8.2 (4.7 to 11.5)	+7.8 (5.0 to 12.3)	+12.3 (7.4 to 18.5)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative the the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP)245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Snake River Plain Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the ecoregion, with the largest increases projected for summer. Summer average temperature is projected to increase by as much as 8°F for the 2040-2069 period and as much as 12°F by the end of the century for a high (SSP585) scenario, relative to the historical period.



Precipitation

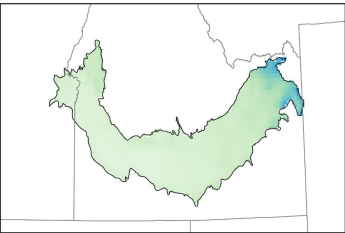
Late summer precipitation is projected to increase or decrease depending on time period, location, and future scenario. Confidence is low in these projections due to model variability. Projections of cool season precipitation show an *increase* of as much as 20% by the end of the century



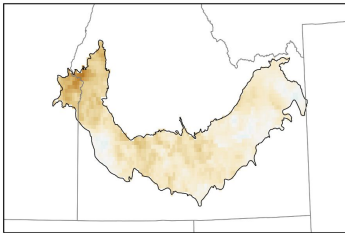
Growing Season

By the end of the century and under a high (SSP585) scenario, growing degree days, an indicator of growing season length, are projected to double, and frost days are projected to decrease from over 150 per year until there are fewer than 100 per year, on average by the end of the century.

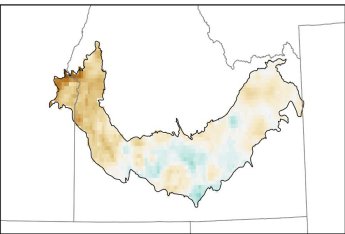
Historical



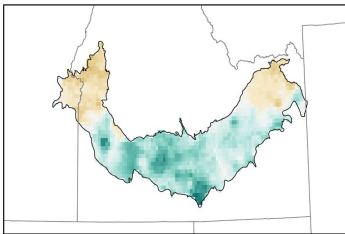
2010-2039



2040-2069



2070-2099



Total Late Summer Precipitation. Model median historical (1950-2010) and percent change for three future periods (2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Late summer precipitation is projected to decrease across the northern Snake River Plain throughout the century, with a slight increase for the southern Snake River Plain in the 2070-2099 time period. Confidence is low in projected changes in late summer precipitation for all future time periods due to variability among models. Data Source: Localised Constructed Analogs v.2 [LOCA2](#). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]

Variable	1950-2010	2010-2039		2040-2069		2070-2099	
	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	1.5in (±1.0)	-4% (-29 to 22)	-5% (-38 to 43)	-14% (-40 to 79)	-2% (-35 to 71)	-3% (-24 to 75)	3% (-41 to 164)
Cool Season Precipitation	6.9in (±2.0)	+4% (-2 to 16)	+6% (-7 to 18)	+12% (2 to 25)	+11% (0 to 29)	+12% (-3 to 24)	+21% (3 to 37)
GDD (deg-days)	2158 (±930)	+588 (381 to 930)	+633 (373 to 990)	+998 (528 to 1556)	+1300 (904 to 2095)	+1274 (713 to 2048)	+2120 (1428 to 3695)
Frost Days	168 (±15)	-18 (-29 to -12)	-22 (-33 to -12)	-34 (-57 to -25)	-45 (-73 to -31)	-48 (-78 to -31)	-73 (-114 to -54)

Historical precipitation (inches) and future percent change relative to the historical values. The range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days (GDD) is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on the sign of the change. Data Source: <https://loca.ucsd.edu/>

Southeastern Idaho Climate Projections

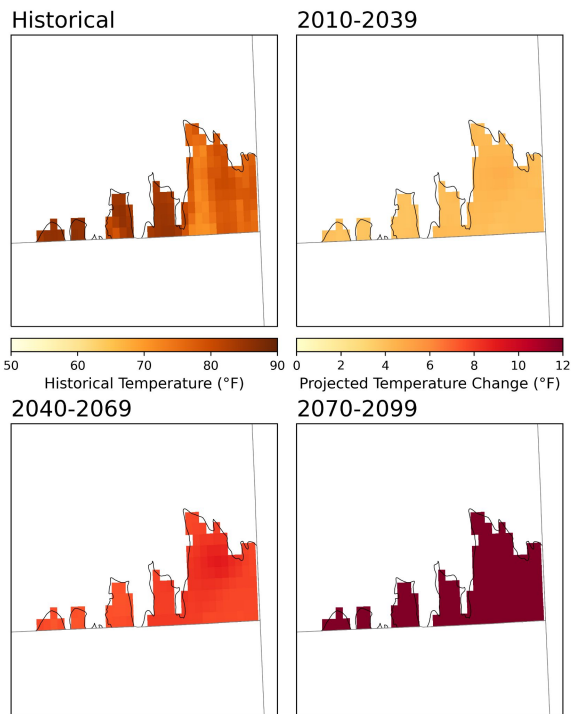


Climate Overview

Southeastern Idaho combines parts of the Wyoming Basin, Central Basin and Range, and Wasatch and Uinta Mountains and generally has a dry, mid-latitude steppe and desert climate. Summers are warm to hot; winters are cold. Mean annual precipitation and mean annual temperatures vary considerably depending on the elevation.

Climate Projections

The median temperature change for 25 CMIP6 model projections in southeastern Idaho is spatially uniform, and tends to be warmer than the CMIP5 projections in the 2070-2099 period. Precipitation projections between CMIP5 and CMIP6 models are similar, but the CMIP6 models project slightly wetter winters and summers. With warming temperatures, precipitation is expected to increase in the winters with more of it falling as rain.



Summer Maximum Temperature. Model median historical (1950-2010) and change (2010-2039, 2040-2069, 2070-2099) for the high (SSP585) scenario. Future projections show increasing temperatures over the century across the Southeastern Idaho ecoregion. Data Source: Localised Constructed Analogs [LOCA2](#). Resolution: 6km.

	CMIP 6 (LOCA2) Temperature Projections [median (range)]						
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	61.5 (±1.8)	+3.5 (2.2 to 5.7)	+4.0 (2.4 to 6.1)	+5.8 (2.7 to 8.7)	+7.8 (5.1 to 10.5)	+7.5 (3.7 to 10.5)	+12.1 (7.7 to 16.7)
Summer Tmax (°F)	79.0 (±2.4)	+3.8 (2.0 to 6.6)	+4.3 (2.4 to 7.2)	+6.5 (2.6 to 9.5)	+8.1 (5.3 to 12.3)	+7.5 (3.4 to 11.6)	+13.3 (7.4 to 19.6)
Winter Tavg (°F)	19.0 (±1.4)	+2.6 (1.2 to 4.2)	+3.0 (0.9 to 4.6)	+4.8 (2.5 to 7.2)	+6.3 (3.9 to 9.5)	+6.6 (4.2 to 9.2)	+10.7 (6.7 to 14.4)
Winter Tmax (°F)	29.9 (±1.5)	+2.3 (0.5 to 4.4)	+2.5 (0.8 to 4.2)	+3.9 (1.8 to 7.2)	+5.8 (3.0 to 9.2)	+5.4 (3.3 to 9.4)	+9.2 (5.4 to 12.6)
Winter Tmin (°F)	8.0 (±1.7)	+2.9 (1.4 to 4.7)	+3.0 (0.0 to 5.3)	+6.1 (3.1 to 8.3)	+8.0 (5.0 to 11.7)	+8.0 (4.5 to 11.8)	+12.8 (8.0 to 19.1)

Summer is June-August and winter is December-February. The historical column shows the average temperature and 2010-2039, 2040-2069, and 2070-2099 values are the changes for those 30-year periods relative the the historical period. Values in parenthesis are measures of historical variability and future model range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and the future range is the model maximum and minimum. Shared Socioeconomic Pathways (SSP)245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Southeastern Idaho Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the region, with the largest increases projected for summer. Summer average temperature is projected to increase as much as 8°F for the 2040-2069 period and as much as 12°F for the 2070-2099 period under the high (SSP585) scenario.



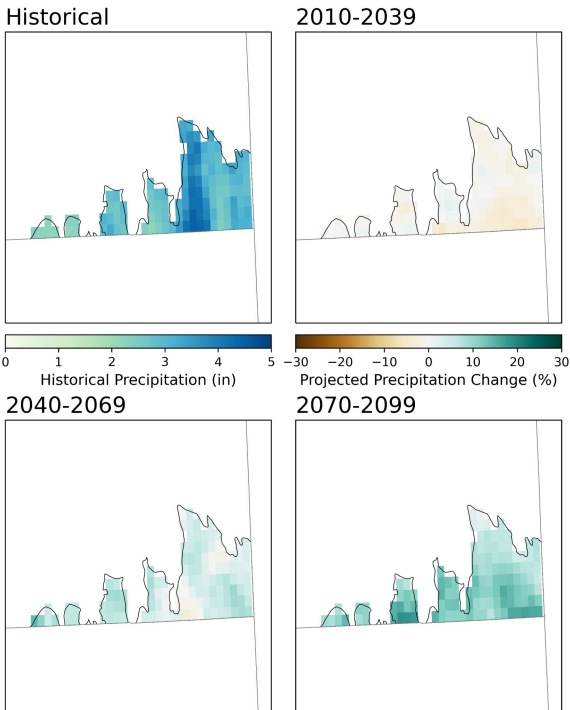
Precipitation

Late summer total precipitation is projected to *increase* as much as 10% in the 2070-2099 period and cool season is projected to increase as much as 15% during the same period. The confidence in the cool season projections is higher than late summer projections.



Growing Season

Growing degree days are projected to more than double in the 2070-2099 for Southeastern Idaho under the high (SSP585) scenario. Frost days are projected to decrease from more than 200 per year until there are fewer than 150 days per year, on average by the end of the century.



Total Late Summer Precipitation. Model median historical (1950-2010; Jul-Sept) and percent change in for three future periods (2010-2039, 2040-2069, 2070-2099) under the high scenario (SSP585). Future projections show increasing late summer precipitation across southeastern Idaho throughout the next century. Confidence is low in the projected changes in late summer precipitation for every future period due to variability among models. Data Source: [LOCA2](#). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	3.1in (±1.7)	-1% (-28 to 32)	-2% (-40 to 48)	-6% (-37 to 75)	8% (-41 to 94)	3% (-20 to 83)	12% (-27 to 174)
Cool Season Precipitation	10.6in (±2.9)	+6% (-2 to 14)	+5% (-11 to 16)	+9% (-2 to 19)	+8% (-1 to 27)	+10 (-7 to 23)	+15% (-3 to 38)
GDD (deg-days)	1393 (±793)	+497 (348 to 750)	+528 (335 to 806)	+836 (409 to 1264)	+1150 (756 to 1735)	+1109 (567 to 1676)	+1855 (1202 to 3191)
Frost Days	214 (±14)	-18 (-31 to -12)	-20 (-31 to -14)	-33 (-52 to -22)	-41 (-70 to -30)	-40 (-72 to -30)	-68 (-111 to -52)

Historical precipitation is in inches and future changes are in percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loca.ucsd.edu/>

Willamette Valley Climate Projections

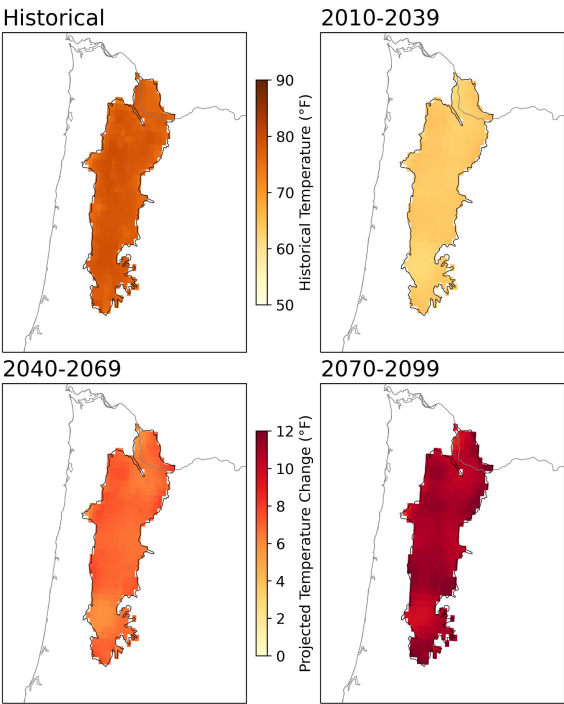


Climate Overview

The Willamette Valley is mostly a low elevation valley with terraces and floodplains encompassed by rolling hills. The climate is Mediterranean, with mild, wet winters and warm, dry summers. Mean annual precipitation varies by elevation, with more occurring in the mountainous foothills. Many rivers join the Willamette River, entering this ecoregion from the Cascades to the east and coastal hills to the west.

Climate Projections

The median temperature change for 25 CMIP6 model projections for the Willamette valley is spatially uniform and is warmer on average than the CMIP5 projections for the 2070-2099 period. The CMIP6 model median also projects less summer precipitation for 2010-2039 compared to the median for CMIP5 model projections but changes are similar for the 2070-2099 period. Warming temperatures will lead to wetter winter, drier summers.



Summer Maximum Temperature. Model median historical (1950-2010) and projected change for three future periods ((2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Future projections show increasing temperatures over the century, with slightly less warming in the southern Willamette Valley. Data Source: Localised Constructed Analogs [LOCA2](#). Resolution: 6km.

CMIP 6 (LOCA2) Temperature Projections [median (range)]							
	1950-2010	2010-2039		2040-2069		2070-2099	
Climate Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Summer Tavg (°F)	63.9 (±1.4)	+2.7 (1.8 to 4.7)	+3.2 (1.7 to 5.5)	+4.7 (3.4 to 7.6)	+6.3 (4.9 to 9.5)	+6.1 (4.4 to 9.8)	+10.2 (7.9 to 16.1)
Summer Tmax (°F)	77.7 (±2.2)	+3.3 (1.8 to 5.6)	+3.6 (2.0 to 6.4)	+5.0 (3.4 to 8.9)	+6.9 (4.9 to 11.2)	+6.4 (4.3 to 11.1)	+11.2 (7.6 to 18.6)
Winter Tavg (°F)	40.5 (±1.0)	+1.8 (0.6 to 3.4)	+2.1 (1.0 to 3.3)	+3.3 (2.1 to 5.5)	+4.2 (3.1 to 7.0)	+4.7 (2.9 to 7.5)	+6.9 (5.0 to 10.6)
Winter Tmax (°F)	47.2 (±1.2)	+2.0 (0.5 to 3.2)	+2.2 (0.9 to 3.8)	+3.4 (1.8 to 5.7)	+4.3 (3.0 to 6.7)	+5.0 (2.6 to 7.4)	+7.1 (4.7 to 10.9)
Winter Tmin (°F)	33.7 (±1.1)	+1.8 (0.7 to 3.6)	+2.1 (1.1 to 3.8)	+3.4 (2.4 to 5.7)	+4.1 (2.8 to 7.4)	+4.7 (2.8 to 7.6)	+7.1 (5.2 to 10.8)

Summer is June-August and winter is December-February. Historical values are the average temperature and 2010-2039, 2040-2069, and 2069-2099 values are the change in temperature for those 30-year periods relative to the historical period. Values in parenthesis are measures of historical variability future range for 25 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The historical variability is the standard deviation over 1950-2010, and future range is the model maximum and minimum. Shared Socioeconomic Pathway (SSP) 245 is a low scenario and SSP585 is a high scenario. Data Source: <https://loca.ucsd.edu/>

Willamette Valley Climate Projections



Overview of Ecoregion Trends



Temperature

Warming is projected in all seasons across the region, with the largest increases projected for summer. Summer average temperature is projected to increase as much as 6°F for the 2040-2069 period, and as much as 10°F for the 2070-2099 period for a high (SSP585) scenario.



Precipitation

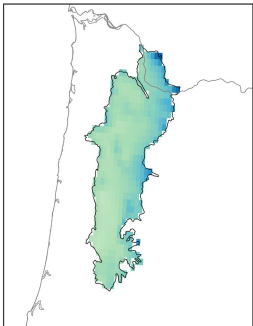
Late summer precipitation is projected to *decrease* as much as 20% by the end of the century period. Projections of cool season precipitation show an *increase* of 6% for the same period under a high (SSP585) scenario. Little agreement among models indicates less confidence in changes in cool season precipitation.



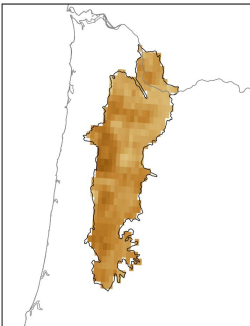
Growing Season

Under a high (SSP585) scenario, growing degree days are projected to double for the 2070-2099 period. Frost days are projected to decrease from 50 per year on average to fewer than 20 per year on average.

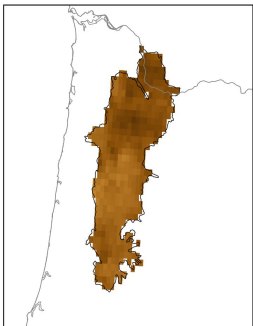
Historical



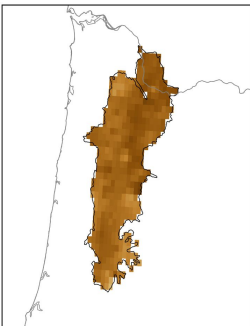
2010-2039



2040-2069



2070-2099



Total Late Summer (Jul-Sept.) Precipitation. Model median historical (1950-2010) and percent change for three future periods (2010-2039, 2040-2069, 2070-2099) under a high (SSP585) scenario. Future projections show decreasing late summer precipitation across the Willamette Valley ecoregion, with the greatest decrease in the 2040-2069 period under a high (SSP585) scenario. Models generally agree on late summer precipitation projections, so confidence in these projections is high. Data Source: [LOCA2](#). Resolution: 6km.

CMIP6 (LOCA2) Growing Season Projections [median (range)]

	1950-2010	2010-2039		2040-2069		2070-2099	
Variable	Historical	SSP245	SSP585	SSP245	SSP585	SSP245	SSP585
Late Summer Precipitation	3.0in (±1.8)	-18% (-37 to 6)	-16% (-42 to 9)	-21% (-39 to 15)	-22% (-43 to -2)	-20% (-47 to 9)	-20% (-66 to 20)
Cool Season Precipitation	38.1in (±8.1)	+2% (-6 to 10)	+3% (-6 to 13)	+5% (-5 to 18)	+3% (-13 to 19)	+5% (-5 to 19)	+6% (-12 to 25)
GDD (deg-days)	2015 (±884)	+497 (370 to 869)	+580 (348 to 910)	+916 (637 to 1485)	+1241 (901 to 1904)	+1167 (889 to 1964)	+2069 (1673 to 3435)
Frost Days	50 (±15)	-11 (-25 to -5)	-15 (-26 to -8)	-22 (-39 to -16)	-27 (-46 to -16)	-29 (-46 to -19)	-39 (-51 to -29)

Historical precipitation (inches) and future percent change relative to the historical values. Range is the model minimum and model maximum change for 25 models. Late summer is July-September and the cool season is October-March. Growing degree-days is the total number of degrees in a year that exceed 50°F. Frost days are days when minimum daily temperature is at or below 32°F. SSP245 is a low scenario and SSP585 is a high scenario. Gray text indicates less than 80% of models agree on sign of change. Data Source: <https://loca.ucsd.edu/>

REFERENCES - OVERVIEW

- Bock, L., Lauer, A., Schlund, M., Barreiro, M., Bellouin, N., Jones, C., Meehl, G. A., Predoi, V., Roberts, M. J., & Eyring, V. (2020). Quantifying Progress Across Different CMIP Phases With the ESMValTool. *Journal of Geophysical Research: Atmospheres*, 125(21), e2019JD032321. <https://doi.org/10.1029/2019JD032321>
- Davini, P., & D'Andrea, F. (2020). From CMIP3 to CMIP6: Northern Hemisphere Atmospheric Blocking Simulation in Present and Future Climate. *Journal of Climate*, 33(23), 10021–10038. <https://doi.org/10.1175/JCLI-D-19-0862.1>
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.*, 9(5), 1937–1958. <https://doi.org/10.5194/gmd-9-1937-2016>
- Gettelman, A., Hannay, C., Bacmeister, J. T., Neale, R. B., Pendergrass, A. G., Danabasoglu, G., Lamarque, J. -F., Fasullo, J. T., Bailey, D. A., Lawrence, D. M., & Mills, M. J. (2019). High Climate Sensitivity in the Community Earth System Model Version 2 (CESM2). *Geophysical Research Letters*, 46(14), 8329–8337. <https://doi.org/10.1029/2019GL083978>
- Hausfather, Z. (2022, May 4). Guest post: How climate scientists should handle 'hot models.' Carbon Brief. <https://www.carbonbrief.org/guest-post-how-climate-scientists-should-handle-hot-models/>
- Hawkins, E., & Sutton, R. (2009). The Potential to Narrow Uncertainty in Regional Climate Predictions. *Bulletin of the American Meteorological Society*, 90(8), 1095–1108. <https://doi.org/10.1175/2009BAMS2607.1>
- Intergovernmental Panel On Climate Change (IPCC) (Ed.). (2023). Technical Summary. In *Climate Change 2022—Mitigation of Climate Change* (1st ed., pp. 51–148). Cambridge University Press. <https://doi.org/10.1017/9781009157926.002>
- Intergovernmental Panel On Climate Change (IPCC) (Ed.). (2023). Technical Summary. In *Climate Change 2022—Mitigation of Climate Change* (1st ed., pp. 51–148). Cambridge University Press. <https://doi.org/10.1017/9781009157926.002>
- Kim, Y.-H., Min, S.-K., Zhang, X., Sillmann, J., & Sandstad, M. (2020). Evaluation of the CMIP6 multi-model ensemble for climate extreme indices. *Weather and Climate Extremes*, 29, 100269. <https://doi.org/10.1016/j.wace.2020.100269>
- Knutti, R., Furrer, R., Tebaldi, C., Cermak, J., & Meehl, G. A. (2010). Challenges in Combining Projections from Multiple Climate Models. *Journal of Climate*, 23(10), 2739–2758. <https://doi.org/10.1175/2009JCLI3361.1>
- Li, S., Wahl, T., Barroso, A., Coats, S., Dangendorf, S., Piecuch, C., Sun, Q., Thompson, P., & Liu, L. (2022). Contributions of Different Sea-Level Processes to High-Tide Flooding Along the U.S. Coastline. *Journal of Geophysical Research: Oceans*, 127(7), e2021JC018276. <https://doi.org/10.1029/2021JC018276>
- Livneh, B., Bohn, T. J., Pierce, D. W., Munoz-Arriola, F., Nijssen, B., Vose, R., Cayan, D. R., & Brekke, L. (2015). A spatially comprehensive, hydrometeorological data set for

- Mexico, the U.S., and Southern Canada 1950–2013. *Scientific Data*, 2(1), 150042. <https://doi.org/10.1038/sdata.2015.42>
- Meehl, G. A., Boer, G. J., Covey, C., Latif, M., & Stouffer, R. J. (2000). The Coupled Model Intercomparison Project (CMIP). *Bulletin of the American Meteorological Society*, 81, 313–318. [https://doi.org/10.1175/1520-0477\(2000\)081<0313:TCMIPC>2.3.CO;2](https://doi.org/10.1175/1520-0477(2000)081<0313:TCMIPC>2.3.CO;2)
- Meehl, G. A., Senior, C. A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R. J., Taylor, K. E., & Schlund, M. (2020). Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. *Science Advances*, 6(26), eaba1981. <https://doi.org/10.1126/sciadv.aba1981>
- NCA5 Chapter 1: Overview. *Fifth National Climate Assessment*. (2023). U.S. Global Change Research Program. <https://doi.org/10.7930/NCA5.2023.CH1>
- O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9(9), 3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>
- Pierce, D. W., Kalansky, J. F., & Cayan, D. R. (2018). *Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment*. (CNRA-CEC-2018-006.; California's Fourth Climate Change Assessment, California Energy Commission). Scripps Institution of Oceanography.
- Pierce, D. W., Su, L., Cayan, D. R., Risser, M. D., Livneh, B., & Lettenmaier, D. P. (2021). An extreme-preserving long-term gridded daily precipitation data set for the conterminous United States. *Journal of Hydrometeorology*. <https://doi.org/10.1175/JHM-D-20-0212.1>
- Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., ... Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>
- Risser, M. D., Feldman, D. R., Wehner, M. F., Pierce, D. W., & Arnold, J. R. (2021). Identifying and correcting biases in localized downscaling estimates of daily precipitation return values. *Climatic Change*, 169(3–4), 33. <https://doi.org/10.1007/s10584-021-03265-z>
- Sherwood, S. C., Webb, M. J., Annan, J. D., Armour, K. C., Forster, P. M., Hargreaves, J. C., Hegerl, G., Klein, S. A., Marvel, K. D., Rohling, E. J., Watanabe, M., Andrews, T., Braconnot, P., Bretherton, C. S., Foster, G. L., Hausfather, Z., Von Der Heydt, A. S., Knutti, R., Mauritsen, T., ... Zelinka, M. D. (2020). An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Reviews of Geophysics*, 58(4), e2019RG000678. <https://doi.org/10.1029/2019RG000678>
- Srivastava, A., Grotjahn, R., & Ullrich, P. A. (2020). Evaluation of historical CMIP6 model simulations of extreme precipitation over contiguous US regions. *Weather and Climate Extremes*, 29, 100268. <https://doi.org/10.1016/j.wace.2020.100268>
- Stouffer, R. J., Eyring, V., Meehl, G. A., Bony, S., Senior, C., Stevens, B., & Taylor, K. E. (2017).

- CMIP5 Scientific Gaps and Recommendations for CMIP6. *Bulletin of the American Meteorological Society*, 98(1), 95–105. <https://doi.org/10.1175/BAMS-D-15-00013.1>
- Tebaldi, C., & Knutti, R. (2007). The use of the multi-model ensemble in probabilistic climate projections. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 365(1857), 2053–2075. <https://doi.org/10.1098/rsta.2007.2076>
- Tian, B., & Dong, X. (2020). The Double-ITCZ Bias in CMIP3, CMIP5, and CMIP6 Models Based on Annual Mean Precipitation. *Geophysical Research Letters*, 47(8), e2020GL087232. <https://doi.org/10.1029/2020GL087232>
- Tokarska, K. B., Stolpe, M. B., Sippel, S., Fischer, E. M., Smith, C. J., Lehner, F., & Knutti, R. (2020). Past warming trend constrains future warming in CMIP6 models. *Science Advances*, 6(12), eaaz9549. <https://doi.org/10.1126/sciadv.aaz9549>
- Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., Klein, S. A., & Taylor, K. E. (2020). Causes of Higher Climate Sensitivity in CMIP6 Models. *Geophysical Research Letters*, 47(1), e2019GL085782. <https://doi.org/10.1029/2019GL085782>
- Zhu, J., Poulsen, C. J., & Otto-Bliesner, B. L. (2020). High climate sensitivity in CMIP6 model not supported by paleoclimate. *Nature Climate Change*, 10(5), 378–379. <https://doi.org/10.1038/s41558-020-0764-6>

The State of Climate Adaptation Science for Ecosystems in the Northwest U.S.

HYDROLOGIC PROJECTIONS



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REFERENCES - OVERVIEW

- Abatzoglou, J. T., C. S. Juang, A. P. Williams, C. A. Kolden, and A. L. Westerling. 2021. Increasing Synchronous Fire Danger in Forests of the Western United States. *Geophysical Research Letters* 48:e2020GL091377.
- AghaKouchak, A., F. Chiang, L. S. Huning, C. A. Love, I. Mallakpour, O. Mazdiyasni, H. Moftakhari, S. M. Papalexiou, E. Ragno, and M. Sadegh. 2020. Climate Extremes and Compound Hazards in a Warming World. *Annual Review of Earth and Planetary Sciences* 48:519–548.
- Apurv, T., and X. Cai. 2021. Regional Drought Risk in the Contiguous United States. *Geophysical Research Letters* 48:e2020GL092200.
- Beyene, M. T., S. G. Leibowitz, C. J. Dunn, and K. D. Bladon. 2023. To burn or not to burn: An empirical assessment of the impacts of wildfires and prescribed fires on trace element concentrations in Western US streams. *Science of The Total Environment* 863:160731.
- Brunner, M. I., D. L. Swain, E. Gilleland, and A. W. Wood. 2021. Increasing importance of temperature as a contributor to the spatial extent of streamflow drought. *Environmental Research Letters* 16:024038.
- Bumbaco, K. A., and P. W. Mote. 2010. Three Recent Flavors of Drought in the Pacific Northwest.
- Cao, Q., A. Gershunov, T. Shulgina, F. M. Ralph, N. Sun, and D. P. Lettenmaier. 2020. Floods due to Atmospheric Rivers along the U.S. West Coast: The Role of Antecedent Soil Moisture in a Warming Climate. *Journal of Hydrometeorology* 21:1827–1845.
- Cartwright, J. M., C. E. Littlefield, J. L. Michalak, J. J. Lawler, and S. Z. Dobrowski. 2020. Topographic, soil, and climate drivers of drought sensitivity in forests and shrublands of the Pacific Northwest, USA. *Scientific Reports* 10:18486.
- Chatterjee, S., A. R. Desai, J. Zhu, P. A. Townsend, and J. Huang. 2022. Soil moisture as an essential component for delineating and forecasting agricultural rather than meteorological drought. *Remote Sensing of Environment* 269:112833.
- Chegwidden, O. S., D. E. Rupp, and B. Nijssen. 2020. Climate change alters flood magnitudes and mechanisms in climatically-diverse headwaters across the northwestern United States. *Environmental Research Letters* 15:094048.
- Chen, X., L. R. Leung, M. Wigmosta, and M. Richmond. 2019. Impact of Atmospheric Rivers on Surface Hydrological Processes in Western U.S. Watersheds. *Journal of Geophysical Research: Atmospheres* 124:8896–8916.
- Clifton, C. F., K. T. Day, C. H. Luce, G. E. Grant, M. Safeeq, J. E. Halofsky, and B. P. Staab. 2018. Effects of climate change on hydrology and water resources in the Blue Mountains, Oregon, USA. *Climate Services* 10:9–19.
- Crausbay, S. D., A. R. Ramirez, S. L. Carter, M. S. Cross, K. R. Hall, D. J. Bathke, J. L. Betancourt, S. Colt, A. E. Cravens, M. S. Dalton, J. B. Dunham, L. E. Hay, M. J. Hayes, J. McEvoy, C. A. McNutt, M. A. Moritz, K. H. Nislow, N. Raheem, and T. Sanford. 2017. Defining Ecological Drought for the Twenty-First Century. *Bulletin of the American Meteorological Society* 98:2543–2550.

HYDROLOGY PROJECTIONS

- Crimmins, M. A., D. B. Ferguson, A. M. Meadow, and J. L. Weiss. 2017. Discerning “Flavors” of Drought Using Climate Extremes Indices.
- Freudiger, D., I. Kohn, K. Stahl, and M. Weiler. 2014. Large-scale analysis of changing frequencies of rain-on-snow events with flood-generation potential. *Hydrology and Earth System Sciences* 18:2695–2709.
- Gershunov, A., T. Shulgina, R. E. S. Clemesha, K. Guirguis, D. W. Pierce, M. D. Dettinger, D. A. Lavers, D. R. Cayan, S. D. Polade, J. Kalansky, and F. M. Ralph. 2019. Precipitation regime change in Western North America: The role of Atmospheric Rivers. *Scientific Reports* 9:9944.
- Gorguner, M., and M. L. Kavvas. 2020. Modeling impacts of future climate change on reservoir storages and irrigation water demands in a Mediterranean basin. *Science of The Total Environment* 748:141246.
- Gullacher, A., D. M. Allen, and J. D. Goetz. 2023. Early Warning Indicators of Groundwater Drought in Mountainous Regions. *Water Resources Research* 59:e2022WR033399.
- Kampf, S. K., K. A. Dwire, M. P. Fairchild, J. Dunham, C. D. Snyder, K. L. Jaeger, C. H. Luce, J. C. Hammond, C. Wilson, M. A. Zimmer, and M. Sidell. 2021. Managing nonperennial headwater streams in temperate forests of the United States. *Forest Ecology and Management* 497:119523.
- Klos, P. Z., T. E. Link, and J. T. Abatzoglou. 2014. Extent of the rain-snow transition zone in the western U.S. under historic and projected climate. *Geophysical Research Letters* 41:4560–4568.
- Kovach, R. P., J. B. Dunham, R. Al-Chokhachy, C. D. Snyder, B. H. Letcher, J. A. Young, E. A. Beever, G. T. Pederson, A. J. Lynch, N. P. Hitt, C. P. Konrad, K. L. Jaeger, A. H. Rea, A. J. Sepulveda, P. M. Lambert, J. Stoker, J. J. Giersch, and C. C. Muhlfeld. 2019. An Integrated Framework for Ecological Drought across Riverscapes of North America. *BioScience* 69:418–431.
- Leibowitz, S. G., R. L. Comeleo, P. J. Wigington, M. H. Weber, E. A. Sproles, and K. A. Sawicz. 2016. Hydrologic Landscape Characterization for the Pacific Northwest, USA. *JAWRA Journal of the American Water Resources Association* 52:473–493.
- Li, D., D. P. Lettenmaier, S. A. Margulis, and K. Andreadis. 2019. The Role of Rain-on-Snow in Flooding Over the Conterminous United States. *Water Resources Research* 55:8492–8513.
- Livneh, B., and A. M. Badger. 2020. Drought less predictable under declining future snowpack. *Nature Climate Change* 10:452–458.
- Musselman, K. N., N. Addor, J. A. Vano, and N. P. Molotch. 2021. Winter melt trends portend widespread declines in snow water resources. *Nature Climate Change* 11:418–424.
- Musselman, K. N., F. Lehner, K. Ikeda, M. P. Clark, A. F. Prein, C. Liu, M. Barlage, and R. Rasmussen. 2018. Projected increases and shifts in rain-on-snow flood risk over western North America. *Nature Climate Change* 8:808–812.
- Niemeyer, R. J., K. D. Bladon, and R. D. Woodsmith. 2020. Long-term hydrologic recovery after wildfire and post-fire forest management in the interior Pacific Northwest. *Hydrological Processes* 34:1182–1197.
- Payne, A. E., M.-E. Demory, L. R. Leung, A. M. Ramos, C. A. Shields, J. J. Rutz, N. Siler, G.

HYDROLOGY PROJECTIONS

- Villarini, A. Hall, and F. M. Ralph. 2020. Responses and impacts of atmospheric rivers to climate change. *Nature Reviews Earth & Environment* 1:143–157.
- Pepin, N. C., E. Arnone, A. Gobiet, K. Haslinger, S. Kotlarski, C. Notarnicola, E. Palazzi, P. Seibert, S. Serafin, W. Schöner, S. Terzago, J. M. Thornton, M. Vuille, and C. Adler. 2022. Climate Changes and Their Elevational Patterns in the Mountains of the World. *Reviews of Geophysics* 60:e2020RG000730.
- Perry, L. G., L. V. Reynolds, T. J. Beechie, M. J. Collins, and P. B. Shafroth. 2015. Incorporating climate change projections into riparian restoration planning and design. *Ecohydrology* 8:863–879.
- Safeeq, M., G. E. Grant, S. L. Lewis, M. G. Kramer, and B. Staab. 2014. A hydrogeologic framework for characterizing summer streamflow sensitivity to climate warming in the Pacific Northwest, USA. *Hydrology and Earth System Sciences* 18:3693–3710.
- Siirila-Woodburn, E. R., A. M. Rhoades, B. J. Hatchett, L. S. Huning, J. Szinai, C. Tague, P. S. Nico, D. R. Feldman, A. D. Jones, W. D. Collins, and L. Kaatz. 2021. A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment* 2:800–819.
- Srivastava, A., J. Q. Wu, W. J. Elliot, E. S. Brooks, and D. C. Flanagan. 2018. A Simulation Study to Estimate Effects of Wildfire and Forest Management on Hydrology and Sediment in a Forested Watershed, Northwestern U.S. *Transactions of the ASABE* 61:1579–1601.
- Stagge, J. H., L. M. Tallaksen, L. Gudmundsson, A. F. V. Loon, and K. Stahl. 2015. Candidate Distributions for Climatological Drought Indices (SPI and SPEI). *International Journal of Climatology* 35:4027–4040.
- Svoboda, M., B. Fuchs, and I. (IDMP. 2016. Handbook of Drought Indicators and Indices.
- Tohver, I. M., A. F. Hamlet, and S. Lee. 2014. Impacts of 21st-Century Climate Change on Hydrologic Extremes in the Pacific Northwest Region of North America. *JAWRA Journal of the American Water Resources Association* 50:1461–1476.
- Touma, D., S. Stevenson, D. L. Swain, D. Singh, D. A. Kalashnikov, and X. Huang. 2022. Climate change increases risk of extreme rainfall following wildfire in the western United States. *Science Advances* 8:eabm0320.
- Vano, J. A. 2020. Implications of losing snowpack. *Nature Climate Change* 10:388–390.
- Ward, A. S., S. M. Wondzell, N. M. Schadel, and S. P. Herzog. 2020. Climate Change Causes River Network Contraction and Disconnection in the H.J. Andrews Experimental Forest, Oregon, USA. *Frontiers in Water* 2:7.
- Warner, M. D., C. F. Mass, and E. P. Salathé. 2015. Changes in Winter Atmospheric Rivers along the North American West Coast in CMIP5 Climate Models. *Journal of Hydrometeorology* 16:118–128.
- Wrzesien, M. L., and T. M. Pavelsky. 2020. Projected Changes to Extreme Runoff and Precipitation Events From a Downscaled Simulation Over the Western United States. *Frontiers in Earth Science* 7:355.
- Yan, H., N. Sun, M. Wigmosta, R. Skaggs, Z. Hou, and R. Leung. 2018. Next-Generation Intensity-Duration-Frequency Curves for Hydrologic Design in Snow-Dominated Environments. *Water Resources Research* 54:1093–1108.

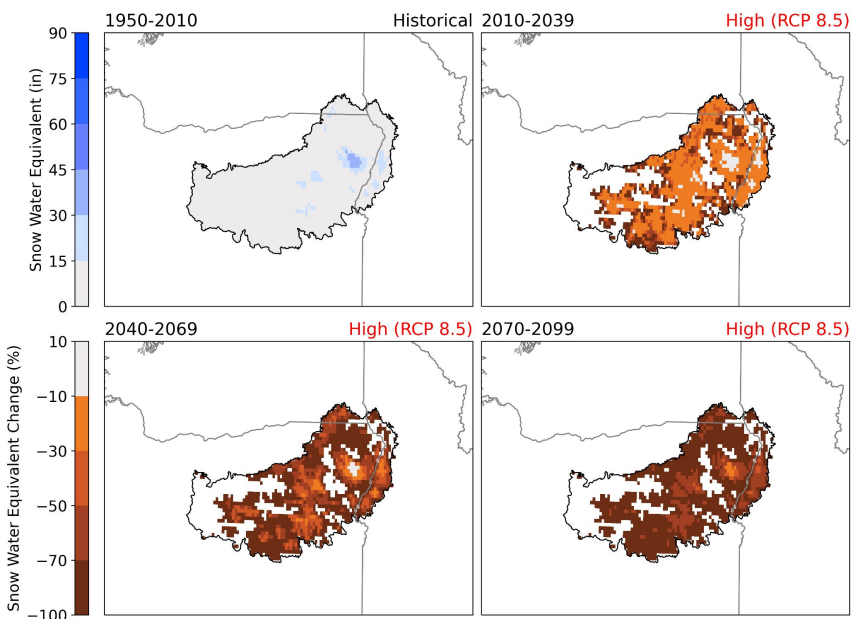
- Zhang, F., J. A. Biederman, M. P. Dannenberg, D. Yan, S. C. Reed, and W. K. Smith. 2021. Five Decades of Observed Daily Precipitation Reveal Longer and More Variable Drought Events Across Much of the Western United States. *Geophysical Research Letters* 48:e2020GL092293.
- Zipper, S. C., J. C. Hammond, M. Shanafield, M. Zimmer, T. Datry, C. N. Jones, K. E. Kaiser, S. E. Godsey, R. M. Burrows, J. R. Blaszcak, M. H. Busch, A. N. Price, K. S. Boersma, A. S. Ward, K. Costigan, G. H. Allen, C. A. Krabbenhoft, W. K. Dodds, M. C. Mims, J. D. Olden, S. K. Kampf, A. J. Burgin, and D. C. Allen. 2021. Pervasive changes in stream intermittency across the United States. *Environmental Research Letters* 16:084033.
- Zscheischler, J., O. Martius, S. Westra, E. Bevacqua, C. Raymond, R. M. Horton, B. Van Den Hurk, A. AghaKouchak, A. Jézéquel, M. D. Mahecha, D. Maraun, A. M. Ramos, N. N. Ridder, W. Thiery, and E. Vignotto. 2020. A typology of compound weather and climate events. *Nature Reviews Earth & Environment* 1:333–347.

Blue Mountains Hydrology Projections



Hydrology Description

The Blue Mountains ecoregion is in a mediterranean snow-rain hydrologic zone. Precipitation falls primarily in the middle to high elevations during the winter. The stored winter snowpack feeds streams during the early spring as temperatures increase and the snow melts.



April 1st Snow Water Equivalent (SWE) for a historical period and percent change for three future periods for a high (RCP 8.5) scenario. April 1 SWE is projected to decrease in all areas of the Blue Mountains ecoregion that have April 1st SWE historically. Low elevations are expected to have the largest decreases. By the end of the century, April 1st SWE is projected to decrease by 59% (range: -84 to -36) relative to 1950-2010, for a high (RCP 8.5) scenario.

Ecoregion Trends

Late Summer (July-September) Runoff

Summer runoff in the Blue Mountains ecoregion is mainly influenced by snowmelt from high elevations. As temperatures increase in winter, less snow will be available to melt in the late summer. By the end of the century, late summer runoff in the Blue Mountains ecoregion is projected to decrease by 34% (range: -50 to -0) relative to 1950-2010, for a high (RCP 8.5) scenario.

Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase across the Blue Mountains ecoregion, with the largest increases projected for the lowest elevations of the Blue Mountains. By the end of the century, CMD averaged for the ecoregion is projected to increase by about 33% (range: +24 to +52) for a high (SSP585) scenario.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for the future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	3.2in (1.5 to 5.0)	1.2in (0.74 to 1.56)
2020-2049	High (RCP 8.5)	-16% (-51 to +69)	-19% (-28 to -7)
2040-2069	High (RCP 8.5)	-42% (-73 to +14)	-25% (-43 to -7)
2070-2099	Low (RCP 4.5)	-43% (-68 to +13)	-17% (-39 to +1)
2070-2099	High (RCP 8.5)	-59% (-84 to -36)	-34% (-50 to +0)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.83 inches
2011-2040	High (SSP585)	+12% (+8 to +22)
2041-2070	High (SSP585)	+20% (+15 to +36)
2071-2100	Low (SSP245)	+21% (+14 to +35)
2071-2100	High (SSP585)	+33% (+24 to +52)

Blue Mountains Hydrology Projections



Ecoregion Trends



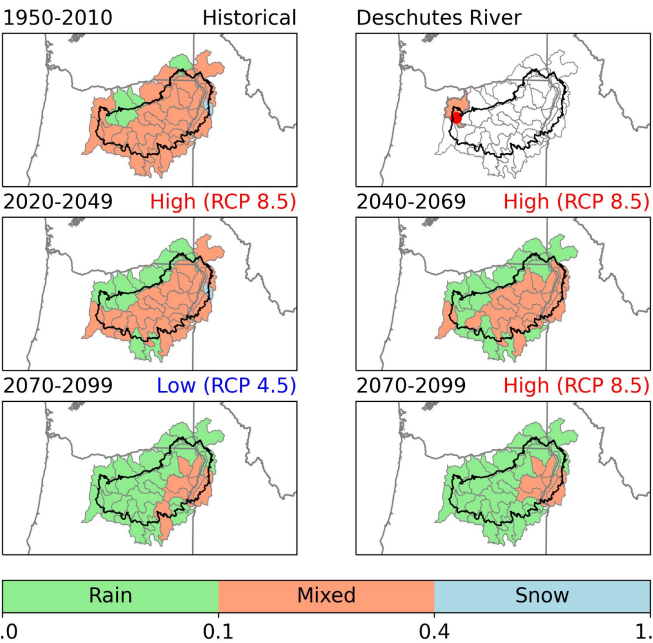
Watershed Classification

Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. For the Blue Mountains ecoregion, watersheds are expected to become more rain-dominant in the future. More precipitation as rain during the wet season at low to mid elevations is expected to increase streamflow in winter and decrease streamflow in summer as snowpack declines. Most watersheds in the ecoregion are classified as mixed-rain-and-snow, for which streamflow patterns are highly sensitive to increasing temperature.

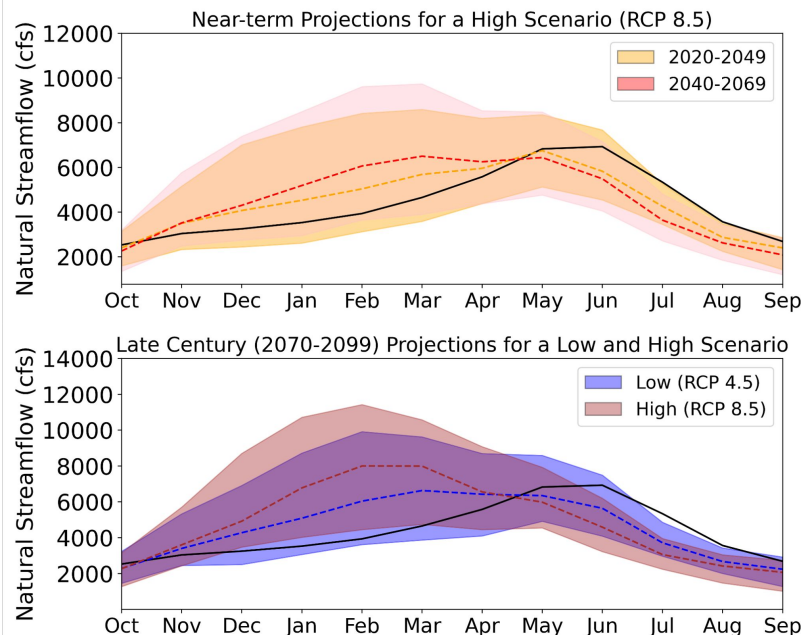


Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years, for the Deschutes River is projected to decrease by about 33% (range: -64 to -12) by 2100, relative to 1981-2010, for a high (RCP 8.5) scenario. Confidence is low in the magnitude of change for the projections of 7Q2, but confidence is high in the direction of change because all models project a decrease.



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale, and shown for all basins that intersect the ecoregion. The projections show a general shift from mixed-rain-and-snow watersheds to more rain-dominant watersheds. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Deschutes River.



Deschutes River Historical and Projected Future Monthly Streamflow: The timing of peak annual flow is projected to shift from early summer to early spring and winter. The black line is the simulated historical and dashed lines are the median hydrographs of 40 models. Shaded areas show the 10th and 90th percentile range. Streamflow projections are without withdrawals and regulation by dams.

Projections: Summer Low Flow

The table below shows model median values of historical and projected change in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Fisher River. Summer low streamflow on the Fischer River is projected to decrease through the century. Summer low streamflow (7Q2) is an indicator of water availability for aquatic habitat. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for three future periods.

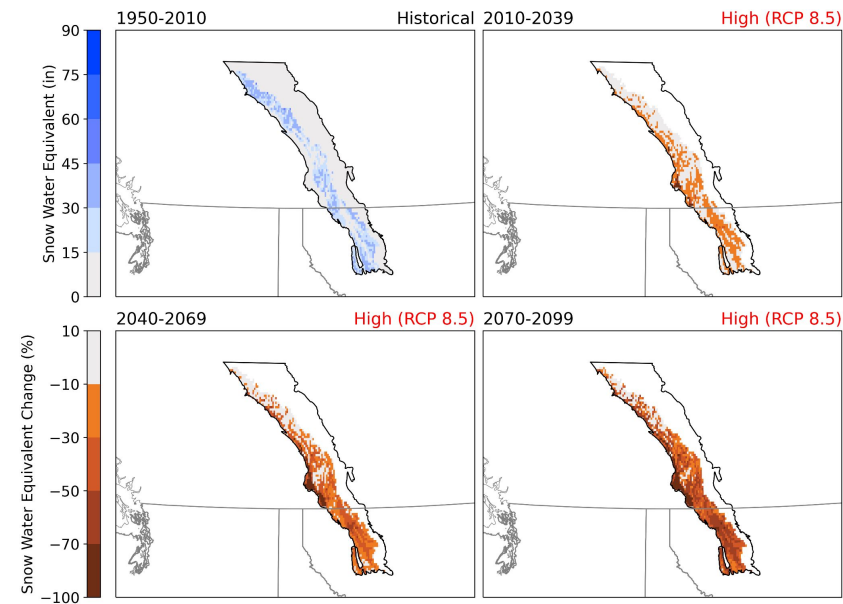
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	2380 cfs (1310 to 3450)
2011-2040	High (RCP 8.5)	-14% (-38 to -3)
2041-2070	High (RCP 8.5)	-25% (-55 to -10)
2071-2100	Low (RCP 4.5)	-20% (-58 to -6)
2071-2100	High (RCP 8.5)	-33% (-64 to -12)

Canadian Rockies Hydrology Projections



Hydrology Description

The Canadian Rockies ecoregion is in a mediterranean snow hydrologic zone. This ecoregion accumulates substantial snow over the winter months at the high elevations. This snowpack feeds a large network of streams throughout the spring and summer.



April 1st Snow Water Equivalent (SWE) for a historical period and percent change for three future periods for a high (RCP 8.5) scenario. April 1 SWE is projected to decrease for nearly all of the Canadian Rockies ecoregion, with larger decreases projected for the middle and low elevations. By the end of the century, April 1st SWE averaged for the ecoregion is projected to decrease by 64% (range: -71 to -48) relative to 1950-2010, for a high (RCP 8.5) scenario. Data is not available for the eastern sections of the ecoregion.

Ecoregion Trends



Late Summer (July-September) Runoff

Late summer runoff in the Canadian Rockies ecoregion is mainly influenced by snowmelt from high elevations. As temperatures increase, less of this snow will be available to melt in the late summer. By the end of the century, late summer runoff averaged for the ecoregion is projected to decrease by 50% (range: -74 to -25) relative to 1950-2010, for a high (RCP 8.5) scenario.



Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase everywhere in the Canadian Rockies ecoregion, with greater increases projected for low elevations. By the end of the century, CMD for the Canadian Rockies is projected to increase by 89% (range: +42 to +235) relative to 1981-2010, for a high (SSP585) scenario.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for the future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	19.2in (15.0 to 23.2)	4.8in (3.4 to 6.3)
2020-2049	High (RCP 8.5)	-52% (-58 to -49)	-23% (-34 to -15)
2040-2069	High (RCP 8.5)	-56% (-64 to -45)	-35% (-52 to -19)
2070-2099	Low (RCP 4.5)	-55% (-60 to -43)	-33% (-54 to -8)
2070-2099	High (RCP 8.5)	-64% (-71 to -48)	-50% (-74 to -25)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.16 inches
2011-2040	High (SSP585)	+14% (+8 to +62)
2041-2070	High (SSP585)	+41% (+13 to +146)
2071-2100	Low (SSP245)	+43% (+3 to +130)
2071-2100	High (SSP585)	+89% (+42 to +235)

Canadian Rockies Hydrology Projections



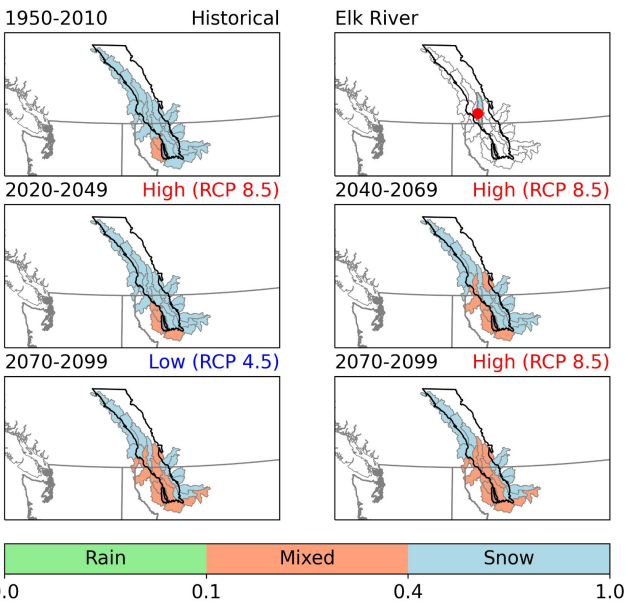
Ecoregion Trends

Watershed Classification

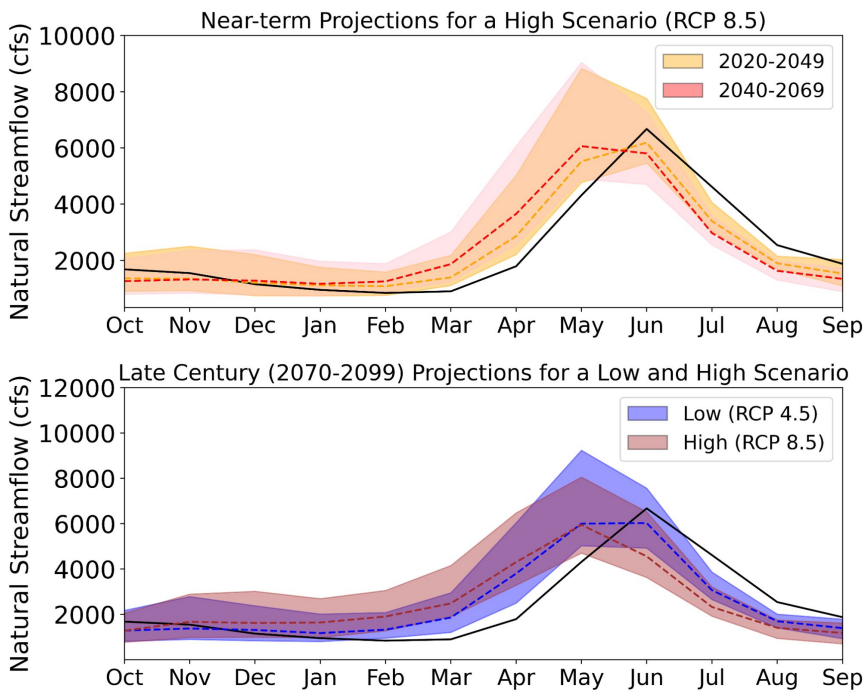
Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. Historically, most watersheds in the Canadian Rockies ecoregion have been classified as snow-dominant but are projected to exhibit more mixed-rain-and-snow streamflow patterns in the future. More precipitation as rain during the wet season at low to mid elevations is expected to increase streamflow in winter and decrease streamflow in summer as snowpack declines.

Summer Low Streamflow (7Q2)

Summer (June - Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years, for the Elk River is projected to decrease by about 41% (range: -71 to -18) by the end of the century relative to 1981-2010, for a high (RCP 8.5) scenario. Confidence is high in the direction of change because all models project a decrease in the future, but there is a wide spread in the magnitude of projected changes.



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. The projections show a general shift from snow-dominant to mixed-rain-and-snow streamflow patterns in the future. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Elk River.



Elk River Historical and Projected Future Monthly Streamflow: The timing of peak annual flow is expected to shift from summer to late spring. The black line is the simulated historical and dashed lines are the median hydrographs of 40 models. Shaded areas show the 10th and 90th percentile range. Projections are without withdrawals and dam regulation.

Projections: Summer Low Flow

The table below shows model median values of historical and projected change in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Fisher River. Summer low streamflow on the Fisher River is projected to decrease through the century for both a high (RCP 8.5) and low (RCP 4.5) scenario. Summer low streamflow (7Q2) is an indicator of water availability for aquatic habitat. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for three future periods.

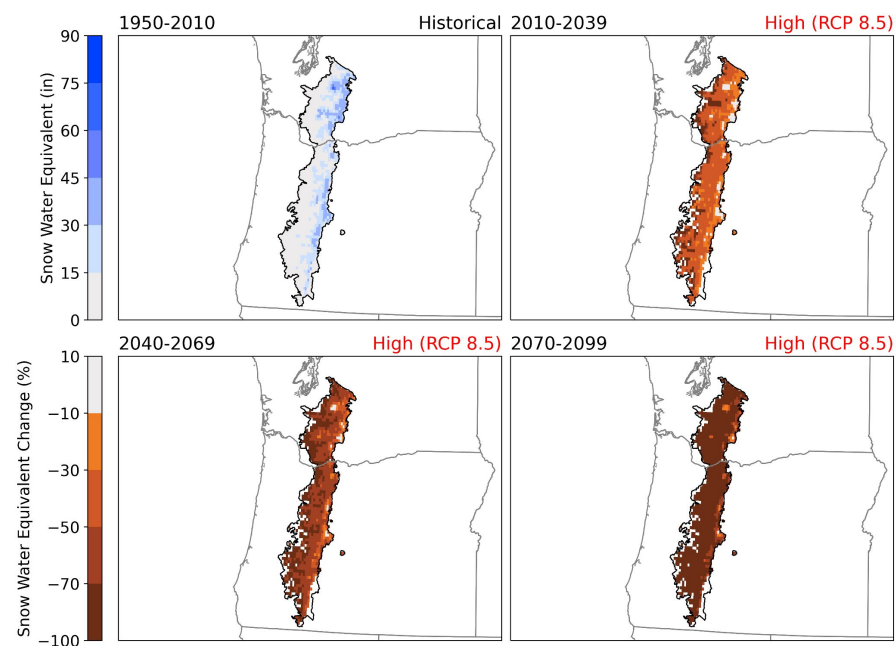
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	1329 cfs (1039 to 1620)
2011-2040	High (RCP 8.5)	-23% (-43 to -10)
2041-2070	High (RCP 8.5)	-33% (-58 to -16)
2071-2100	Low (RCP 4.5)	-30% (-55 to -12)
2071-2100	High (RCP 8.5)	-41% (-71 to -18)

Cascades Hydrology Projections



Hydrology Description

The Cascades ecoregion is in a maritime snow-rain hydrologic zone, with snow falling primarily in the high elevations during the winter. The stored winter snowpack feeds streams during the early spring as temperatures warm and the snow melts.



April 1st Snow Water Equivalent (SWE) for a historical period and percent change for three future periods for a high (RCP 8.5) scenario. April 1st SWE is projected to decrease for all areas in the Cascades ecoregion, with the largest decreases projected for the low to mid elevations. By the end of the century, April 1st SWE averaged for the ecoregion is projected to decrease by 75% (range: -89 to -50) relative to 1950-2010, for a high (RCP 8.5) scenario.

Ecoregion Trends

Late Summer (July-September) Runoff

Late summer runoff in the Cascades ecoregion is mainly influenced by snowmelt from high elevations. With increasing temperatures, less of this snow will be available to melt in the late summer. By the end of the century, late summer runoff averaged across the ecoregion is projected to decrease by 50% (range: -69 to -29) relative to 1950-2010 (high scenario, RCP 8.5).

Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase everywhere in the Cascades ecoregion, with largest increases projected for the lowest elevations. By the end of the century, CMD averaged for the ecoregion is projected to increase by 56% (range: +33 to +79) relative to 1981-2010 for a high (SSP585) scenario.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for the future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	12.0in (7.4 to 16.6)	5.4in (3.6 to 7.2)
2020-2049	High (RCP 8.5)	-30% (-55 to -6)	-28% (-51 to -16)
2040-2069	High (RCP 8.5)	-50% (-73 to -21)	-38% (-61 to -20)
2070-2099	Low (RCP 4.5)	-57% (-77 to -19)	-38% (-62 to -16)
2070-2099	High (RCP 8.5)	-75% (-89 to -50)	-50% (-69 to -29)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.43 inches
2011-2040	High (SSP585)	+20% (+14 to +39)
2041-2070	High (SSP585)	+35% (+16 to +61)
2071-2100	Low (SSP245)	+35% (+14 to +58)
2071-2100	High (SSP585)	+56% (+33 to +79)

Cascades Hydrology Projections



Ecoregion Trends



Watershed Classification

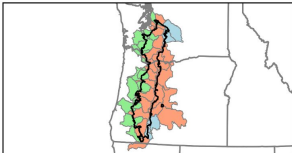
Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. Most watersheds in the Cascades ecoregion had a mixed-rain-and-snow streamflow pattern historically. With future warming, more watersheds are expected to have a rain-dominant streamflow pattern. More precipitation as rain during the wet season at low to mid elevations is expected to increase streamflow in winter and decrease streamflow in summer as snowpack declines.



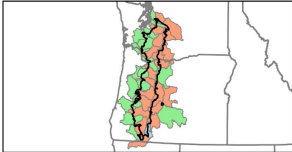
Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years, for the Cowlitz River, is projected to decrease by 54% (range: -89 to -38) by the end of the century relative to 1981-2010 (high scenario, RCP 8.5). Despite a wide range in the magnitude of projections, all models project decreases, indicating high confidence in the change.

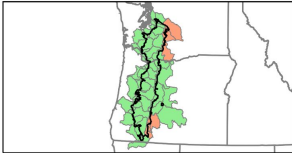
1950-2010 Historical



2020-2049 High (RCP 8.5)



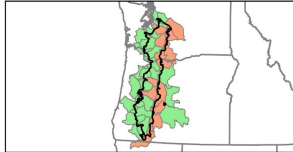
2070-2099 Low (RCP 4.5)



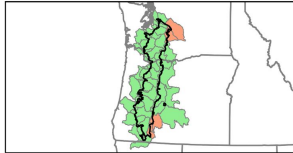
Cowlitz River



2040-2069 High (RCP 8.5)

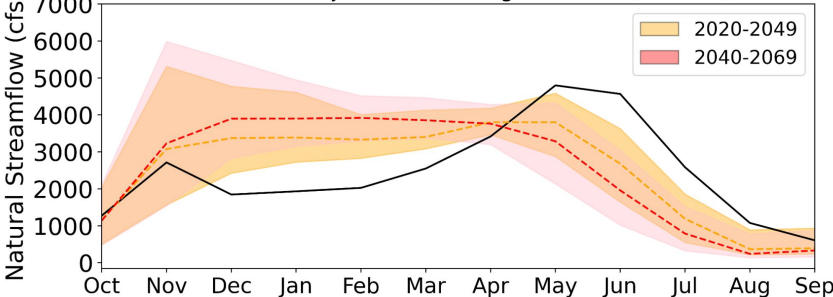


2070-2099 High (RCP 8.5)

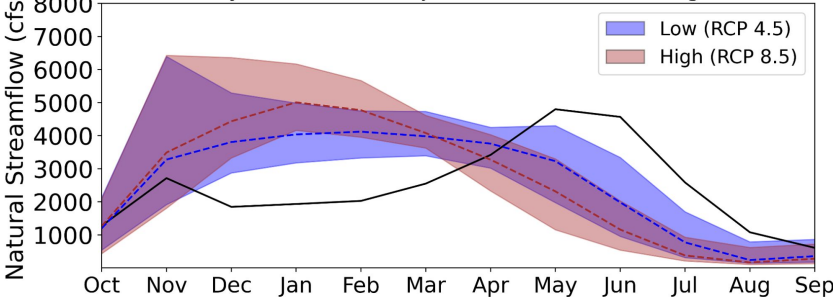


Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale, and shown for all basins that intersect the ecoregion. The projections show a general shift from mixed-rain-and-snow watersheds to more rain-dominant watersheds in the future. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Cowlitz River.

Near-term Projections for a High Scenario (RCP 8.5)



Late Century (2070-2099) Projections for a Low and High Scenario



Cowlitz River Historical and Projected Future Monthly Streamflow: The timing of Peak annual flow is expected to shift from summer to a more broad peak throughout the winter months. The black line is the simulated historical and dashed lines are the median hydrographs of 40 models. Shaded areas show the 10th and 90th percentile range. Streamflow projections are without withdrawals and dam regulation.

Data Sources: CMD: [AdaptWest](#), Watershed Classification, Low Flows, Runoff, SWE: [CRCC](#) [Request Data Here](#)

Projections: Summer Low Flow

The table below shows projected model median change values in summer (June-Sept.) low flows (7Q2) in cubic feet per second (cfs) at a location on the Cowlitz River. Summer low streamflow on the Cowlitz river is projected to decrease through the century for both a high (RCP 8.5) and low (RCP 4.5) scenario. Summer low streamflow (7Q2) is an indicator of water availability for aquatic habitat. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for three future periods.

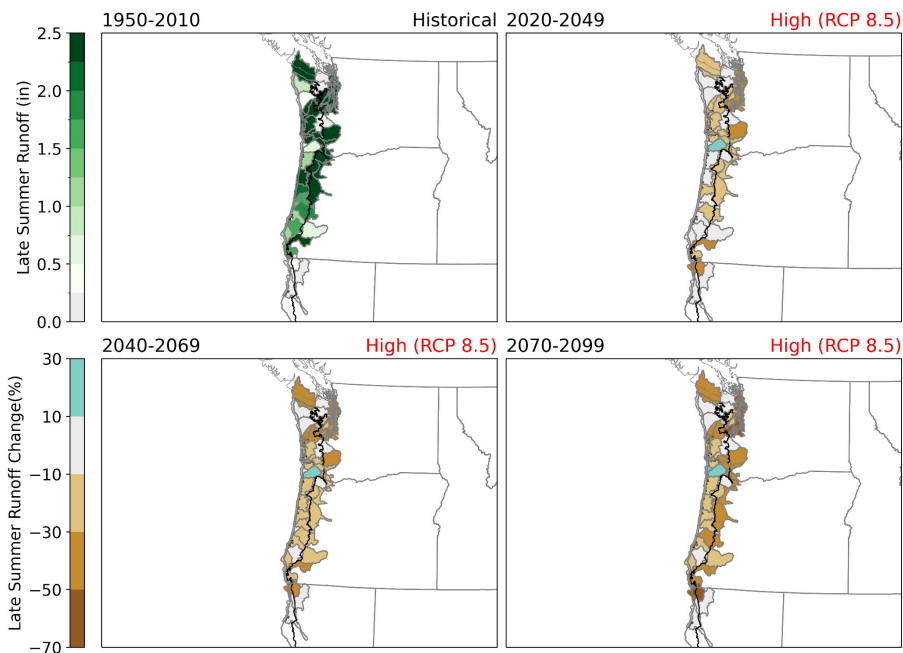
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	333 cfs (85 to 582)
2011-2040	High (RCP 8.5)	-38% (-69 to -22)
2041-2070	High (RCP 8.5)	-47% (-83 to -30)
2071-2100	Low (RCP 4.5)	-47% (-84 to -25)
2071-2100	High (RCP 8.5)	-54% (-89 to -38)

Coast Range Hydrology Projections



Hydrology Description

The Coast Range ecoregion is a maritime rain hydrologic zone. This ecoregion receives abundant precipitation in the winter that falls mostly as rain with little snowpack. This leads to high winter streamflow and lower flows in spring and summer, except some streams that are fed by snowmelt from the high elevations of the coastal mountains.



Late Summer (July-Sept.) Runoff for a historical period and projected change for three future periods for a high (RCP 8.5) scenario. Late summer runoff is expected to decrease, especially at the highest elevations in the ecoregion where snowmelt contributes substantially to surface water runoff into the summer. By the end of the century, late summer runoff is projected to decrease by 33% (range: -47 to -18) relative to 1950-2010 for a high (RCP 8.5) scenario.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. Both spring snowmelt and summer precipitation contribute to late summer runoff. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for the future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	2.6in (1.2 to 3.9)	3.0in (2.0 to 3.9)
2020-2049	High (RCP 8.5)	-54% (-80 to -23)	-22% (-34 to -8)
2040-2069	High (RCP 8.5)	-74% (-93 to -32)	-26% (-45 to -4)
2070-2099	Low (RCP 4.5)	-78% (-92 to -53)	-26% (-41 to -2)
2070-2099	High (RCP 8.5)	-90% (-97 to -64)	-33% (-47 to -18)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.46 inches
2011-2040	High (SSP585)	+18% (+11 to +29)
2041-2070	High (SSP585)	+28% (+21 to +47)
2071-2100	Low (SSP245)	+28% (+19 to +46)
2071-2100	High (SSP585)	+46% (+32 to +61)

Ecoregion Trends

April 1st Snow Water Equivalent (SWE)

Historical April 1st Snowpack in this ecoregion is confined mainly to the higher elevations of the Olympic Mountains. With future warming, seasonal snowpack is expected to melt earlier in spring. By the end of the century, April 1st SWE is expected to decrease by 90% (range: -97 to -64) relative to 1950-2010, for a high (RCP 8.5) scenario.

Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase throughout the ecoregion, with the greater increases projected for the eastern Coast Range ecoregion. By the end of the century, CMD averaged for the ecoregion is projected to increase by 46% (range: 32 to 61) for a high (SSP585) scenario, relative to 1981-2010.

Coast Range Hydrology Projections



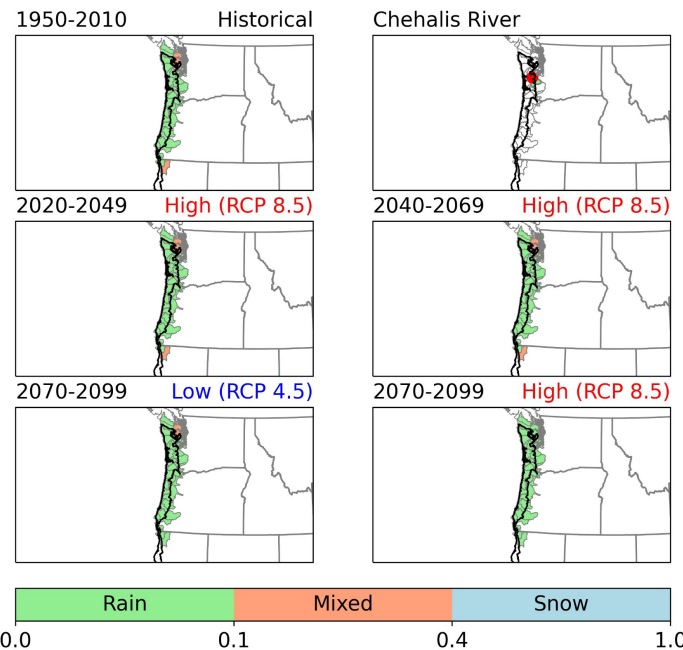
Ecoregion Trends

Watershed Classification

Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. For the Coast Range, watershed classifications are not expected to change substantially in the future, but more precipitation during the wet season and more precipitation as rain rather than snow is expected to increase winter streamflow. Because most of the precipitation in the region falls as rain currently, the majority of watersheds in this ecoregion are and will continue be rain-dominant.

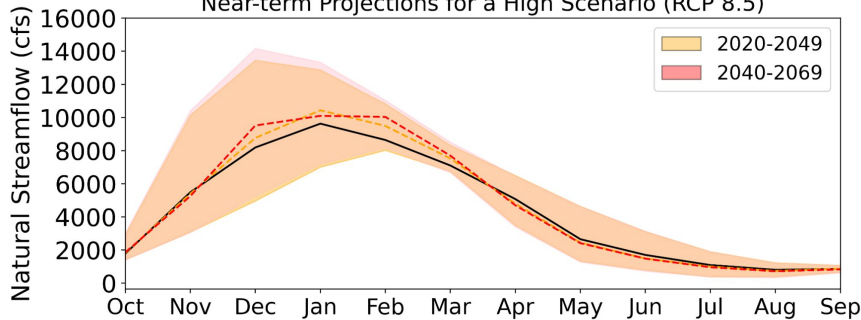
Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow, the lowest 7-day average flow that occurs on average every 2 years in summer, for the Chehalis River is projected to decrease by -9% (range: -18 to -3) by the end of the century relative to 1981-2010 for a high (RCP 8.5) scenario. Summer 7Q2 is an important indicator of water availability for aquatic habitat during the dry period.

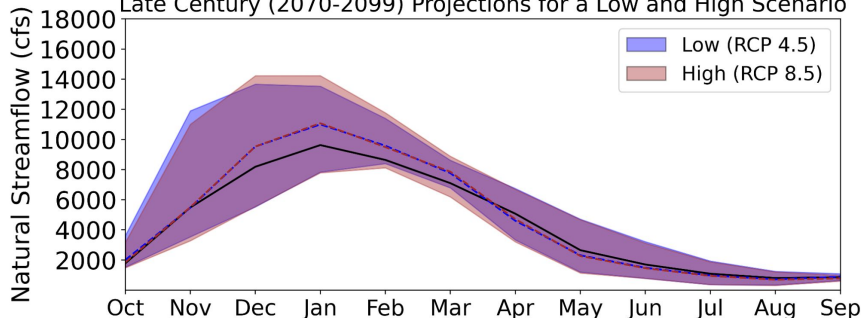


Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. The projections show little change, as most watersheds are already classified as rain-dominant. The red dot in the upper-right subplot denotes the location of the monthly hydrographs on the Chehalis River.

Near-term Projections for a High Scenario (RCP 8.5)



Late Century (2070-2099) Projections for a Low and High Scenario



Chehalis River Historical and Projected Future Monthly Streamflow:

Winter streamflow is projected to increase substantially and spring streamflow is projected to decrease slightly. The black line is the simulated historical and dashed lines are the median hydrographs of 40 models. Shaded areas show the 10th and 90th percentile range. Streamflow projections are without withdrawals and regulation by dams.

Projections: Summer Low Flow

The table below shows model median values of historical and projected change in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Chehalis River. Summer low streamflow for the Chehalis is projected to decrease modestly through the century for both a high (RCP 8.5) and low (RCP 4.5) scenario. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for the listed future periods.

Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	504 cfs (285 to 723)
2011-2040	High (RCP 8.5)	-5% (-10 to +0)
2041-2070	High (RCP 8.5)	-8% (-16 to +0)
2071-2100	Low (RCP 4.5)	-7% (-13 to -1)
2071-2100	High (RCP 8.5)	-9% (-18 to -3)

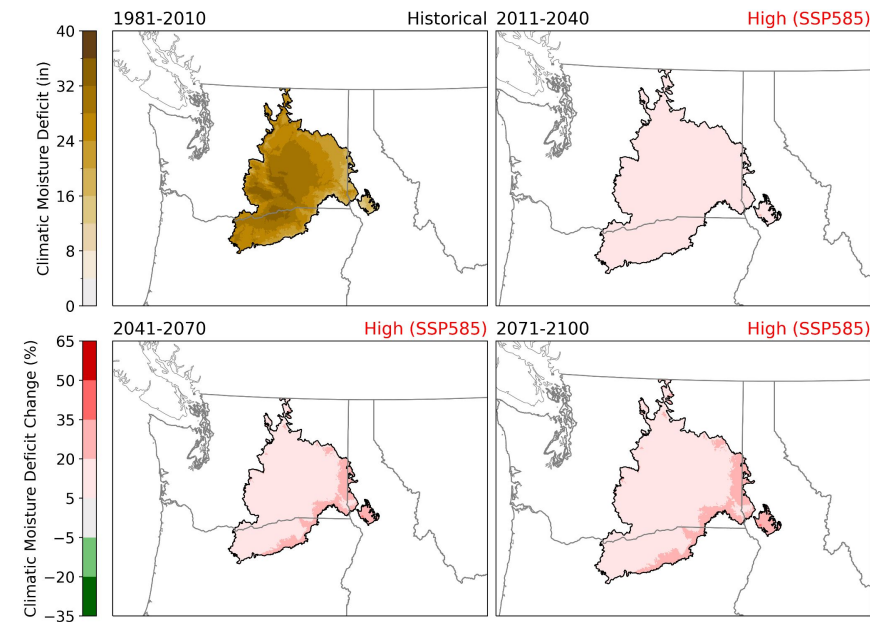
Data Sources: CMD: [AdaptWest](#), Watershed Classification, Low Flows, Runoff, SWE: [CRCC Request Data Here](#)

Columbia Plateau Hydrology Projections



Hydrology Description

The Columbia Plateau ecoregion is in a cold semi-arid and desert hydrologic zone and receives little annual precipitation. Larger streams in this region receive rain and snowmelt from upstream head waters year-round. Smaller streams are ephemeral, often becoming completely dry during the summer when precipitation is minimal.



Climatic Moisture Deficit (CMD) for a historical period and projected change for three future periods for a high (RCP 8.5) scenario. CMD, an indicator of drought stress for plants, has historically been greater at low elevations in the ecoregion. By the end of the century, CMD averaged for the ecoregion is projected to increase by 25% (range: +22 to +50) under a high (SSP585) scenario relative to 1981-2010. The largest increases are projected for the eastern part of the ecoregion.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values for historical and projected change in April 1 snow water equivalent (SWE), late summer (July-Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of available water during the dry season. CMD is a measure of moisture stress on vegetation. Higher values and increases in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for the future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	0.3in (0 to 0.6)	0.3in (0.1 to 0.7)
2020-2049	High (RCP 8.5)	-55% (-88 to +54)	+0% (-19 to +16)
2040-2069	High (RCP 8.5)	-76% (-97 to -7)	-1% (-27 to +29)
2070-2099	Low (RCP 4.5)	-83% (-95 to +7)	+5% (-21 to +34)
2070-2099	High (RCP 8.5)	-93% (-98 to -53)	+3% (-24 to +42)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	1.0 inches
2011-2040	High (SSP585)	+10% (+6 to +20)
2041-2070	High (SSP585)	+16% (+13 to +35)
2071-2100	Low (SSP245)	+17% (+12 to +34)
2071-2100	High (SSP585)	+25% (+22 to +50)

Ecoregion Trends

Late Summer (July - September) Runoff

Late summer runoff is projected to increase slightly through the century under both a low (RCP 4.5) and high (RCP 8.5) scenario, with areas showing slight increases and others slight decreases. By 2100, late summer runoff averaged for the ecoregion is projected to increase by 3% (range: -24 to 42) relative to 1950-2010, for a high (RCP 8.5) scenario. Confidence is low in these changes because some models project increases and others decreases.

April 1st Snow Water Equivalent (SWE)

Historical (1950-2010) April 1st SWE in the Columbia Plateau is already low and sensitive to changes in precipitation, not just temperature, so confidence is low in near-term projections. By the end of the century, April 1st SWE is projected to decrease by 93% (range: -98 to -53) relative to 1950-2010, for a high (RCP 8.5) scenario.

Columbia Plateau Hydrology Projections



Ecoregion Trends



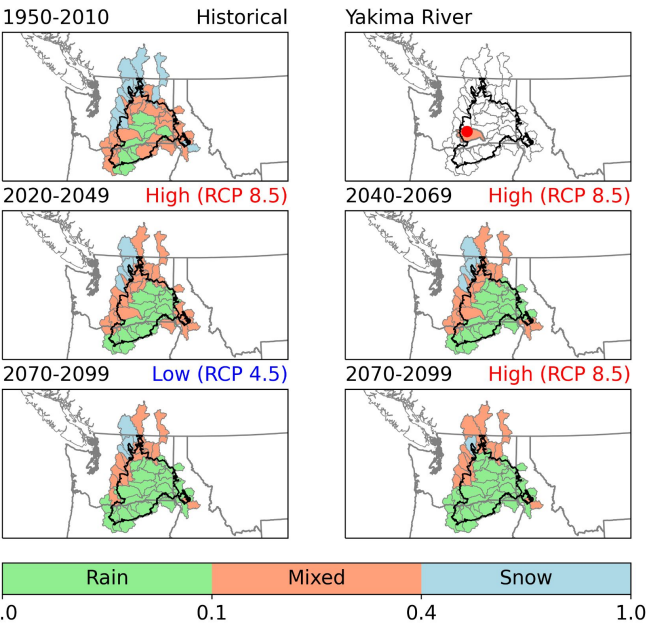
Watershed Classification

Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. Watersheds in the Columbia Plateau ecoregion are expected to become more rain-dominant with increasing temperatures. More precipitation falling as rain during the wet season at low and middle elevations is expected to increase streamflows in winter and decrease streamflows in spring and summer.

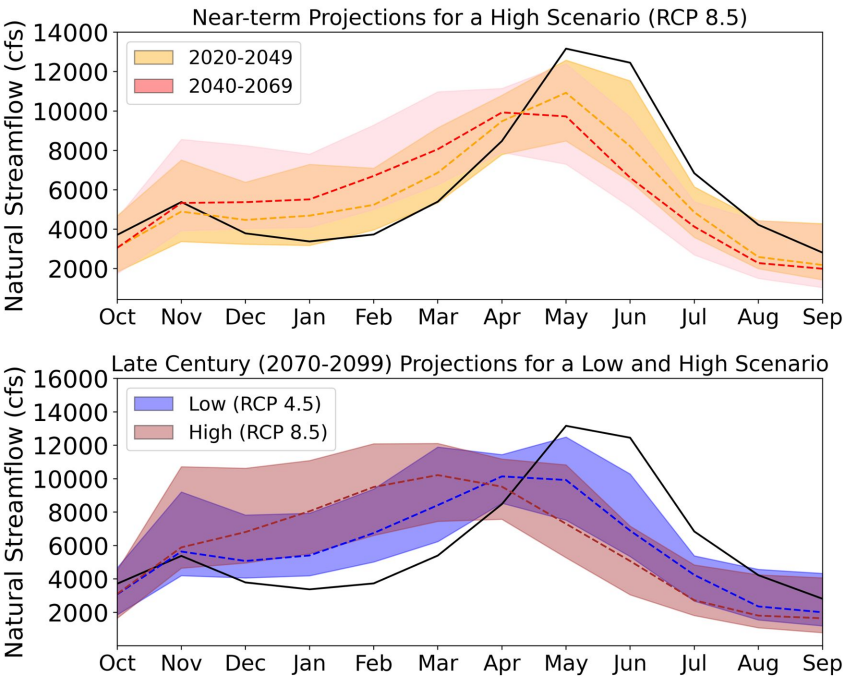


Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest average flow that occurs on average every 2 years, for the Yakima River is projected to decrease by about 33% (range: -64 to -12) by end of century relative to 1981-2010, for a high (RCP 8.5) scenario. Summer 7Q2 is an indicator of availability for aquatic habitat during the driest period. Confidence is high that summer low flows will decrease given that all models project decreases.



Watershed Classification: Ratio (model median) of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. The projections show a general shift from mixed-rain-and-snow basins to more rain-dominant basins. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Yakima River.



Yakima River Historical and Projected Future Monthly Streamflow: The timing of peak annual streamflow is expected to shift earlier in spring with an increasing secondary peak in early winter. The black line is the simulated historical hydrograph. Dashed lines are the median hydrographs of 40 models, and shaded areas show the 10th and 90th percentile range of all projections. Streamflow projections are without withdrawals and regulation by dams.

Projections: Summer Low Flow

The table below shows model median values of historical and projected change in summer (June-Sept) low flows (7Q2) in cubic feet per second (cfs) at a location on the Yakima River. Summer low streamflow for the Yakima is projected to decrease modestly through the century, with a decrease of -33% (range: -64 to -12) by the end of the century for a high (RCP8.5) scenario. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for the listed future periods.

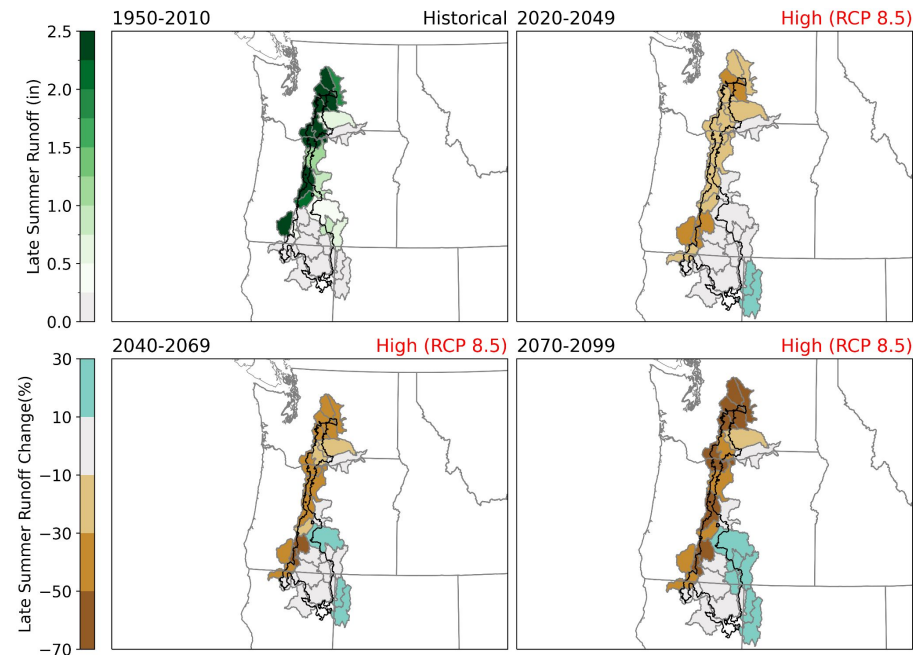
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	2380 cfs (1310 to 3450)
2011-2040	High (RCP 8.5)	-14% (-38 to -3)
2041-2070	High (RCP 8.5)	-25% (-55 to -10)
2071-2100	Low (RCP 4.5)	-20% (-58 to -6)
2071-2100	High (RCP 8.5)	-33% (-64 to -12)

Eastern Cascades Foothills Hydrology Projections



Hydrology Description

The Eastern Cascades ecoregion is in a maritime snow hydrologic zone. This ecoregion does not receive much snow, but the hydrology is heavily influenced by upstream snowmelt from the Cascade Mountain Range during the spring and summer.



Late Summer (July-Sept.) Runoff for a historical period and projected change for three future periods for a high (RCP 8.5) scenario. Late summer runoff is projected to decrease for most of the Eastern Cascades ecoregion, except for the southeast. By the end of the century, late summer runoff is projected to decrease by 30% (range: -60 to +9) relative to 1950-2010 for a high scenario.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. In the Eastern Cascades, spring snowmelt from the high elevations and summer precipitation contribute to spring and summer streamflow. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for the future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	5.2in (2.7 to 7.8)	0.7in (0.5 to 0.9)
2020-2049	High (RCP 8.5)	-64% (-78 to -39)	-17% (-36 to +1)
2040-2069	High (RCP 8.5)	-75% (-88 to -53)	-22% (-52 to +2)
2070-2099	Low (RCP 4.5)	-77% (-90 to -56)	-17% (-52 to +3)
2070-2099	High (RCP 8.5)	-86% (-94 to -72)	-30% (-60 to +9)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.94 inches
2011-2040	High (SSP585)	+10% (+5 to +15)
2041-2070	High (SSP585)	+18% (+12 to +24)
2071-2100	Low (SSP245)	+18% (+11 to +52)
2071-2100	High (SSP585)	+29% (+19 to +32)

Ecoregion Trends

April 1st Snow Water Equivalent (SWE)

With future warming, snowpack is expected to melt earlier in spring and a snowpack that persists until April 1st will be increasingly rare. By the end of the century, April 1st SWE averaged for the Eastern Cascades ecoregion is expected to decrease by 86% (range: -94 to -72) relative to 1950-2010, for a high scenario (RCP 8.5).

Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase throughout the Eastern Cascades ecoregion, with greater increases projected for the low elevations. By the end of the century, CMD averaged for the ecoregion is projected to increase by as much as 29% (range: +19 to +32) for a high (SSP585) scenario, relative to 1981-2010.

Eastern Cascades Foothills Hydrology Projections



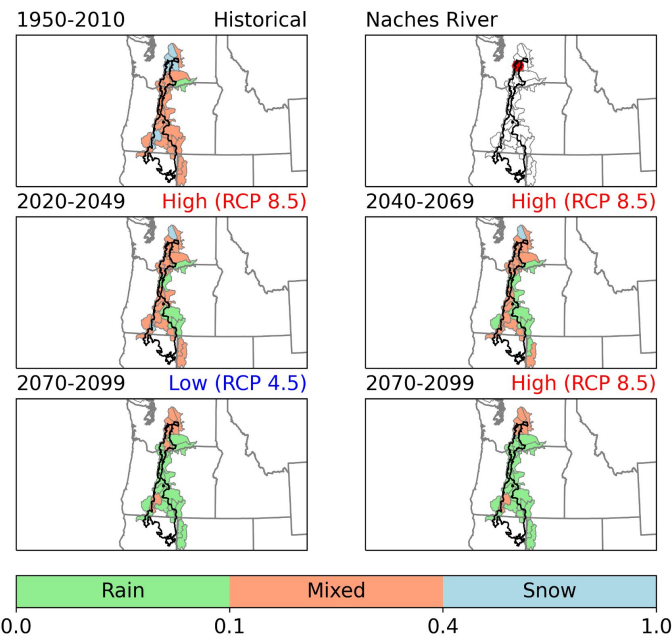
Ecoregion Trends

Watershed Classification

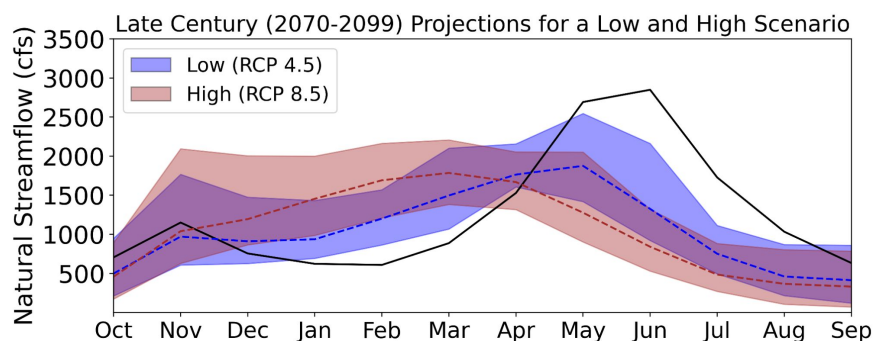
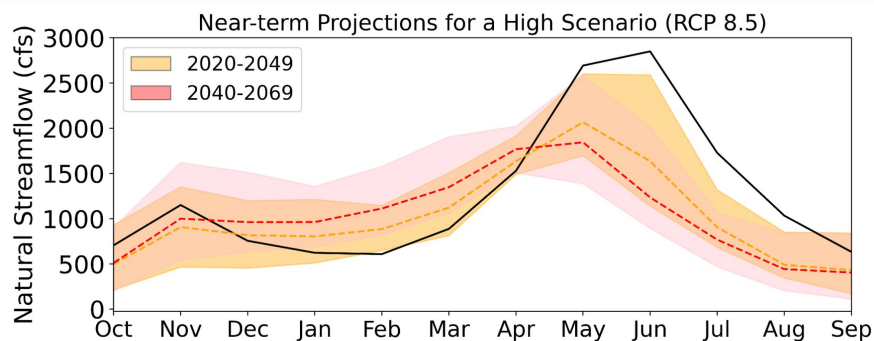
Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. Watersheds in the Eastern Cascades have historically exhibited mixed-rain-and-snow streamflow patterns. Fewer watersheds will exhibit this pattern in the future. More precipitation during the wet season is expected to fall as rain, increasing streamflows in winter, shifting peak flows earlier in the spring, and decreasing flows in mid-to-late summer.

Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years for the Naches River is projected to decrease by 35% (range: -79 to -8) by the end of the century relative to 1981-2010 (high scenario, RCP 8.5). Confidence is high in this projection because all models project a decrease.



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. The projections show a general change from mixed-rain-and-snow to more rain-dominant watersheds in the future. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Naches River.



Naches River Historical and Projected Future Monthly Streamflow

The timing of peak annual flow is expected to shift from early summer to a more broad peak during spring. The black line is the simulated historical and dashed lines are the median hydrographs of 40 models. Shaded areas show the 10th and 90th percentile range. Streamflow projections are without withdrawals and dam regulation

Projections: Summer Low Flow

The table below shows projected model median change in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Naches River. Summer low streamflow is an important indicator of water availability for aquatic habitat. Summer low flows for the Naches River are projected to decrease steadily through the century. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for the three future periods.

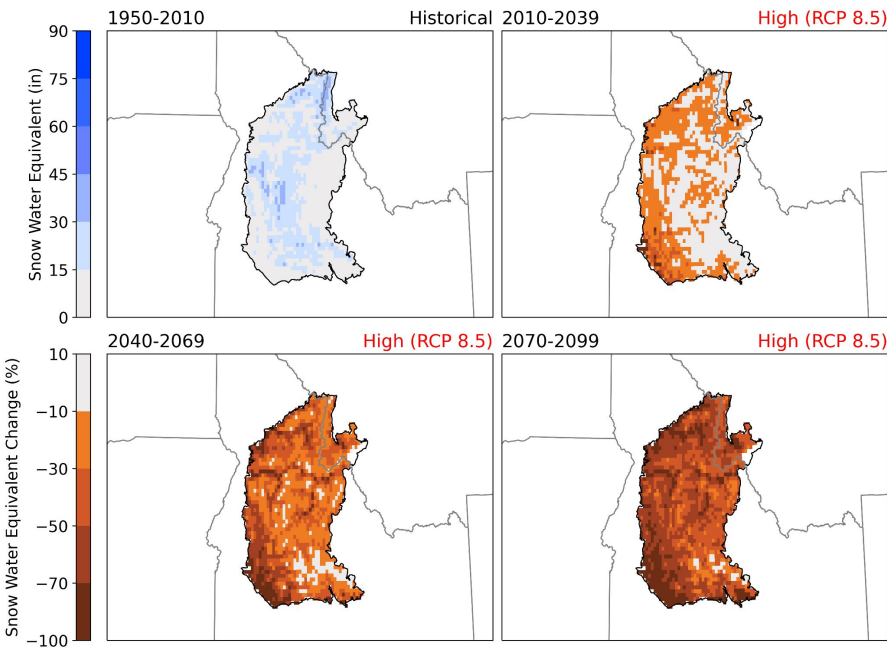
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	460 cfs (225 to 696)
2011-2040	High (RCP 8.5)	-15% (-48 to -2)
2041-2070	High (RCP 8.5)	-25% (-70 to -5)
2071-2100	Low (RCP 4.5)	-19% (-70 to -2)
2071-2100	High (RCP 8.5)	-35% (-79 to -8)

Idaho Batholith Hydrology Projections



Hydrology Description

The Idaho Batholith ecoregion is in a mediterranean snow hydrologic zone. This ecoregion accumulates considerable snow over the winter, which feeds a large network of streams throughout the spring and summer as it melts.



April 1st Snow Water Equivalent (SWE) for a historical period and percent change for three future periods for a high (RCP 8.5) scenario. In the Idaho Batholith ecoregion, April 1st SWE is projected to decrease considerably, with the largest decreases projected for the low to middle elevations. By the end of the century, April 1st SWE averaged for the ecoregion is projected to decrease by 48% (range: -68 to -14) relative to 1950-2010, for a high (RCP 8.5) scenario.

Ecoregion Trends



Late Summer (July - September) Runoff

As winter temperatures increase and snowpack melts earlier, less snow will be available to melt and runoff later in the summer in the Idaho Batholith ecoregion. By the end of the century, late summer runoff is expected to decrease by 55% (range: -81 to -33) relative to 1950-2010, for a high (RCP 8.5) scenario.



Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase everywhere in the Idaho Batholith ecoregion except at the highest elevations and larger increases are projected for the lowest elevations. By the end of the century, CMD averaged for the ecoregion is projected to increase by 42% (range: +24 to +60) relative to 1981-2010, for a high (SSP585) scenario.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for three future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	13.4in (9.4 to 17.8)	3.5in (1.8 to 5.4)
2020-2049	High (RCP 8.5)	-12% (-34 to +1)	-29% (-50 to -14)
2040-2069	High (RCP 8.5)	-25% (-51 to +8)	-43% (-71 to -22)
2070-2099	Low (RCP 4.5)	-24% (-49 to +5)	-41% (-69 to -9)
2070-2099	High (RCP 8.5)	-48% (-68 to -14)	-55% (-81 to -33)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.54 inches
2011-2040	High (SSP585)	+12% (+8 to +23)
2041-2070	High (SSP585)	+25% (+11 to +39)
2071-2100	Low (SSP245)	+26% (+8 to +38)
2071-2100	High (SSP585)	+42% (+24 to +60)

Idaho Batholith Hydrology Projections



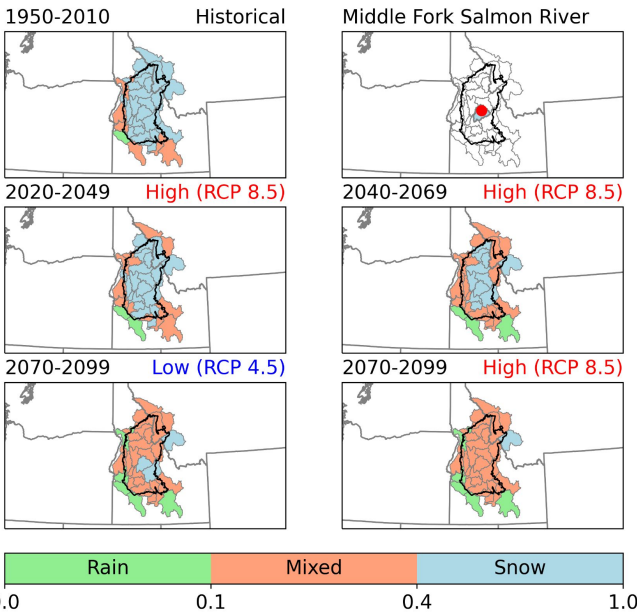
Ecoregion Trends

Watershed Classification

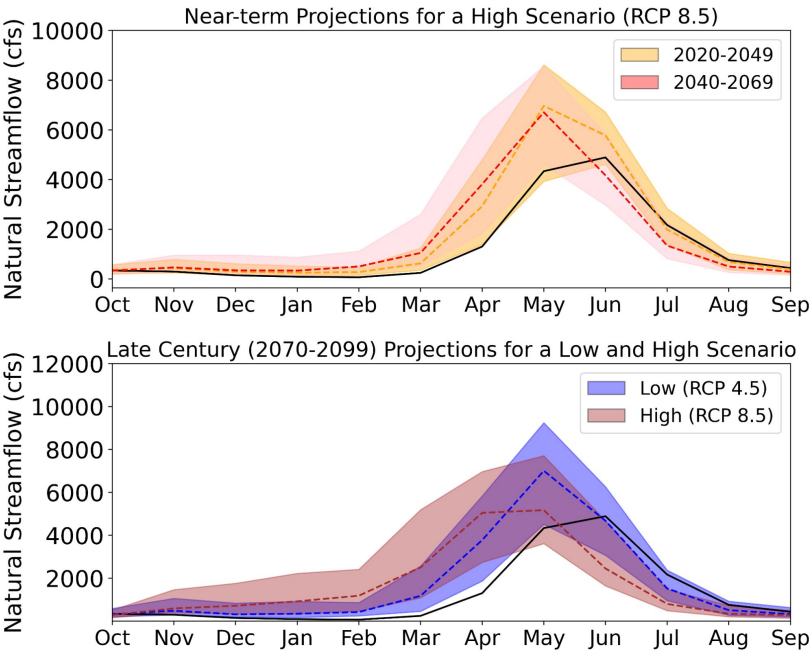
Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. Historically, most watersheds in the Idaho Batholith ecoregion had a snow-dominant streamflow pattern. In the future, more watershed are projected to have a mixed-rain-and-snow streamflow pattern with some rain-dominant watersheds at the lowest elevations. More precipitation as rain during the wet season at low to mid elevations, is expected to increase streamflow in winter and decrease flows in summer as spring snowpack declines.

Summer Low Streamflow (7Q2)

Summer (June - Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years, for Salmon River is projected to decrease by about 55% (range: -81 to -28) by the end of the century relative to 1981-2010, for a high (RCP 8.5) scenario. Confidence is high in projected decreases in summer low streamflow because all models consistently project decreases.



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale, and shown for all basins that intersect the ecoregion. The projections show a general shift from snow-dominant watersheds to more mixed-rain-and-snow watersheds. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Salmon River.



Salmon River Historical and Projected Future Monthly Streamflow: The timing of peak annual flow is projected to shift from early summer to spring. The black line is the simulated historical hydrograph. Dashed lines are the median hydrographs of 40 models, and the shaded areas show the 10th and 90th percentile range of all projections. Streamflow projections are without withdrawals and regulation by dams.

Projections: Summer Low Flow

The table below shows projected model median change values in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Salmon River. Summer low streamflow is projected to decrease considerably for the Salmon River throughout the century. Summer low flow (7Q2) is an important indicator of water availability for aquatic habitat. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for the listed future periods.

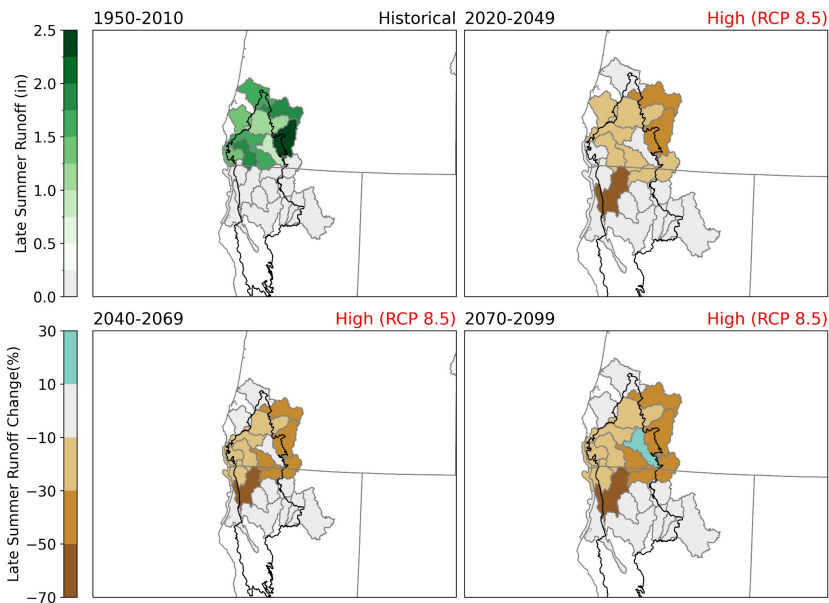
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	274 cfs (97 to 451)
2011-2040	High (RCP 8.5)	-24% (-49 to -6)
2041-2070	High (RCP 8.5)	-45% (-74 to -22)
2071-2100	Low (RCP 4.5)	-39% (-65 to -13)
2071-2100	High (RCP 8.5)	-55% (-81 to -28)

Klamath Mountains Hydrology Projections



Hydrology Description

The Klamath Mountains ecoregion is in a maritime snow-rain hydrologic zone with rain falling primarily in the middle to high elevations during the winter. The water stored in winter snowpack feeds streams during the early spring as temperatures rise and the snow melts.



Late Summer (July-Sept.) Runoff for a historical period and projected change for three future periods for a high (RCP 8.5) scenario. Most watersheds show a decrease in late summer runoff, especially in the north and east. By end of the century, late summer runoff is projected to decrease by 19% (range: -39 to +26) relative to 1950-2010. Confidence is low in these projections because some models project increases and others project decreases. Data for late summer runoff is not available for the southern Klamath Mountains ecoregion.

Ecoregion Trends

April 1st Snow Water Equivalent (SWE)

Future April 1st SWE is projected to decrease throughout the century for both a low (RCP 4.5) and high (RCP 8.5) scenario. By end of the century under, April 1st SWE averaged for the Klamath Mountains ecoregion is projected to decrease by 96% (range: -100 to -60) relative to 1950-2010, for a high (RCP 8.5) scenario.

Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase throughout the Klamath Mountains ecoregion, with greater increases in the lowest elevations. By the end of the century, CMD averaged for the ecoregion is projected to increase by 27% (range: +14 to +31) relative to 1981-2010, for a high (SSP585) scenario.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. CMD is projected to decrease throughout the century. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	2.5in (0.7 to 4.1)	0.8in (0.5 to 1.1)
2020-2049	High (RCP 8.5)	-76% (-90 to -41)	-13% (-23 to +1)
2040-2069	High (RCP 8.5)	-84% (-95 to -38)	-18% (-35 to +5)
2070-2099	Low (RCP 4.5)	-89% (-97 to -62)	-13% (-36 to +25)
2070-2099	High (RCP 8.5)	-96% (-100 to -60)	-19% (-39 to +26)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.9 inches
2011-2040	High (SSP585)	+10% (+6 to +14)
2041-2070	High (SSP585)	+18% (+10 to +20)
2071-2100	Low (SSP245)	+16% (+11 to +20)
2071-2100	High (SSP585)	+27% (+14 to +31)

Klamath Mountains Hydrology Projections



Ecoregion Trends



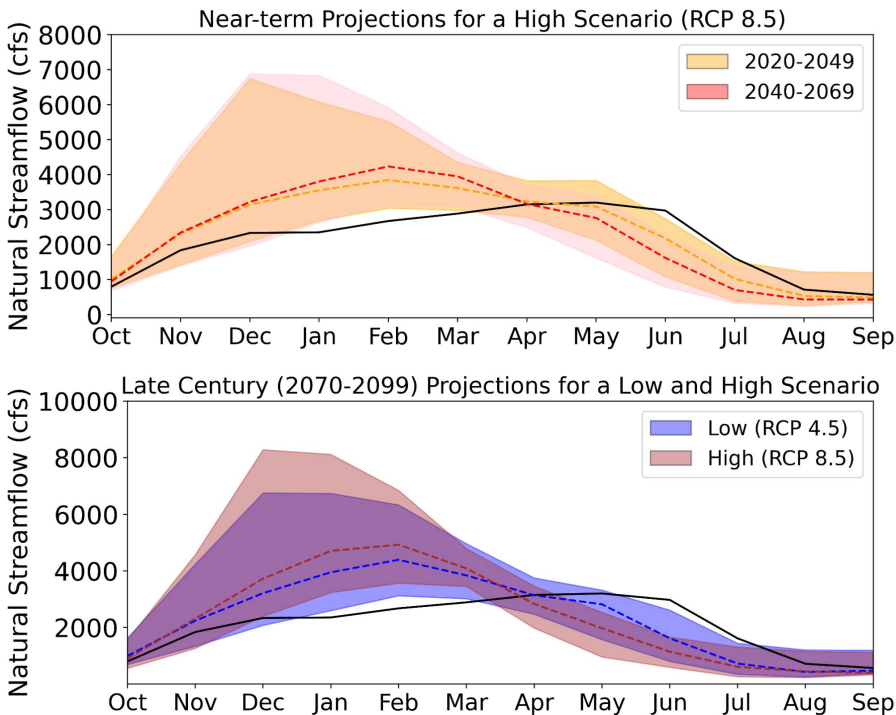
Watershed Classification

Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. Watersheds in the Klamath Mountains are projected to become more rain-dominant in the future, especially in the eastern area of this ecoregion. More precipitation during the wet season is expected to fall as rain in the middle elevations, leading to larger flows in winter and lower flows in mid-to-late summer.

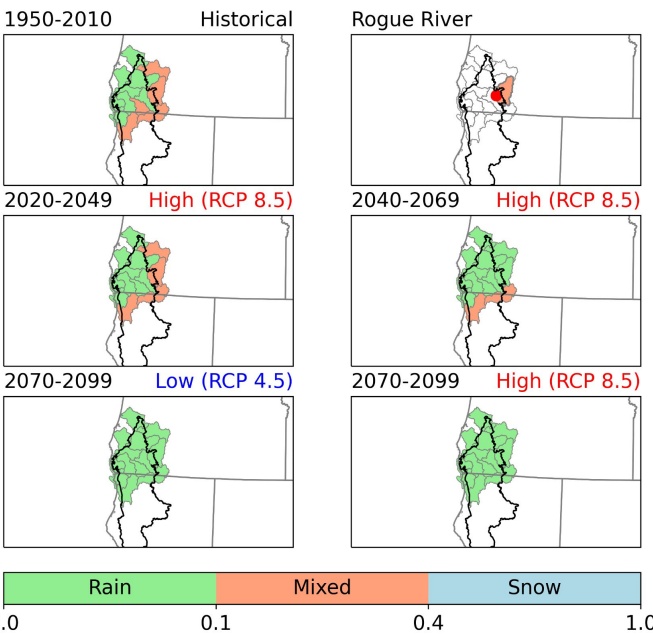


Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years, for the Rogue River is projected to decrease by 15% (range: -54 to -5) by the end of the century, for a high (RCP 8.5) scenario. Confidence is high in these projected decreases in summer streamflow because all models project a decrease.



Rogue River Historical and Projected Future Monthly Streamflow: The timing of peak annual flow is expected to shift from early summer to a more broad peak throughout the winter months. The black line is the simulated historical and dashed lines are the median hydrographs of 40 models. Shaded areas show the 10th and 90th percentile range. Streamflow projections are without withdrawals and dam regulation.



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. The projections show a change from slightly more mixed-rain-snow watersheds in the east to all rain-dominant watersheds. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Rogue River.

Projections: Summer Low Flow

The table below shows projected model median change in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Rogue River. Summer low streamflow for the Rogue Rivers is projected to decrease slightly throughout the century for both a low and higher scenario. Summer low streamflow (7Q2) is an indicator of water availability for aquatic habitat. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for the listed future periods.

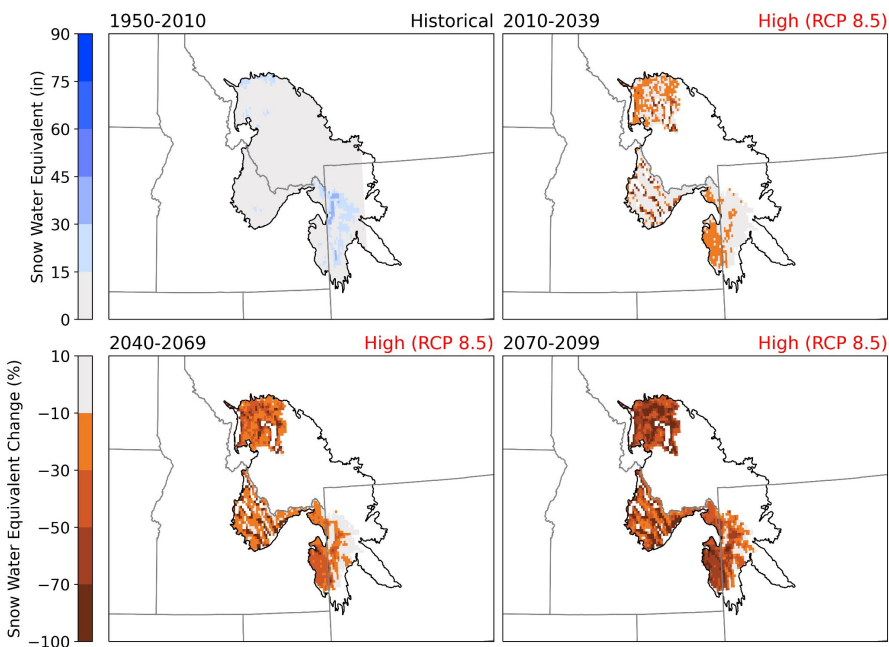
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	524 cfs (159 to 890)
2011-2040	High (RCP 8.5)	-8% (-25 to -1)
2041-2070	High (RCP 8.5)	-13% (-40 to -4)
2071-2100	Low (RCP 4.5)	-10% (-40 to -1)
2071-2100	High (RCP 8.5)	-15% (-54 to -5)

Middle Rockies Hydrology Projections



Hydrology Description

The Middle Rockies ecoregion is in a mediterranean snow hydrologic zone. This ecoregion accumulates substantial snowpack over the winter, which feeds a large network of streams throughout the spring and summer as it melts.



Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for the future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	7.7in (5.3 to 10.1)	1.2in (0.8 to 1.6)
2020-2049	High (RCP 8.5)	-54% (-61 to -48)	-16% (-33 to -6)
2040-2069	High (RCP 8.5)	-59% (-67 to -47)	-24% (-48 to -8)
2070-2099	Low (RCP 4.5)	-58% (-66 to -48)	-22% (-48 to -5)
2070-2099	High (RCP 8.5)	-68% (-78 to -50)	-31% (-60 to -8)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.51 inches
2011-2040	High (SSP585)	+12% (+8 to +24)
2041-2070	High (SSP585)	+27% (+14 to +45)
2071-2100	Low (SSP245)	+28% (+10 to +45)
2071-2100	High (SSP585)	+45% (+27 to +69)

April 1st Snow Water Equivalent (SWE) for a historical period and percent change for three future periods for a high (RCP 8.5) scenario. In the Middle Rockies, all areas with historical April 1st SWE are projected to have a decrease in the future. By the end of the century, April 1st SWE averaged for the ecoregion is projected to decrease by 68% (range: -78 to -50) relative to 1950-2010, (high scenario, RCP 8.5).

Ecoregion Trends

Late Summer (July-September) Runoff

Late summer runoff is projected to decrease in the Middle Rockies ecoregion through the century for both a low (RCP 4.5) and high (RCP 8.5) scenario. As temperatures increase, less snowpack will be available to melt and supply streams with water in late summer. By the end of the century, late summer runoff averaged for the ecoregion is projected to decrease by 31% (range: -60 to -8) relative to 1950-2010 (high scenario, RCP 8.5).

Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase everywhere in the Middle Rockies, with the greater increases projected for the low elevations. By the end of the century, CMD averaged for the ecoregion is projected to increase by 45% (range: +27 to +69) relative to 1981-2010, for a high (SSP585) scenario.

Middle Rockies Hydrology Projections



Ecoregion Trends

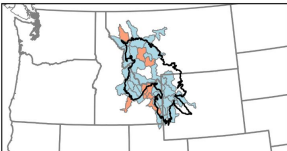
Watershed Classification

Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. Historically, most watersheds in the Middle Rockies ecoregion had snow-dominant streamflow patterns. With future warming, more watersheds in this ecoregion will have mixed-rain-and-snow streamflow patterns. More precipitation as rain during the cold season is expected to shift snowmelt and runoff earlier in spring in watersheds at low and middle elevations. Colder, high elevation watersheds will remain snow-dominated.

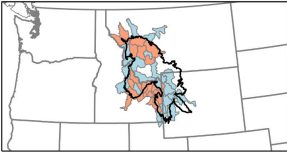
Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years for the Jackson Lake Inflow, is projected to decrease by about 18% (range: -50 to -4) by the end of the century, relative to 1981-2010, for a high (RCP 8.5) scenario. Through mid-century (2041-2070), confidence is high in projected decreases in summer low streamflow because all models project a decrease.

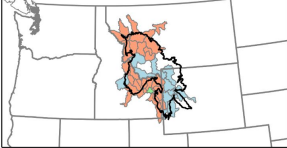
1950-2010 Historical



2020-2049 High (RCP 8.5)



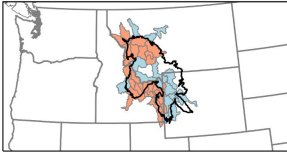
2070-2099 Low (RCP 4.5)



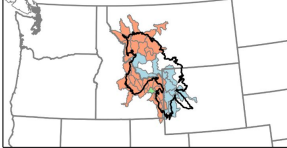
Jackson Lake Inflow



2040-2069 High (RCP 8.5)



2070-2099 High (RCP 8.5)

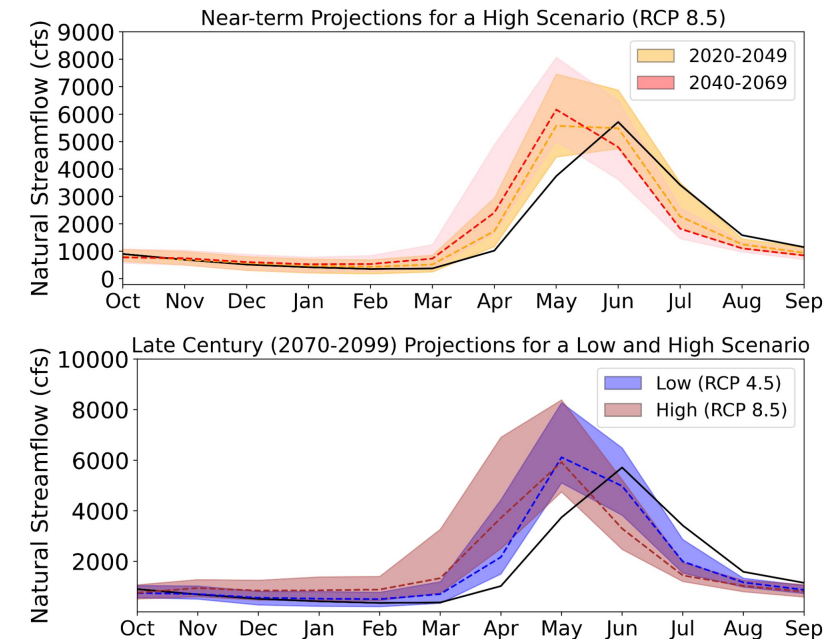


Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. The projections show a general shift from snow-dominant streamflow patterns to more mixed-rain-and-snow watersheds. The red dot in the upper-right map denotes the location of the monthly hydrographs for the Jackson Lake Inflow.

Projections: Summer Low Flow

The table below shows projected model median change in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Jackson Lake Inflow. Summer low streamflow is projected to decrease steadily throughout the century for the Fisher River for both a high (RCP 8.5) and low (RCP 4.5) scenario. Summer low flow (7Q2) is indicator of water availability for aquatic habitat during the driest period. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for future periods.

Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	778 cfs (679 to 877)
2011-2040	High (RCP 8.5)	-8% (-20 to +0)
2041-2070	High (RCP 8.5)	-13% (-37 to -5)
2071-2100	Low (RCP 4.5)	-14% (-33 to -5)
2071-2100	High (RCP 8.5)	-18% (-50 to -4)



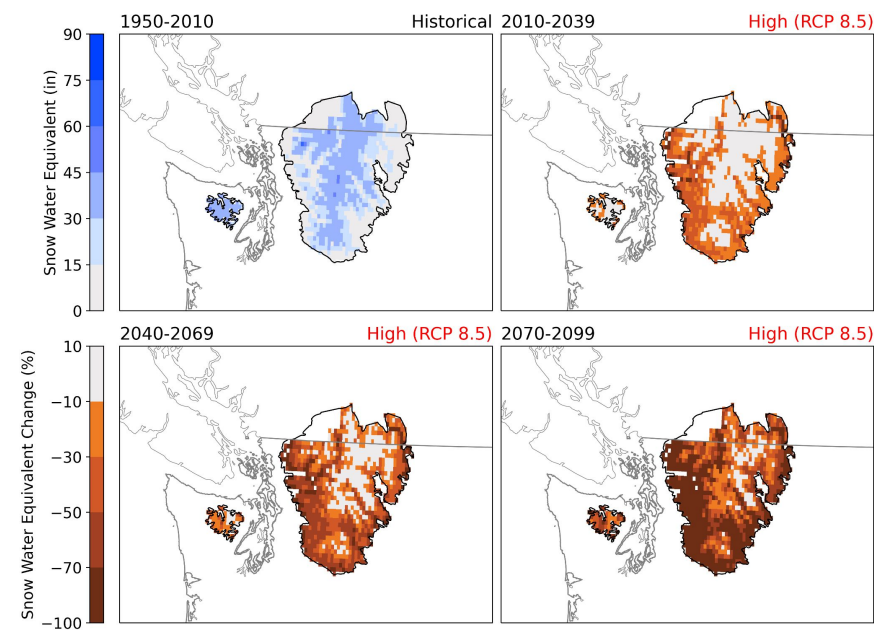
Jackson Lake Inflow Historical and Projected Future Monthly Streamflow The timing of peak annual flow is projected to shift from summer to late spring. Summer flows are projected to decrease, especially by the end of the century. The black line is the simulated historical and dashed lines are the median hydrographs of 40 models. Shaded areas show the 10th and 90th percentile range. Projections are without withdrawals and regulation by dams.

North Cascades Hydrology Projections



Hydrology Description

The North Cascades ecoregion is in a maritime snow hydrologic zone. The high elevations of this ecoregion receive abundant snow that melts and feeds a high density of streams during the spring and early summer. The projected changes in spring snowpack and associated changes to streamflow in the ecoregion will affect downstream ecoregions, as well as the effects within this ecoregion.



April 1st Snow Water Equivalent (SWE) for a historical period and percent change for three future periods for a high (RCP 8.5) scenario. By the end of the century, April 1st SWE averaged for the ecoregion is projected to decrease by 68% (range: -78 to -29) relative to 1950-2010 for a high (RCP 8.5) scenario. Data is unavailable for the northwestern part of the ecoregion.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. In the North Cascades ecoregion, spring snowpack contributes substantially to spring and summer streamflow. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for the future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	22.4in (18.9 to 26.2)	12.3in (8.2 to 16.2)
2020-2049	High (RCP 8.5)	-21% (-36 to -15)	-31% (-50 to -15)
2040-2069	High (RCP 8.5)	-32% (-51 to -17)	-43% (-65 to -19)
2070-2099	Low (RCP 4.5)	-33% (-48 to -12)	-45% (-67 to -19)
2070-2099	High (RCP 8.5)	-52% (-74 to -29)	-64% (-74 to -33)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.33 inches
2011-2040	High (SSP585)	+23% (+12 to +53)
2041-2070	High (SSP585)	+40% (+31 to +96)
2071-2100	Low (SSP245)	+40% (+23 to +93)
2071-2100	High (SSP585)	+66% (+48 to +141)

Ecoregion Trends

Late Summer (July-September) Runoff

Summer runoff in the North Cascades ecoregion is mainly influenced by snowmelt from high elevations. With increasing temperatures, snowpack will decline and less snow will be available to melt in late summer. By the end of the century, late summer runoff in the ecoregion is projected to decrease by 64% (range: -74 to -33) relative to 1950-2010, for a high (RCP 8.5) scenario.

Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase across the North Cascades ecoregion, with the largest increases expected at the lowest elevations. By the end of the century, CMD averaged for the ecoregion is projected to increase by 66% (range: +48 to +141) relative to 1981-2010, for a high (SSP585) scenario.

North Cascades Hydrology Projections



Ecoregion Trends

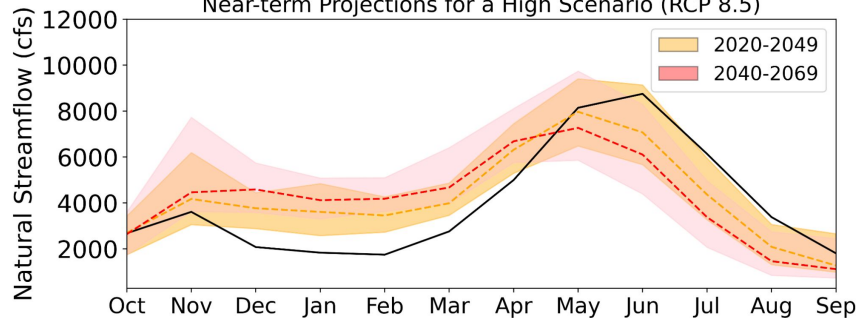
Watershed Classification

Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. For the North Cascades ecoregion, few watersheds are expected to exhibit snow-dominant streamflow patterns in the future. More precipitation is expected to fall as rain during the wet season, increasing streamflows in winter, shifting peak flows earlier in spring, and decreasing flows in mid-to-late summer. Projected changes in watershed classification here are substantial because historically most watersheds exhibited snow-dominant patterns.

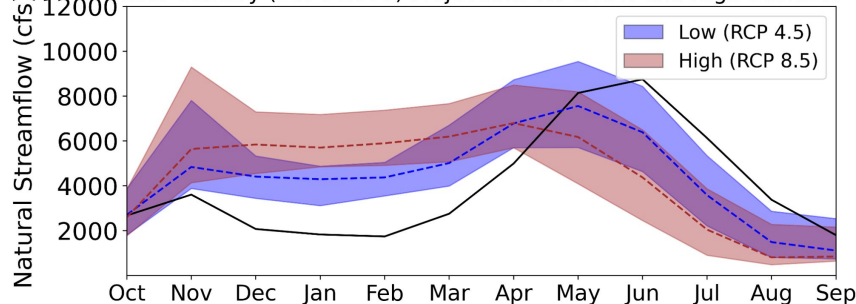
Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years in summer, for the Sauk River is projected to decrease by 63% (range: -33 to -77) by the end of the century, relative to 1950 -2010 for a high (RCP 8.5) scenario. The 7Q2 is an indicator of water availability for aquatic habitat. Confidence is high in future projections because all models consistently project decreases.

Near-term Projections for a High Scenario (RCP 8.5)



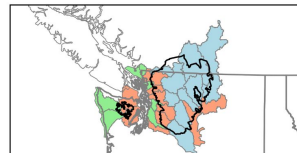
Late Century (2070-2099) Projections for a Low and High Scenario



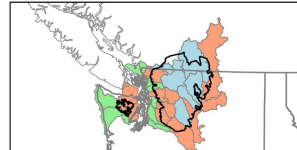
Sauk River Historical and Projected Future Monthly Streamflow:

Winter streamflow is projected to increase and late summer streamflow is projected to decrease. The black line is the simulated historical and dashed lines are the median hydrographs of 40 models. Shaded areas show the 10th and 90th percentile range. Streamflow projections are without withdrawals and regulation by dams.

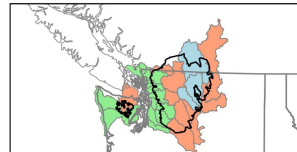
1950-2010 Historical



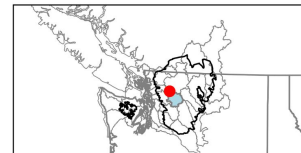
2020-2049 High (RCP 8.5)



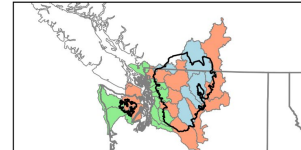
2070-2099 Low (RCP 4.5)



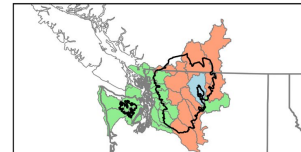
Sauk River



2040-2069 High (RCP 8.5)



2070-2099 High (RCP 8.5)



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. The projections show a change from snow and mixed-rain-and-snow dominated watersheds to mostly mixed-rain-and-snow watersheds in the future. The red dot in the upper-right map denotes the monthly hydrograph location on the Sauk River.

Projections: Summer Low Flow

The table below shows projected model median change values in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Sauk River. Summer low streamflow for the Sauk River is projected to decrease considerably in the near-term and even more by the end of the century. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for three future periods.

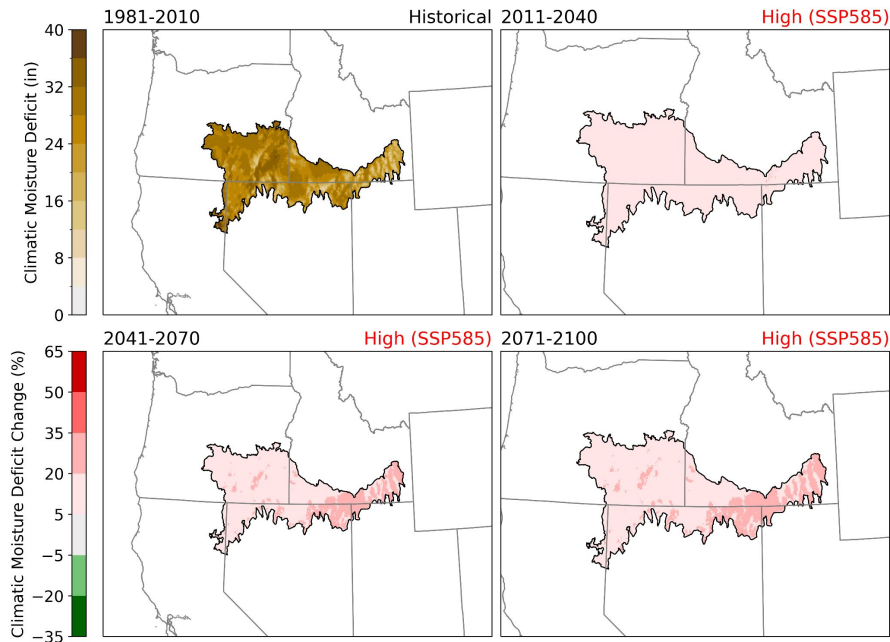
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	1470 cfs (720 to 2220)
2011-2040	High (RCP 8.5)	-43% (-55 to -12)
2041-2070	High (RCP 8.5)	-53% (-68 to -26)
2071-2100	Low (RCP 4.5)	-56% (-71 to -22)
2071-2100	High (RCP 8.5)	-63% (-77 to -33)

Northern Basin and Range Hydrology Projections



Hydrology Description

The Northern Basin and Range ecoregion is in a cold semi-arid and desert hydrologic zone. The water stored in winter snowpack in the northern sections of the ecoregion feeds larger rivers during the early spring as temperatures rise and the seasonal snow melts.



Climatic Moisture Deficit (CMD) for the historical period and projected change for three future periods for a high (RCP 8.5) scenario, relative to 1981-2010. CMD is an indicator of drought stress for plants. By 2100, the CMD averaged for the ecoregion is projected to increase by 27% (range: +22 to +31) for a high (SSP585) scenario relative to 1981-2010, with greater increases at low elevations.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values for historical and projected change in April 1 snow water equivalent (SWE), late summer (July-Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of available water during the dry season. CMD is a measure of moisture stress on vegetation. *Higher* values and increases in CMD indicate *less* water available for vegetation and *more* ecological drought. CMD is projected to increase throughout the century. The change in late summer runoff is more variable, though generally shows a decrease. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	0.6in (0.0 to 1.1)	0.4in (0.2 to 0.6)
2020-2049	High (RCP 8.5)	-31% (-75 to +175)	+8% (-20 to +40)
2040-2069	High (RCP 8.5)	-31% (-75 to +27)	+15% (-27 to +83)
2070-2099	Low (RCP 4.5)	-49% (-86 to +36)	+16% (-24 to +65)
2070-2099	High (RCP 8.5)	-79% (-96 to -11)	+23% (-28 to +137)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	1.04 inches
2011-2040	High (SSP585)	+11% (+7 to +14)
2041-2070	High (SSP585)	+18% (+14 to +21)
2071-2100	Low (SSP245)	+16% (+11 to +20)
2071-2100	High (SSP585)	+27% (+22 to +31)

Ecoregion Trends

Late Summer (July -September) Runoff

Late summer runoff is projected to slightly increase throughout the century. By the end of the century, late summer runoff is projected to increase by 23% (range: -28 to +137) relative to 1950-2010, for a high (RCP 8.5) scenario. However, confidence is low in the direction of these changes because some models project increases and some project decreases.

April 1st Snow Water Equivalent (SWE)

Snow in this ecoregion is primarily confined to winter months and snowpack melts earlier than April 1st. By the end of the century, April 1st SWE is projected to decrease by 79% (range: -96 to -11) relative to 1950-2011 for a high (RCP 8.5) scenario. Confidence is low in near-term projections due to uncertainty in precipitation trends.

Northern Basin and Range Hydrology Projections



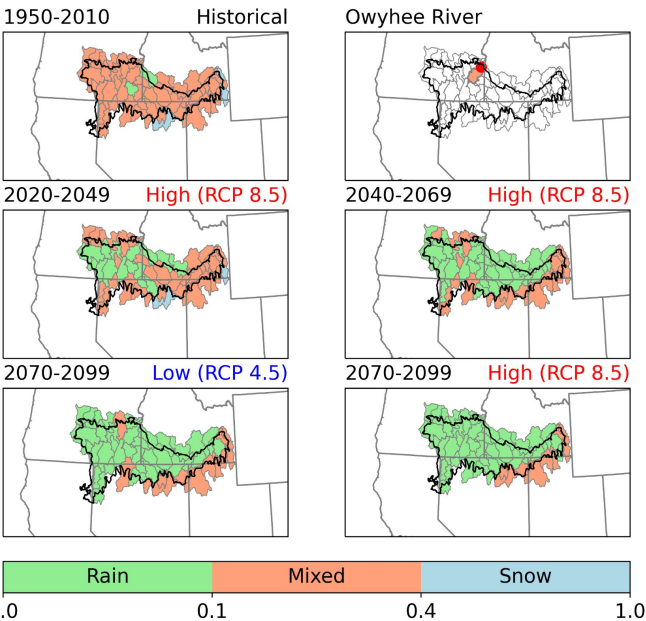
Ecoregion Trends

Watershed Classification

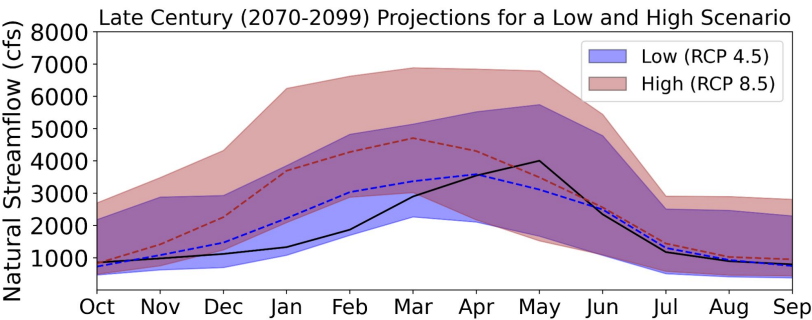
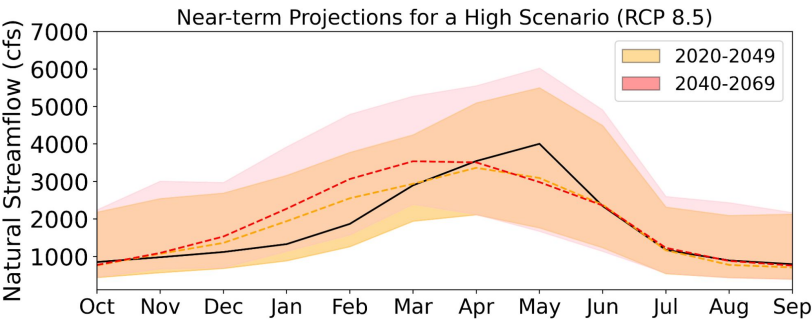
Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. More rain-dominant watersheds are expected in the future, especially in the southern parts of this ecoregion. More precipitation falling as rain during the wet season at low and middle elevations is expected to increase streamflows in winter and decrease streamflows in mid- to late-summer.

Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years, for the Owyhee River is projected to increase by about 57% (range: -6 to +280) by the end of the century for a high (RCP 8.5) scenario. However, confidence is low in these projections because some models project increases and others project decreases. The increases projected by the models may be due to increased late summer precipitation in this region but that is uncertain.



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. For the end of the century, the projections show a general change from mixed-rain-and-snow watersheds to primarily rain-dominant watersheds. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Owyhee River.



Owyhee River Historical and Projected Future Monthly Streamflow: The timing of peak annual flow is expected to shift from late spring to early spring. The black line is the simulated historical hydrograph. The black line is the simulated historical hydrograph. Dashed lines are the median hydrographs of 40 models, and the shaded areas show the 10th and 90th percentile range of all projections. Streamflow projections are without withdrawals and regulation by dams.

Projections: Summer Low Flow

The table below shows model median values of historical and projected change in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Owyhee River. Summer low streamflow for the Owyhee River is projected to increase through the century for both a high (RCP 8.5) and low (RCP 4.5) scenario. Summer low flow (7Q2) is indicator of water availability for aquatic habitat during the driest period. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for three future periods.

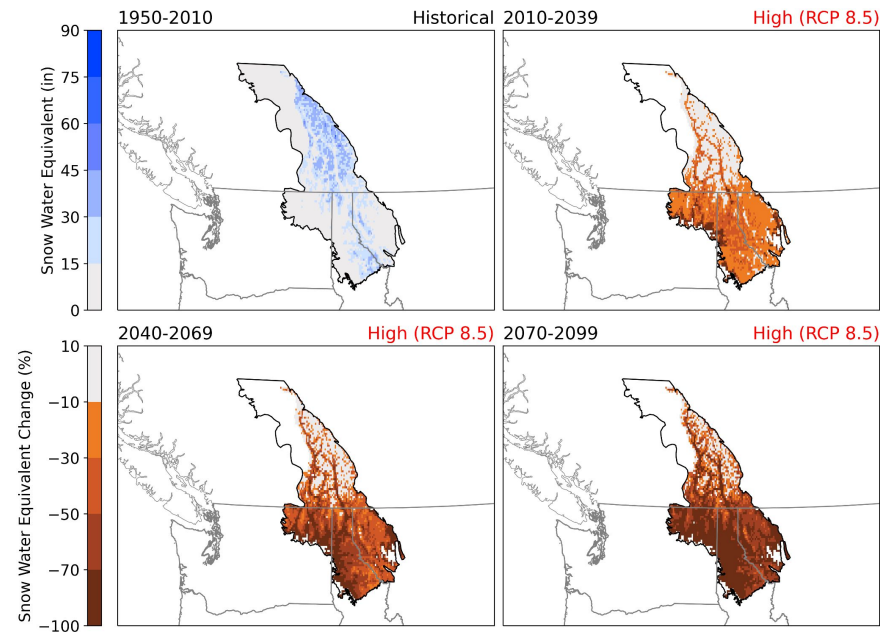
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	433 cfs (191 to 675)
2011-2040	High (RCP 8.5)	+22% (-18 to +106)
2041-2070	High (RCP 8.5)	+28% (-26 to +154)
2071-2100	Low (RCP 4.5)	+34% (-20 to +174)
2071-2100	High (RCP 8.5)	+57% (-6 to +280)

Northern Rockies Hydrology Projections



Hydrology Description

The Northern Rockies ecoregion is in a mediterranean snow hydrologic zone. This ecoregion accumulates considerable snow over the winter. As this abundant snow melts throughout the spring and summer, the runoff contributes substantially to streamflow in a large network of mountain streams.



April 1st Snow Water Equivalent (SWE) for a historical period and percent change for three future periods for a high (RCP 8.5) scenario. Decreases in April 1 SWE are expected for the Northern Rockies ecoregion, except at the highest elevations. By the end of the century, April 1st SWE averaged for the ecoregion is projected to decrease by 51% (range: -62 to -34) relative to 1950-2010, for a high (RCP 8.5) scenario. Data for the northeastern part of the ecoregion is unavailable.

Ecoregion Trends

Late Summer (July-September) Runoff

Late summer runoff in the Northern Rockies ecoregion is influenced by snowmelt from high elevations. With increasing temperatures, less of this snow will be available to melt in the late summer. By the end of the century, late summer runoff in the ecoregion is projected to decrease by 47% (range: -79 to -27) relative to 1950-2010, for a high (RCP 8.5) scenario.

Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase in the Northern Rockies, except at the highest elevations. CMD is projected to increase more at low elevations. By the end of the century, CMD averaged for the ecoregion is projected to increase by 58% (range: +36 to +137) relative to 1981-2010 (high scenario, SSP585).

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for the future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	14.2 inches (10.6 to 17.5)	4.8 inches (4.4 to 5.2)
2020-2049	High (RCP 8.5)	-29% (-39 to -22)	-22% (-38 to -13)
2040-2069	High (RCP 8.5)	-37% (-48 to -18)	-34% (-58 to -19)
2070-2099	Low (RCP 4.5)	-38% (-15 to -49)	-29% (-59 to -9)
2070-2099	High (RCP 8.5)	-51% (-62 to -34)	-47% (-79 to -27)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.34 inches
2011-2040	High (SSP585)	+19% (+17 to +50)
2041-2070	High (SSP585)	+38% (+21 to +90)
2071-2100	Low (SSP245)	+37% (+17 to +86)
2071-2100	High (SSP585)	+58% (+36 to +137)

Northern Rockies Hydrology Projections



Ecoregion Trends

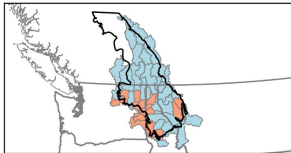
Watershed Classification

Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. Historically, most watersheds in the Northern Rockies ecoregion had a snow-dominated streamflow pattern with peak streamflow associated with spring snowmelt. With warming, more watersheds are projected to exhibit mixed-rain-and-snow streamflow patterns. More precipitation falling as rain in the wet season at low to mid elevations is expected to increase flows in winter and decrease flows in summer as snowpack decreases.

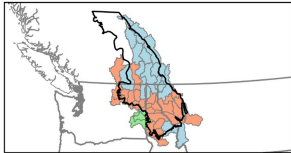
Summer Low Streamflow (7Q2)

Summer (June - Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years, for the Fisher River is projected to decrease by about 31% (range: -62 to -19) by the end of the century, relative to 1981-2010, (high scenario, RCP 8.5). Despite a wide range in the magnitude of projections, all models project decreases, indicating high confidence in the change.

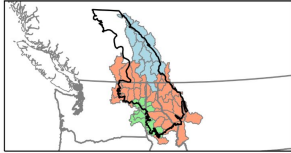
1950-2010 Historical



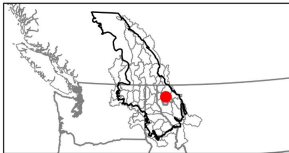
2020-2049 High (RCP 8.5)



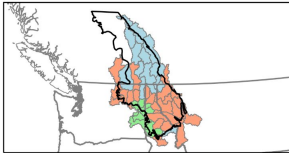
2070-2099 Low (RCP 4.5)



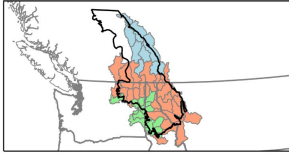
Fisher River



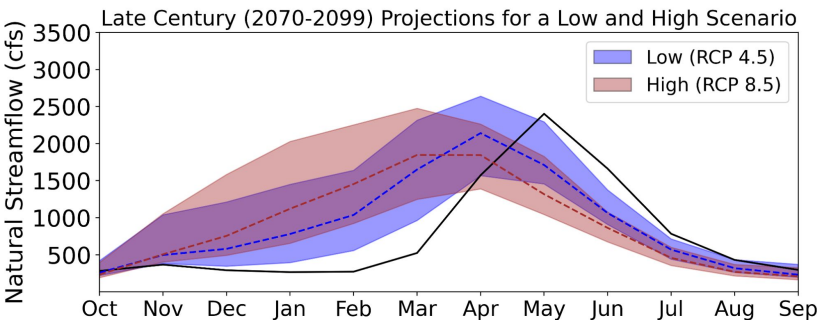
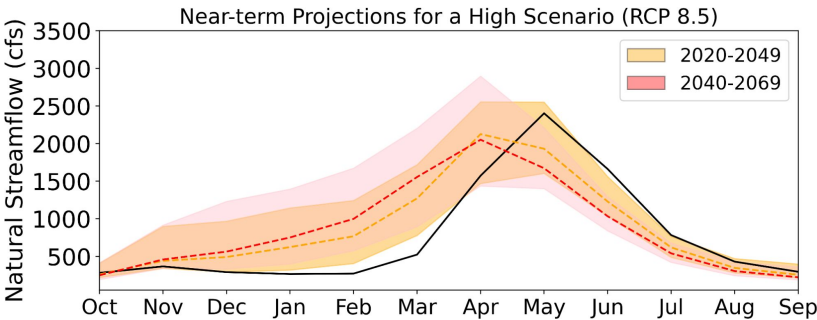
2040-2069 High (RCP 8.5)



2070-2099 High (RCP 8.5)



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. The projections show a general shift from mostly snow-dominant watersheds to more mixed-rain-and-snow watersheds. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Fisher River.



Fisher River Historical and Projected Future Monthly Streamflow: The timing of peak annual flow is projected to shift from late spring to early spring and late spring and summer flows are projected to decrease. The black line is the simulated historical and dashed lines are the median hydrographs of 40 models. Shaded areas show the 10th and 90th percentile range. Projections are without withdrawals and regulation by dams.

Projections: Summer Low Flow

The table below shows projected model median change in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Fisher River. Summer low streamflow is an important indicator of water availability for aquatic habitat. Summer low streamflow on the Fisher River is projected to decrease steadily through the century for the Fisher River for both a high (RCP 8.5) and low (RCP 4.5) scenario. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for future periods.

Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	226 cfs (150 to 302)
2011-2040	High (RCP 8.5)	-17% (-39 to -3)
2041-2070	High (RCP 8.5)	-25% (-50 to -12)
2071-2100	Low (RCP 4.5)	-22% (-47 to -10)
2071-2100	High (RCP 8.5)	-31% (-62 to -19)

IN THE OVERVIEW

HYDROLOGIC SYSTEM DESCRIPTION

INTERACTION OF CLIMATE CHANGE AND HYDROLOGIC RESPONSE

CHANGING PRECIPITATION REGIMES

CHANGING STREAMFLOW REGIMES

CHANGING CHARACTERISTICS OF DROUGHT

DROUGHT DEFINITIONS & INDICATORS

CHANGES IN WILDFIRE AND HYDROLOGIC SYSTEMS

AREAS FOR FUTURE RESEARCH

HYDROLOGIC SYSTEM DESCRIPTION

The Northwest (NW) is among the most hydrologically diverse regions in the United States, with watersheds that span high-elevation alpine systems to lowland estuarine systems (Leibowitz et al., 2016). As such, the impacts of climate change on the hydrologic systems of the region will differ substantially based on multiple antecedent conditions including historical climate, topography, vegetation, underlying lithology, and legacies of hydrologic modification and land management. These factors and their interactions strongly influence the response of watersheds to climate change. For example, variation in topography influences microclimate in ways that can exacerbate or alleviate the influence of higher air temperature.

Climate change is expected to alter the water cycle with changes in precipitation regimes, particularly precipitation form (snow versus rain), as well as the frequency, intensity and duration of extreme precipitation. These changes in the water cycle affect other components of the Earth system, such as vegetation, which feed back to the hydrologic cycle. To effectively achieve their intended purposes, land management decisions, plans, and practices will need to account for expected changes in hydrologic systems (Perry et al. 2015), including infrastructure design that may affect aquatic habitat (Yan et al. 2018).

This section provides a high-level summary of the state of the science on how climate change is influencing, and expected to continue to influence, hydrological systems and processes in the NW, including precipitation regimes, streamflow patterns, drought, and interactions between wildfire and hydrologic processes.

HYDROLOGY PROJECTIONS OVERVIEW

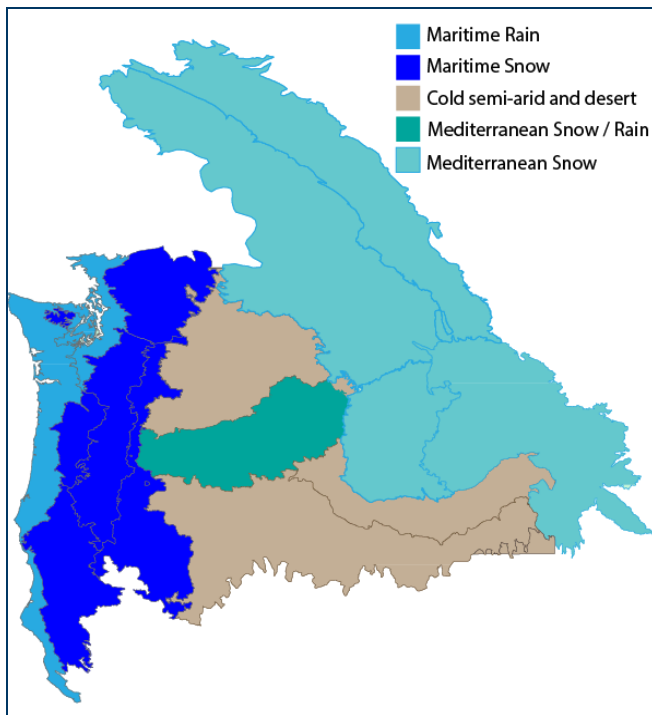


Figure 1. Subregion groupings of ecoregions of the Northwest that broadly exhibit similar characteristics of hydrologic response: mediterranean snow-dominated systems, mediterranean rain-dominated systems; maritime snow-dominated systems, maritime rain-dominated systems; and cold semi-arid and desert systems. This classification, based on the Koppen climate classification, inherently masks sub-regional variability, but the coarse subregions enable broad comparisons and summaries that are relevant for understanding projected changes in hydrologic systems with climate change.

The response of hydrologic processes to climate change in particular watersheds depends on a variety of factors that vary across spatial scales. Key similarities in hydrologic pattern and process among subregions (Figure 1, Table 1) enables synthesis of expected changes in watersheds by subregion.

- The hydrological diversity of the NW complicates projections of how climate change will influence hydrologic patterns in the future. Hydrologic change in any one place (e.g., within an individual watershed) is a product of interactions between global and regional drivers (e.g., precipitation and temperature), local physiographic context (e.g., soil, topography, vegetation), and disturbance history.
- Despite high hydrologic diversity, large-scale patterns of water accumulation, storage, and release exhibit broad similarities across subregions that encompass one or more ecoregions in the NW (Figure 1, Table 1). For example, hydrologic regimes in one subregion are dominated by snow accumulation and melt, whereas hydrologic regimes in another subregion depend more on rainfall. These hydrologic subregions are inherently related to ecoregions because they are a product of climate (e.g., annual patterns of precipitation and temperature), geography (e.g., proximity to coast), and topography (e.g., elevation). Similarly, the traits of what makes an ecoregion are also a product of the hydrologic response to climate, topography, and vegetation.

HYDROLOGY PROJECTIONS OVERVIEW

Table 1. High-level summary of the hydrologic subregions in the NW and the ecoregions within them. Each subregion, or hydrologic zone, has similar climate-related ecosystem stressors and key hydrologic indicators that best capture the impacts of those stressors.

<u>Hydrologic Zone</u>	<u>Ecoregions</u>	<u>Key ecosystem stressors</u>	<u>Key indicators of hydrologic change</u>
Maritime rain-dominated	Coast Range Puget Lowlands	Heavy precipitation, sea level rise, coastal and riverine flooding	Soil moisture, groundwater, Peak streamflows
Maritime snow-dominated	Willamette Valley Cascades North Cascades Klamath Mountains Eastern Cascade Foothills	Heavy precipitation, compound hydrologic effects post wildfire	Snow water equivalent, soil moisture
Cold semi-arid and desert	Columbia Plateau Northern Basin & Range Snake River Plain Southeast Idaho	Increased frequency and severity of drought	Soil moisture, low streamflows
Mediterranean snow-dominated	Northern Rockies Idaho Batholith Middle Rockies Canadian Rockies Blue Mountains	Rain on snow events; increased frequency and severity of drought	Spring snow water equivalent, streamflow, elevation of rain/snow transition, soil moisture, low streamflow, groundwater

INTERACTION OF CLIMATE CHANGE AND HYDROLOGIC RESPONSE

CHANGING PRECIPITATION REGIMES

Some attributes of precipitation regimes are not expected to change substantially, yet others are expected to change in a myriad of ways that can affect ecosystems.

- The magnitude of *mean annual precipitation* in the Columbia River Basin is not projected to change substantially by the end of the century (Chegwidden et al., 2020; Wrzesien & Pavelsky, 2020). The CMIP6 multi-model ensemble projects a slight increase in mean annual precipitation of about 5% (See Climate Overview), which could contribute to higher mean annual runoff and streamflow volume depending on changes in temperature and evaporation. However, some models project increases and other models project decreases, so confidence is low in the projected direction and magnitude of change in total annual precipitation across the NW.
- The intensity and form of precipitation (snow versus rain) are expected to change substantially (Chegwidden et al., 2020; Wrzesien & Pavelsky, 2020) with warming, and confidence is high in these changes.

In historically snow-dominated watersheds, a shift to more rain and less snow is the most prominent effect of climate change on the precipitation regime.

- The decreasing proportion of winter precipitation as snow relative to rain is expected to accelerate with more warming through the end of the century (Chegwidden et al., 2020; Clifton et al., 2018; Siirila-Woodburn et al., 2021).
- The elevation at which precipitation transitions from being primarily rain to primarily snow is expected to increase (Klos et al., 2014; Pepin et al., 2022).
- As a result of this change in precipitation form, the proportion of floods arising from rain rather than snowmelt is expected to increase, with middle and high elevation watersheds expected to have the largest increase (Chegwidden et al., 2020).

Climate change is affecting large-scale global climate patterns, changing the intensity, duration, and frequency of extreme hydrologic events.

- Climate change is expected to increase the frequency and intensity of hydrologic extremes (Warner et al. 2015, Tohver et al., 2014), such as extreme rainfall events, floods, and droughts.
- In the NW, extreme rainfall events tend to be associated with atmospheric rivers, which are anticipated to increase in magnitude and frequency with warming (Chen

et al., 2019; Gershunov et al., 2019; Payne et al., 2020). The degree to which atmospheric rivers produce flooding depends, in part, on the soil moisture conditions that precede these events (Cao et al., 2020).

- Changes in the occurrence of convective precipitation, which is the primary source of rain in summer in much of the NW, are difficult to project because of the complex factors in the land-atmosphere system that control their initiation, growth, and fate. Furthermore, their initiation is typically confined to areas much smaller than the resolution of climate models. Despite this, downscaled climate model projections of summer precipitation in the NW indicate a long-term drying trend (see Climate Overview).

CHANGING STREAMFLOW REGIMES

Changes in streamflow patterns in a given watershed depend on the hydrologic zone where the watershed is located (Chegwidden et al., 2020, ecoregion-specific hydrologic factsheets), and these zones have some distinct patterns of expected changes.

Expected shifts in precipitation form include increases in the frequency of rain-on-snow events in high-elevation areas and decreases in low-elevation areas, with implications for streamflow and flooding.

- Rain-on-snow (ROS) events¹ can cause rapid snowmelt, which increases runoff and depletes snow water storage. This reduces water availability later in the season. These ROS events can, but don't always, contribute substantially to extreme runoff and flooding that can adversely affect aquatic habitat (Li et al. 2019).
- The frequency and magnitude of ROS events are expected to *decrease* in *low-elevation areas* in the western NW with historically warmer winters (e.g. the maritime snow hydrologic zone) as snowpack declines and snow recedes to higher elevations (Musselman et al., 2018).
- The frequency and magnitude of ROS events are expected to *increase* in high-elevation areas that are currently above the snowline and have cold winters (e.g. the mediterranean hydrologic zone) because these areas will warm and not always be above the snowline in the future (Musselman et al., 2018), increasing the chance of ROS events.
- The elevation transition between areas where ROS events are projected to increase and where they are projected decrease is about 5,000 to 6,500 ft (Li et al., 2019).

¹ Rain-on Snow (ROS) events are when rain falls on preexisting snowpack and are defined as at least 3 mm of rain falling on a snowpack with at least 10 mm of snow water equivalent and snowmelt is one fifth of the total rain and snowmelt for that day (Fruehlinger et al 2014).

HYDROLOGY PROJECTIONS OVERVIEW

- ROS events, which are typically in fall and winter in the western NW and spring in the interior NW, are expected to shift earlier everywhere with warming (Li et al., 2019).

In snow-dominant basins, warming is expected to cause earlier snowmelt and higher evaporative demand in summer, with both changes contributing to lower streamflows in summer and a greater extent of intermittent streams.

- The extent of intermittent streams, those that have no flow at some time in the year, are expected to increase across the NW (Ward et al., 2020; Zipper et al., 2021).
- An increase in the number and duration of times with no flow will decrease connectivity of river networks (Ward et al., 2020), with implications for aquatic habitat (see Aquatic Overview).
- Changes in surface streamflow volume and timing will also affect groundwater (Brunner et al., 2021; Gullacher et al., 2023). For example, declining snowmelt and summer drying will lead to lower groundwater levels in summer.
- Earlier snowmelt is expected to reduce summer streamflow and increase water delivery curtailments during the irrigation season, potentially creating greater conflicts over water for out-of-stream uses and in-stream aquatic habitat (Musselman et al., 2021; Vano, 2020).

CHANGING CHARACTERISTICS OF DROUGHT

In the NW, drought is expected to increase in frequency, magnitude, and duration with a warming climate; however, the effects on ecosystems and natural resources will depend on the type of drought (Bumbaco et al., 2010; Crimmins et al. 2017).

Drought impacts will increasingly link across all sectors of land, water, and ecosystem management, requiring a coordinated response among agencies, stakeholders, and water rights holders to minimize conflict and negative impacts on people and ecosystems.

- Meteorological droughts (see Drought Definitions & Indicators), soil moisture droughts, and snow droughts (i.e., thinner and less expansive seasonal snowpacks) are becoming longer and more variable (Apurv & Cai, 2021; Zhang et al., 2021).
- Historically, snowpack conditions have been an important predictor of seasonal water availability, but with declining snowpack, it will be more difficult to predict drought and water availability in the following season (Livneh & Badger, 2020)
- Models project that lower streamflows in summer, earlier and lower peak streamflow in spring, and altered streamflow timing will increase the frequency and severity of snow and hydrological droughts (Kampf et al., 2021; Kovach et al., 2019; Safeeq et al., 2014).

HYDROLOGY PROJECTIONS OVERVIEW

- Increasing air temperatures are expected to increase atmospheric evaporative demand, which would enhance vegetation drying and water stress (i.e. ecological drought), as well as evaporation from reservoirs (Gorguner & Kavvas, 2020) (related to hydrological, agricultural, and socioeconomic drought).
- Changes in drought characteristics are happening against a backdrop of highly variable climate conditions historically across the NW (Cartwright et al., 2020).
- Ecosystems at high elevations, in drier climates, or with soils that have less capacity to hold water have the highest sensitivity to drought (Cartwright et al., 2020).
- A variety of drought indices exist; many are tailored for specific applications and may or may not be suitable in other contexts. For example, indices that integrate soil moisture, although developed for agricultural applications, may be appropriate for assessing and responding to ecosystem drought (Chatterjee et al., 2022)

BOX 1: OBSERVATIONAL SOURCES OF HYDROLOGIC DATA

Existing hydrologic monitoring networks provide useful data to quantify hydrological change, including snow water equivalent, soil moisture, groundwater and streamflow. However, these networks are insufficient to adequately characterize long-term trends and extreme events. Advances in modeling, remote sensing, and data assimilation may partly compensate.

SNOW TELemetry (SNOTEL)

SNOW TELemetry (SNOTEL) sites are located where measurement of precipitation and snow water equivalent are optimized for water supply forecasting and, therefore, may not be suitable for all hydrological applications (N. P. Molotch & Bales, 2005; Noah P. Molotch & Bales, 2006). Logistical considerations for installation, operation and maintenance of SNOTEL sites make significant expansion of the network unlikely (Fleming et al., 2023). However, innovations at the interface of observational technology, modeling, data fusion, and artificial intelligence/machine learning are providing options to improve monitoring of snow water storage and water supply forecasting (Broxton et al., 2024; Hedrick et al., 2018; Lahmers et al., 2022; Liu et al., 2023; Painter et al., 2016; White et al., 2022, 2023)

National Coordinated Soil Moisture Measurement Network (NCSMMN)

Several networks collect automated soil moisture measurements (e.g., SNOTEL, USDA AgriMet, etc.), but the specific criteria used to locate monitoring stations, the sensors used, the depths at which soil moisture is measured, and quality assessment/control protocols applied to the data differ by network and are not coordinated across the US or NW. A new effort, the National Coordinated Soil Moisture Measurement Network (NCSMMN, (Executive Committee of the National Coordinated Soil Moisture Monitoring Network, 2021)), seeks to engage management agencies, universities, and others to harmonize data from these networks and create value-added products.

USGS National Groundwater Monitoring Network

Groundwater observations are important for supporting climate adaptation, particularly for ecosystems dependent on groundwater. The USGS National Groundwater Monitoring Network is a portal for groundwater data and information from multiple federal agencies. This network encompasses 520 water-level network wells and 32 water-quality network wells across the NW. Of these sites, 242 are located in unconfined aquifers that are more sensitive to climate change (Subcommittee on Ground Water of the Advisory Committee on Water Information, 2013).

DROUGHT DEFINITIONS & INDICATORS

Although it is relatively well understood that drought corresponds to insufficient water, drought is difficult to define. NOAA's National Integrated Drought Information System acknowledges five types of drought: meteorological, hydrological, agricultural, socioeconomic and ecological drought (Svoboda & Fuchs, 2016). Understanding the different types of drought is important for determining the appropriate response to mitigate the impacts of drought on people, ecosystems and economies.

Meteorological: A prolonged duration of dry weather conditions which is defined based on regionally specific degree of dryness and duration of dry weather [Palmer Drought Severity Index & Standardized Precipitation Index].

Hydrological: Lower than normal streamflows, reservoir, or groundwater levels, often occurring after many months of meteorological drought. This type of drought is often defined at the watershed scale [Surface Water Supply Index].

Agricultural: When crops are negatively affected by low water conditions. This is often a combination of meteorological and hydrological drought which means that it could be caused by low precipitation, soil moisture deficits, higher rates of evapotranspiration, or low groundwater or reservoir levels. The degree of agricultural drought depends on plant growth stage and associated water requirements [Vegetation Health Index & Vegetation Drought Response Index, Standardized precipitation and Evapotranspiration Index (Stagge et al., 2014)].

Socioeconomic: When supply and demand of various goods and services are impacted by drought conditions.

Ecological: When a deficit in water availability, including associated water management activities, drives ecosystem responses beyond tolerable thresholds that adversely affect critical ecosystem functions and services (Crausbay et al., 2017; Kovach et al., 2019).

CHANGES IN WILDFIRE AND HYDROLOGIC SYSTEMS

The influences of climate change on wildfire activity and hydrologic systems are connected and can have compounding effects on terrestrial and aquatic ecosystems.

- Larger and more severe wildfires (see Forest Ecosystem Overview) are expected to affect streamflow in the NW. Wildfires can increase erosion, sedimentation, and the potential for flash flooding and debris flows. The loss of vegetation in wildfires decreases interception, transpiration and infiltration. Within the first decade after fire, burned watersheds generally experience an increase in annual runoff, peak streamflows, and low streamflows (Beyene et al., 2021; Niemeyer et al., 2020).

HYDROLOGY PROJECTIONS OVERVIEW

- Post-fire land management (e.g. aerial seeding and fertilizer) can accelerate post-fire vegetation recovery and the return the watershed to pre-fire streamflow patterns more quickly (Niemeyer et al., 2020).
- Post-fire extreme rainfall events are an example of a high-consequence compound climate event that is likely to occur more often in the future with more wildfire and heavier rainfall (Touma et al., 2022).
- The risk of post-fire extreme rainfall events is another factor to consider in the prioritization and co-benefits of fuel reduction treatments or other fire risk reduction activities (Srivastava et al., 2018).

AREAS FOR FUTURE RESEARCH

- Confidence is high that hydrologic systems in the NW will shift from historically snowy conditions to a low- to no-snow future. However, the *timing and rate* of this transition remains uncertain because of large interannual climatic variability and differences in the sensitivity of climate models to increases in atmospheric carbon dioxide (See Climate Overview). Whether this change will be gradual or more abrupt remains uncertain and is an active area of research.
- Given the large interannual hydrologic variability characteristic of the NW, it will remain difficult to separate long-term trends from short-term variation in precipitation, snow water equivalent, soil moisture, groundwater, and streamflow. As such, it will be important to develop tools, methods, and monitoring to better identify long-term trends and shifts in short-term variability.
- It remains difficult to identify sequences of co-occurring events (e.g., fires and precipitation events, etc.) that may yield extreme hydrologic events significant to resource managers.
- Understanding and predicting the potential consequences of compound climatic and hydrologic extremes with low likelihood but high consequence is an active area of research that has not yet yielded actionable insights. Compound extreme events, including the co-occurrence of multiple events that may or may not be independently extreme, are an increasingly recognized consequence of climate change globally and in the NW specifically ([Abatzoglou et al., 2021](#); [AghaKouchak et al., 2020](#); [Zscheischler et al., 2020](#)). Given the evolving science, it may be necessary to include emerging methods to incorporate multihazard extremes in analyzing the likelihood and impact of compound extreme events on the resilience of ecosystems.
- It is not well known how terrestrial ecosystems will mediate or exacerbate climate-driven changes in hydrologic systems. Terrestrial ecosystems and hydrologic systems will respond to climate change as an integrated system. Shifts in

HYDROLOGY PROJECTIONS OVERVIEW

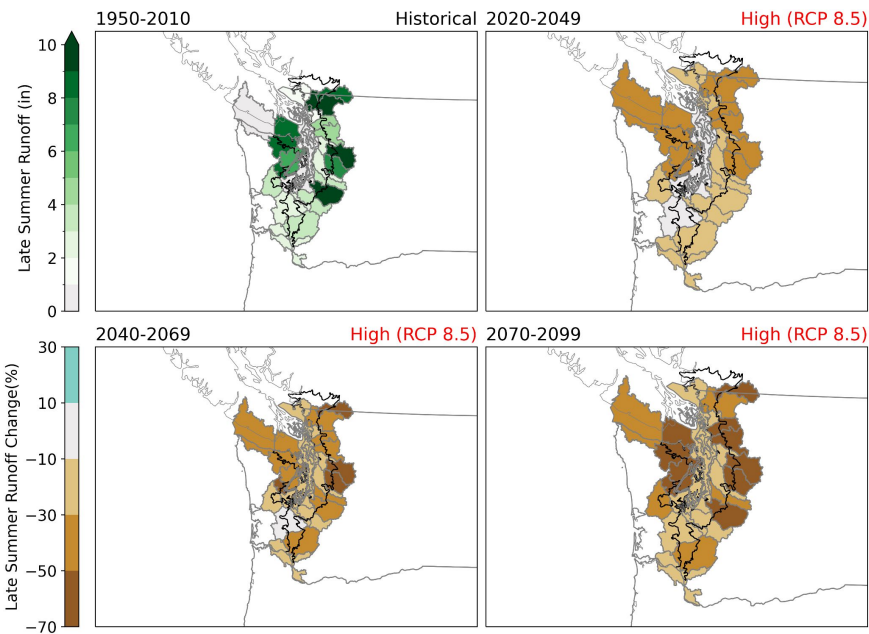
precipitation and snow water storage influence the assemblages and function of terrestrial vegetation in ways that influence hydrologic fluxes, particularly transpiration (plant water uptake) and infiltration (through expansion/contraction of root networks). A more thorough understanding of the changes in future hydrologic regimes requires a better understanding of future ecosystems and vice versa.

Puget Lowlands Hydrology Projections



Hydrology Description

The Puget Lowlands ecoregion is in a maritime hydrologic zone. This ecoregion receives abundant precipitation in winter that falls as rain. This generally leads to high winter streamflow and low streamflow in spring and summer, except for the streams that are fed by snowmelt from the Olympic and Cascade mountains.



Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of water available in the late summer dry period. Both spring snowmelt and summer precipitation contribute to late summer runoff. Climatic moisture deficit (CMD) is a measure of water stress for vegetation. *Increases* in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for the future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	1.8in (1.2 to 2.5)	1.7in (1.3 to 2.1)
2020-2049	High (RCP 8.5)	-90% (-95 to -88)	-11% (-32 to +2)
2040-2069	High (RCP 8.5)	-93% (-99 to -89)	-13% (-40 to +8)
2070-2099	Low (RCP 4.5)	-94% (-98 to -88)	-14% (-36 to +4)
2070-2099	High (RCP 8.5)	-97% (-100 to -94)	-19% (-39 to +1)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.42 inches
2011-2040	High (SSP585)	+17% (+10 to +41)
2041-2070	High (SSP585)	+33% (+23 to +72)
2071-2100	Low (SSP245)	+30% (+17 to +74)
2071-2100	High (SSP585)	+41% (+33 to +104)

Ecoregion Trends

April 1st Snow Water Equivalent (SWE)

Historical April 1st Snowpack in this ecoregion is confined mainly to foothills of the Cascades and Olympic Mountains. With future warming, seasonal snowpack is expected to melt earlier in the spring. By the end of the century, April 1st SWE is expected to decrease by 97% (range: -100 to -94) relative to 1950-2010, for a high (RCP 8.5) scenario.

Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase throughout the Puget Lowlands ecoregion, with greater increases at the lowest elevations. By the end of the century, CMD averaged for the ecoregion is projected to increase by as much as 41% (range: +33 to +104) relative to 1981-2010, for a high (SSP585) scenario.

Puget Lowlands Hydrology Projections



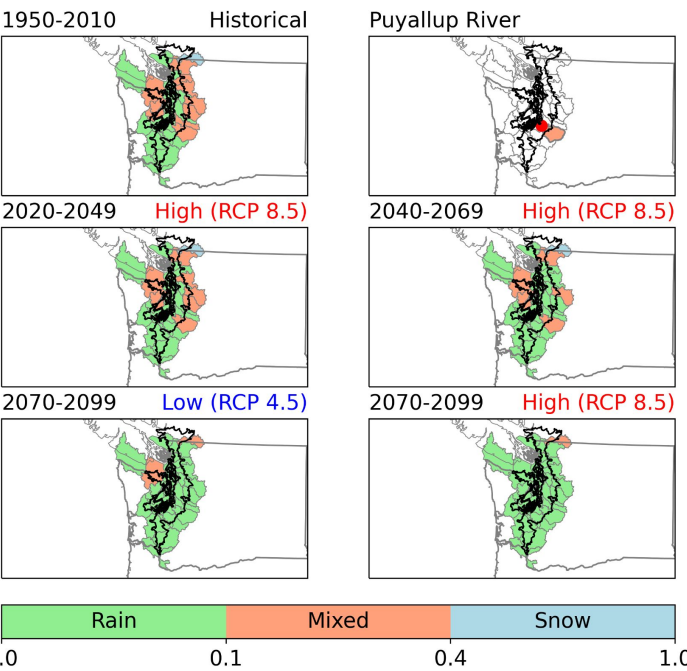
Ecoregion Trends

Watershed Classification

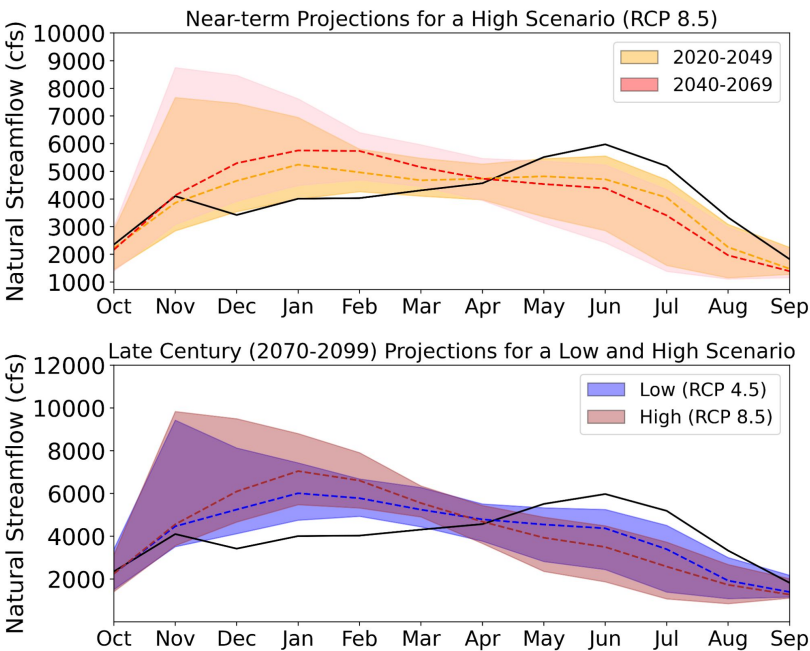
Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. Historically, watersheds in the Puget Lowlands have exhibited both mixed-rain-and-snow and rain-dominant patterns. In the future, more watersheds will exhibit rain-dominant streamflow patterns. More precipitation is expected to fall as rain during the wet season, leading to larger flows in winter, peak flows earlier in the spring, and lower flows in mid-to-late summer.

Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years in summer (June - Sept.), for the Puyallup River is projected to decrease by 28% (range: -39 to -20) by 2100 for a high (RCP 8.5) scenario, relative to 1981-2010. The 7Q2 is an indicator of water availability for aquatic habitat. Confidence is high in future projections because all models consistently project decreases.



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. The projections show a change to almost all rain-dominant watersheds by the end of the century. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Puyallup River.



Puyallup River Historical and Projected Future Monthly Streamflow: The timing of peak annual flow is projected to shift from early summer to mid-winter with a shift from a mixed-rain-snow to a rain-dominant hydrologic pattern. The black line is the simulated historical and dashed lines are the median hydrographs of 40 models. Shaded areas show the 10th and 90th percentile range. Projections are without withdrawals and regulation by dams.

Projections: Summer Low Flow

The table below shows projected model median change values in summer (June-Sept.) low flows at a location on the Puyallup River. Summer low streamflow for the Puyallup River is projected to steadily decrease throughout the century for both a high (RCP 8.5) and low (RCP 4.5) scenario. Summer low streamflow (7Q2) is an important indicator of water availability for aquatic habitat. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for three future periods.

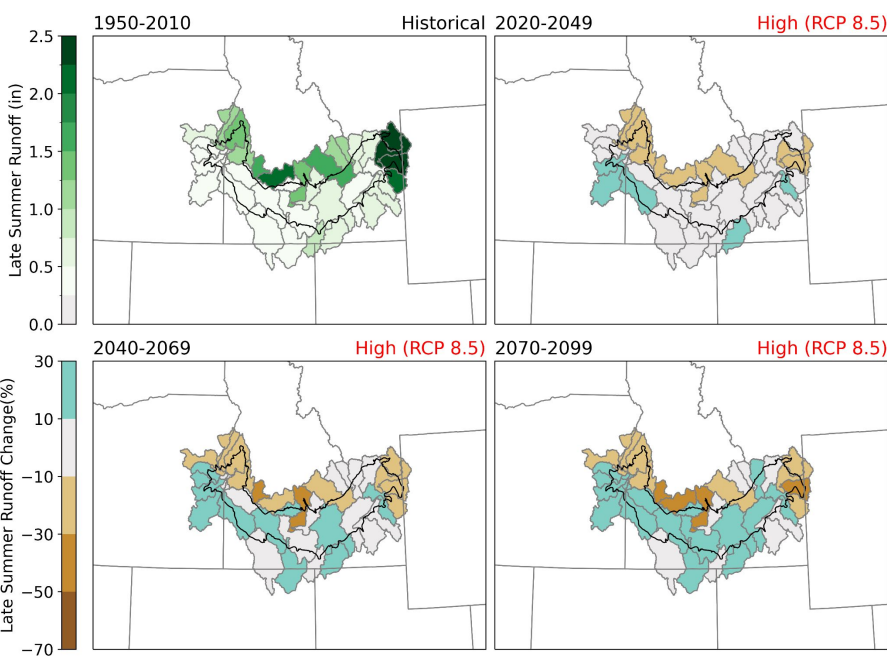
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	1242 cfs (697 to 1787)
2011-2040	High (RCP 8.5)	-19% (-28 to -2)
2041-2070	High (RCP 8.5)	-25% (-35 to -13)
2071-2100	Low (RCP 4.5)	-27% (-38 to -9)
2071-2100	High (RCP 8.5)	-28% (-39 to -20)

Snake River Plain Hydrology Projections



Hydrology Description

The Snake River Plain ecoregion is in a cold semi-arid and desert hydrologic zone. Winter snowpack in the northern sections of this ecoregion feed larger rivers during the early spring as temperatures warm and seasonal snow melts.



Late Summer (July-September) Runoff for a historical period and projected change for three future periods for a high (RCP 8.5) scenario. Some areas in the Snake River Plain ecoregion are projected to have increases in summer runoff and other areas are projected to have decreases. By the end of the century, late summer runoff is projected to increase by 19% (range: -23 to +116) relative to 1950-2010, for a high (RCP 8.5) scenario. Minimal historical late summer runoff means this region is highly sensitive to changes in late summer precipitation trends.

Ecoregion Trends

April 1st Snow Water Equivalent (SWE)
Snow in this ecoregion is primarily confined to winter months and snowpack melts earlier than April 1st. With warming, snow will still be present in winter months but will melt out before spring on average. Due to the minimal historical April 1st SWE, the historical and projected change values are not given.

Climatic Moisture Deficit (CMD)
As the climate warms, CMD is projected to increase everywhere in the Snake River Plain ecoregion, with slightly greater increases projected for the lowest elevations. By the end of the century, CMD for the ecoregion is projected to increase by about 26% (range: +21 to +31) relative to 1981-2010, for a high (SSP585) scenario.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The table below shows model median values of historical and projected change in April 1 snow water equivalent (SWE), late summer (July - Sept.) runoff, and climatic moisture deficit (CMD) for three future periods. April 1 SWE is an indicator of water stored in spring snowpack. Late summer runoff is an indicator of available water. Runoff in the southern Snake River Plain, which was high historically, is projected to decrease in the future. The areas that are expected to have slight increases in future runoff have small magnitudes historically. Increases in CMD indicate *less* water available for vegetation and *more* ecological drought. CMD is projected to increase throughout the Snake River Plain. Values in parenthesis are historical variability (standard deviation) and model range (maximum and minimum) for future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	In this ecoregion,	0.4in (0.3 to 0.6)
2020-2049	High (RCP 8.5)	April snowpack is minimal	+9% (-15 to +37)
2040-2069	High (RCP 8.5)	historically and is expected to be even more rare with future warming	+12% (-21 to +66)
2070-2099	Low (RCP 4.5)		+13% (-26 to +47)
2070-2099	High (RCP 8.5)		+19% (-23 to +116)
Years	Scenario	Climatic Moisture Deficit	
1981-2010	Historical	1.15 inches	
2011-2040	High (SSP585)	+9% (+6 to +12)	
2041-2070	High (SSP585)	+17% (+13 to +21)	
2071-2100	Low (SSP245)	+18% (+11 to +21)	
2071-2100	High (SSP585)	+26% (+21 to +31)	

Snake River Plain Hydrology Projections



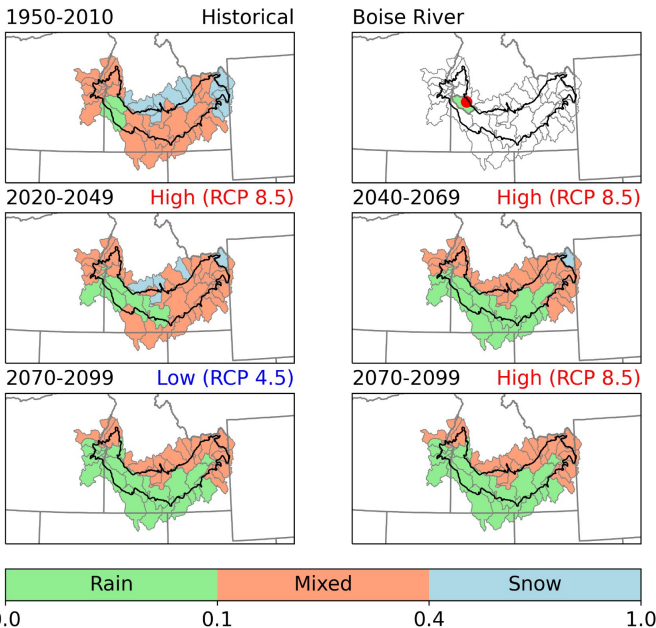
Ecoregion Trends

Watershed Classification

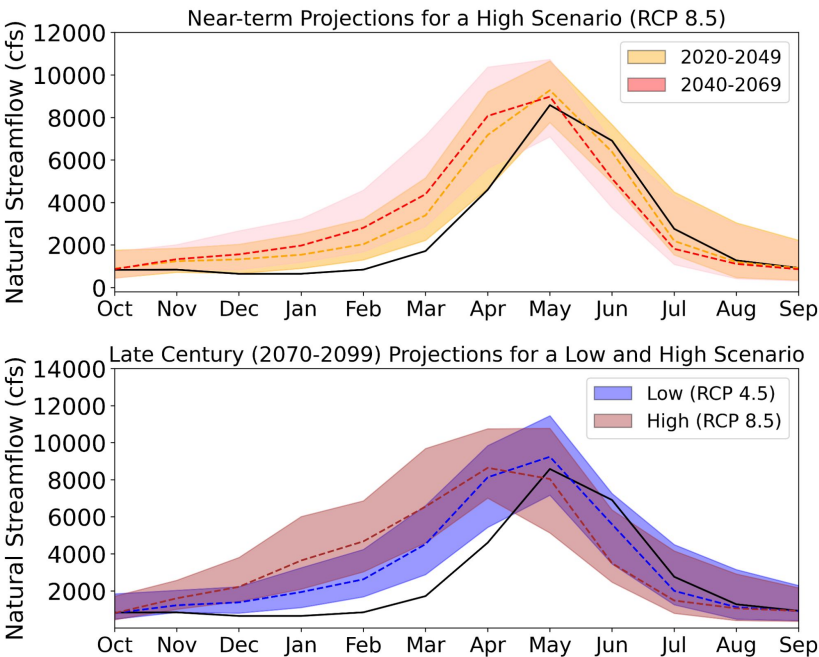
Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. For the Snake River Plain ecoregion, watersheds are expected to become more rain-dominant in the future, especially in the southern part of the ecoregion. More precipitation is expected to fall as rain rather than snow during the wet season in low and mid-elevations, leading to larger flows in winter and lower flows in spring and summer.

Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day flow that occurs on average every 2 years, for the Boise River is projected to decrease by about 5% (range: -25 to +14) by 2100 relative to 1981-2010 for a high (RCP 8.5) scenario. Summer 7Q2 streamflow is an important indicator of water availability for aquatic habitat.



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale, and shown for all basins that intersect the ecoregion. The ecoregion is expected to have a general shift from mixed-rain-snow behavior to more rain-dominant behavior in the future. The red dot in the upper-right map denotes the location of the monthly hydrographs on the Boise River.



Boise River Historical and Projected Future Monthly Streamflow: The timing of peak annual flow is expected to shift from late spring to early spring. The hydrograph shows a transition from a snow-dominant to a mixed-rain-and-snow watershed due to the influence of upstream snowmelt. The black line is the simulated historical hydrograph. Dashed lines are the median hydrographs of 40 models, and the shaded areas show the 10th and 90th percentile range of all projections. Streamflow projections are without withdrawals and regulation by dams.

Projections: Summer Low Flow

Summer (June-Sept.) low streamflow (7Q2) is an important indicator of water availability for aquatic habitat. The table below shows model median values for historical and projected change in summer low flows at a location on the Boise River. Confidence in the projected changes on the Boise River are low, as some models project increases and other models project decrease. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for the listed future periods.

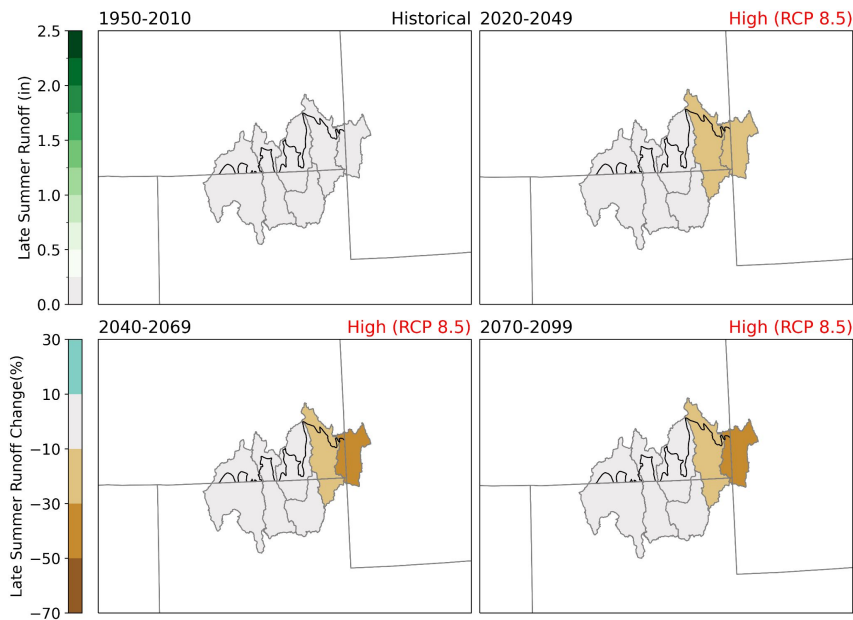
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	903 cfs (237 to 1568)
2011-2040	High (RCP 8.5)	-1% (-13 to +10)
2041-2070	High (RCP 8.5)	-9% (-26 to +6)
2071-2100	Low (RCP 4.5)	-4% (-24 to +9)
2071-2100	High (RCP 8.5)	-5% (-25 to +14)

Southeastern Idaho Hydrology Projections



Hydrology Description

Southeastern Idaho is in a cold semi-arid and desert hydrologic zone. This region receives little annual precipitation. Larger streams in this region are fed year-round by upstream rain and snowmelt. Smaller streams tend to run dry during the summer season when precipitation is minimal.



Historical and Projected Late Summer (July - Sept.) Runoff
Late summer runoff for the historical period and percent change for three future periods for a high (RCP 8.5) scenario, relative to 1950-2010. By the end of the century, late summer runoff in the Southeastern Idaho ecoregion is expected to decrease by 12% (range: -66 to +237) relative to 1950-2010, for a high (RCP 8.5) scenario. Confidence is low in these projections because all models do not project the same direction of change.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show values for projected model median change in late summer (July - Sept.) runoff and climatic moisture deficit (CMD) for three future periods. Late summer runoff is an indicator of available water during the dry season. CMD is a measure of moisture stress on vegetation. *Higher* values and increases in CMD indicate *less* water available for vegetation and *more* ecological drought. Both late summer runoff and CMD are projected to decrease for Southeast Idaho through the century. Values in parenthesis are historical variability (standard deviation) and the model range (maximum and minimum) for future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	In this ecoregion,	0.01in (0 to 0.01)
2020-2049	High (RCP 8.5)	April snowpack is minimal	-6% (-33 to +62)
2040-2069	High (RCP 8.5)	historically and is expected to	-12% (-43 to +114)
2070-2099	Low (RCP 4.5)	be even more rare with future	-6% (-46 to +69)
2070-2099	High (RCP 8.5)	warming	-12% (-66 to +237)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.8 inches
2011-2040	High (SSP585)	+14% (+11 to +17)
2041-2070	High (SSP585)	+23% (+14 to +27)
2071-2100	Low (SSP245)	+19% (+12 to +25)
2071-2100	High (SSP585)	+31% (+19 to +42)

Ecoregion Trends

April 1st Snow Water Equivalent (SWE)

Snow in this ecoregion is primarily confined to winter months and snowpack melts earlier than April 1st. With warming, snow will still be present in winter months but will melt out before springtime on average. Due to the minimal historical April 1st SWE, the historical and projected change values are not given.

Climatic Moisture Deficit (CMD)

As the climate warms, CMD is projected to increase everywhere in the Southwest Idaho ecoregion, with larger increases projected for the lowest elevations. By the end of the century, CMD for Southeast Idaho is projected to increase by as much as 31% (range: +19 to +42) relative to 1981-2010, for a high (SSP585) scenario.

Southeastern Idaho Hydrology Projections



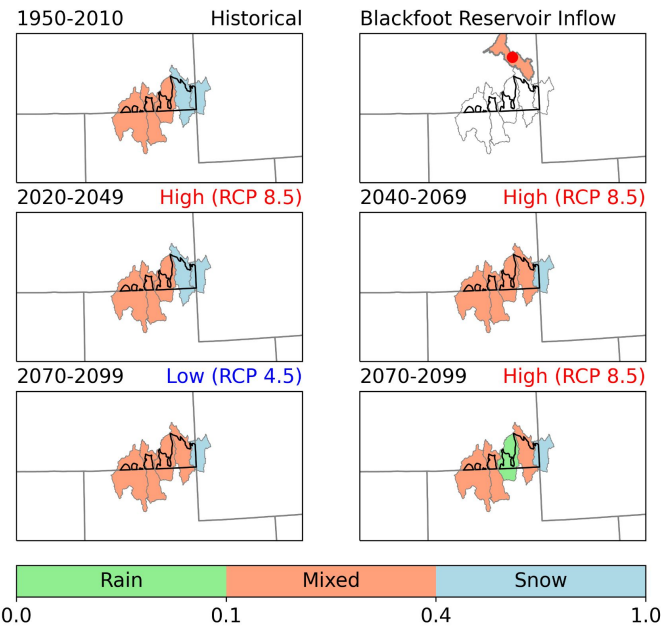
Ecoregion Trends

Watershed Classification

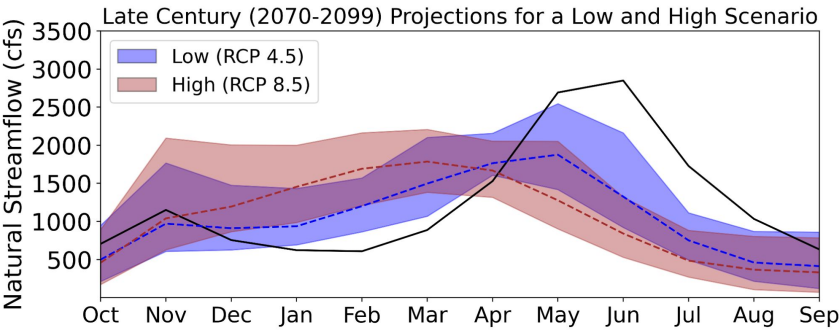
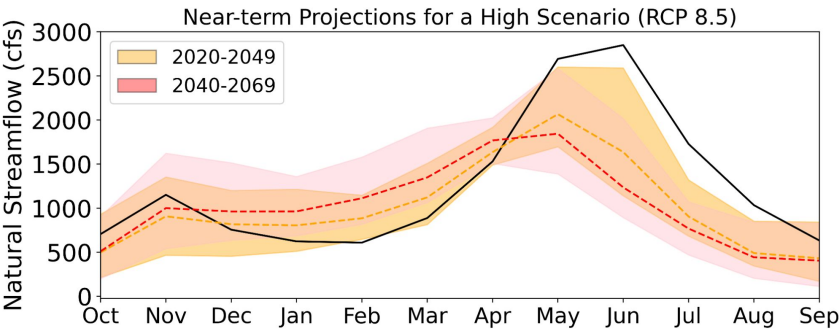
Watersheds in Southeastern Idaho have historically exhibited mixed-rain-and-snow streamflow patterns, but fewer watersheds will exhibit mixed streamflow patterns in the future. More precipitation during the wet season is expected to fall as rain, leading to larger flows in winter, peak flows earlier in spring, and lower flows in mid-to-late summer.

Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years, for the Blackfoot Reservoir inflow is projected to increase by 16% (range: -30 to +63) by the end of the century relative to 1981-2010, for a high (RCP 8.5) scenario. Confidence is low in projected decreases in summer low flows because some models project increases and others project a decrease. Summer 7Q2 is an important indicator of water availability for aquatic habitat.



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. Projections show a general change from mixed-rain-and-snow watersheds to more rain-dominant watersheds in the future. The red dot in the upper-right map denotes the location of the monthly hydrographs for the Blackfoot Reservoir Inflow, which is the closest streamflow site location.



Blackfoot Reservoir Inflow Historical and Projected Future

Monthly Streamflow: The timing of peak annual flow is expected to shift from summer to a more broad peak during spring. The black line is the simulated historical hydrograph. Dashed lines are the median hydrographs of 40 models, and the shaded areas show the 10th and 90th percentile range of all projections. Streamflow projections are without withdrawals and regulation by dams

Projections: Summer Low Flow

The table below shows projected model median change in summer (June-Sept.) low flows (7Q2) at the Blackfoot Reservoir Inflow. Summer low flows for the Blackfoot Reservoir Inflow are projected to increase throughout the century. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for the listed future periods.

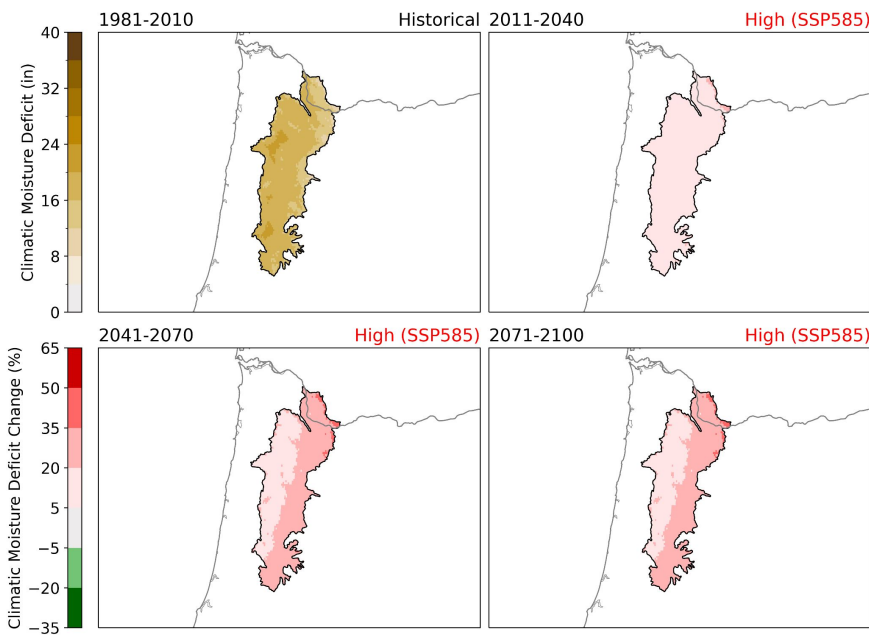
Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	81 cfs (18 to 143)
2011-2040	High (RCP 8.5)	+6% (-19 to +37)
2041-2070	High (RCP 8.5)	+3% (-31 to +54)
2071-2100	Low (RCP 4.5)	+2% (-32 to +37)
2071-2100	High (RCP 8.5)	+16% (-30 to +63)

Willamette Valley Hydrology Projections



Hydrology Description

The Willamette ecoregion is in a maritime snow hydrologic zone. Although this ecoregion does not receive much snow, streamflow patterns are heavily influenced by upstream snowmelt during the spring and early summer.



Climatic Moisture Deficit (CMD) for a historical period and projected change for three future periods for a high (RCP 8.5) scenario. CMD, an indicator of drought stress for plants, has been greater at lower elevations in the Willamette Valley historically. By end of the century, CMD averaged for the ecoregion is projected to increase by 51% (range: +23 to +54) relative to 1981-2010 for a high (SSP585) scenario.

Projections: Snow Water Equivalent, Late Summer Runoff and Climatic Moisture Deficit

The tables below show model median values for historical and projected change in late summer (July-Sept.) runoff and climatic moisture deficit (CMD) for three future periods. Due to the minimal April 1st SWE in this ecoregion, historical and projected change values are not shown. Late summer runoff is an indicator of available water during the dry season. In the Willamette Valley ecoregion, both spring snowpack from the Cascade mountains and summer precipitation contribute to spring and summer streamflow. CMD is a measure of moisture stress on vegetation. *Higher* values and increases in CMD indicate *less* water available for vegetation and *more* ecological drought. Values in parenthesis are historical variability (standard deviation) and model range (maximum and minimum) for future periods.

Years	Scenario	April 1 SWE	Late Summer (JAS) Runoff
1950-2010	Historical	In this ecoregion,	2.0in (1.5 to 2.4)
2020-2049	High (RCP 8.5)	April snowpack is minimal	-5% (-13 to +8)
2040-2069	High (RCP 8.5)	historically and is expected to	-4% (-22 to +12)
2070-2099	Low (RCP 4.5)	be even more rare with future	-4% (-17 to +10)
2070-2099	High (RCP 8.5)	warming	-7% (-17 to +15)

Years	Scenario	Climatic Moisture Deficit
1981-2010	Historical	0.67 inches
2011-2040	High (SSP585)	+12% (+9 to +23)
2041-2070	High (SSP585)	+21% (+14 to +40)
2071-2100	Low (SSP245)	+21% (+15 to +41)
2071-2100	High (SSP585)	+51% (+23 to +54)

Ecoregion Trends

Late Summer (July - September) Runoff

Late summer runoff is projected to decrease slightly through the century under both a low (RCP 4.5) and high (RCP 8.5) scenario. By the end of the century, late summer runoff in the Willamette Valley is projected to decrease by 7% (range: -17 to +15) for a high scenario, relative to 1950-2010. Confidence is low in the direction of these changes because some models project increases and some project decreases.

April 1 Snow Water Equivalent (SWE)

April 1 SWE is an indicator of water stored in spring snowpack. Snow in this ecoregion is primarily confined to winter months and snowpack melts earlier than April 1st. With warming, snow will continue to be present in winter but will melt out before April 1st on average.

Willamette Valley Hydrology Projections



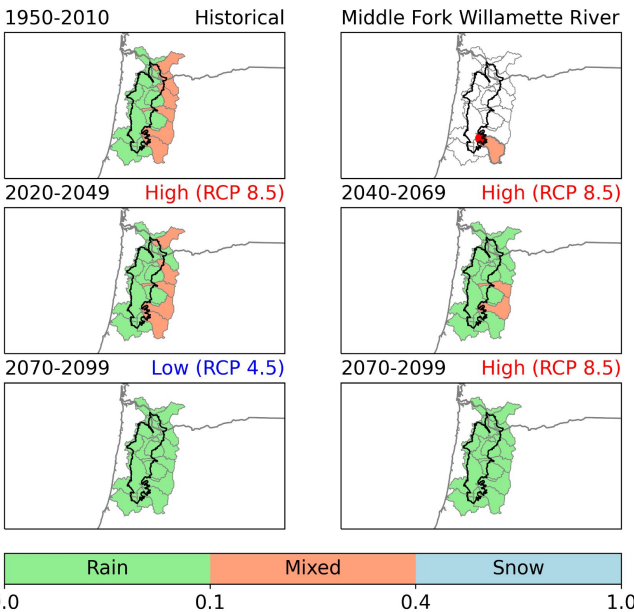
Ecoregion Trends

Watershed Classification

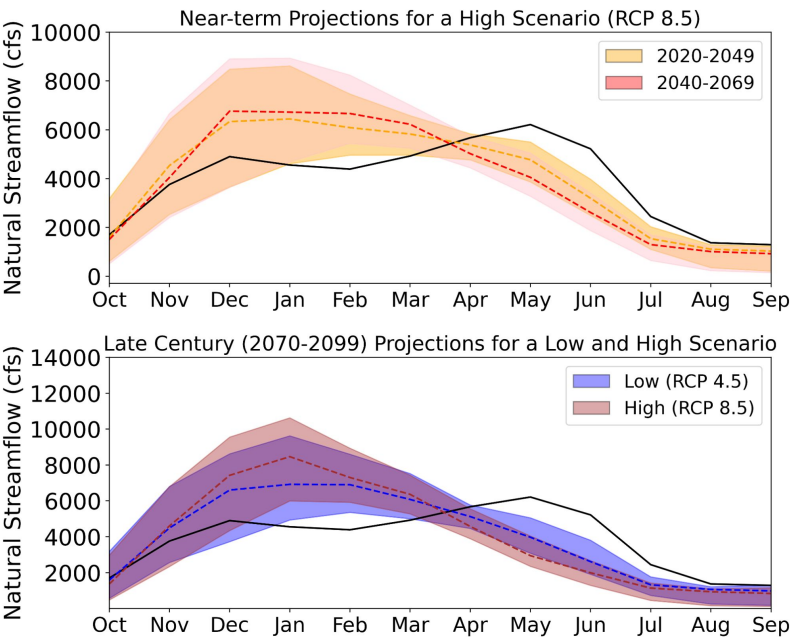
Watershed classification is an indicator of the most common form of precipitation in winter and the pattern of streamflow throughout the year. Watersheds in the Willamette Valley have historically exhibited a mixed-rain-and-snow pattern. In the future, fewer watersheds will exhibit this mixed pattern with all becoming rain-dominant. More precipitation as rain rather than snow in the Cascade foothills during the wet season is expected to increase streamflow in winter, shift peak flows earlier in spring, and decrease summer flows.

Summer Low Streamflow (7Q2)

Summer (June-Sept.) low streamflow (7Q2), the lowest 7-day average flow that occurs on average every 2 years, for the Willamette River is projected to decrease by about 31% (range: -71 to -11) by the end of the century relative to the 1981-2010, for a high (RCP 8.5) scenario. Summer 7Q2 is an indicator of water availability for aquatic habitat during the driest period. Confidence is high that summer low flows will decrease given that all models project decreases.



Watershed Classification: Ratio of peak annual snow water equivalent to total October-March precipitation. Data are summarized at the HUC8 basin scale and shown for all basins that intersect the ecoregion. The projections show a general change from a few mixed-rain-and-snow watersheds in the eastern foothills to all rain-dominant watersheds in the future. The red dot in the upper-right map denotes the location for the monthly hydrographs on the Willamette River.



Willamette River Historical and Projected Future Monthly Streamflow: The timing of peak annual flow is expected to shift from spring to the middle of winter. The black line is the simulated historical hydrograph. Dashed lines are the median hydrographs of 40 models, and the shaded areas show the 10th and 90th percentile range of all projections. Streamflow projections are without withdrawals and regulation by dams.

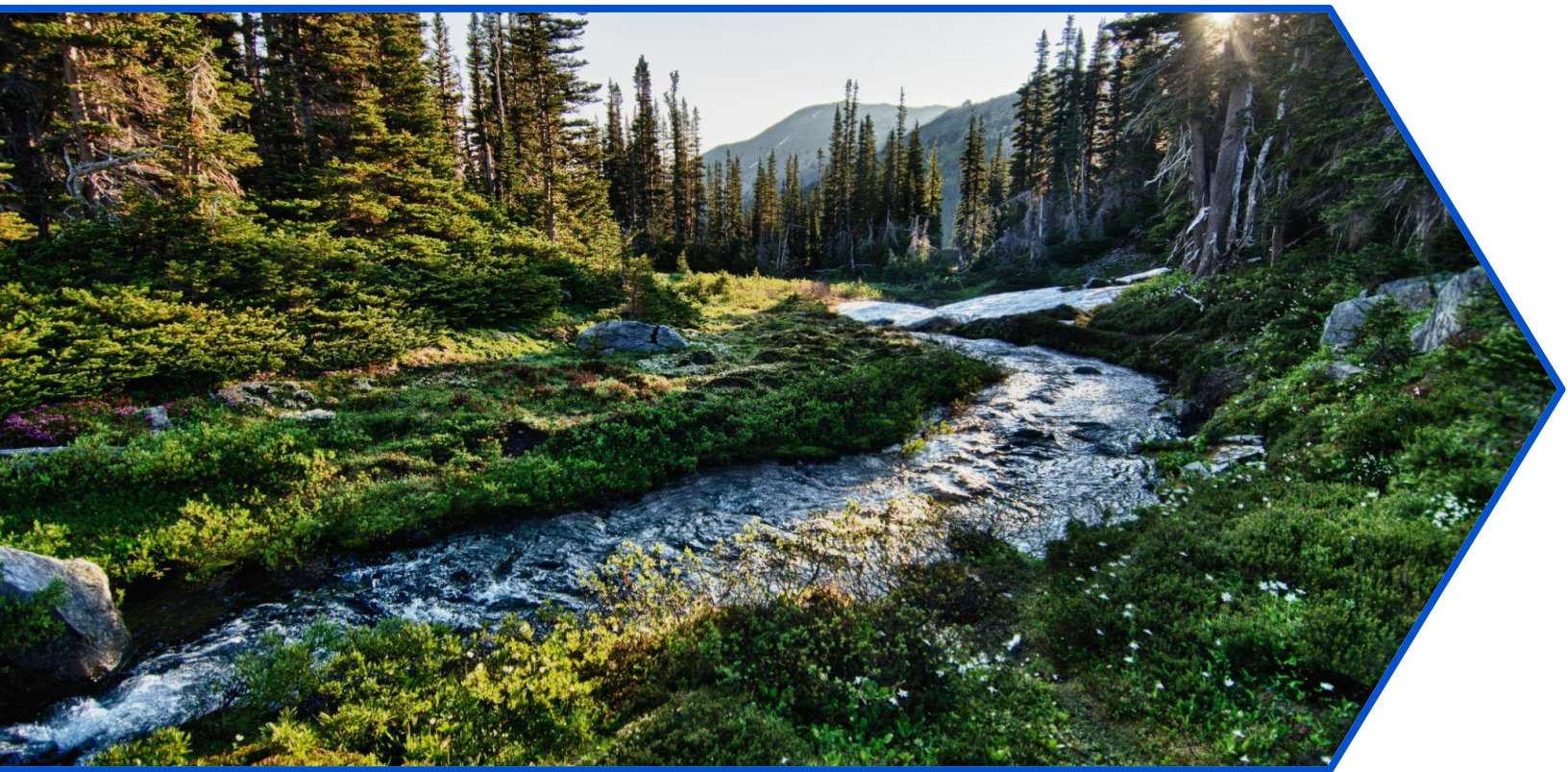
Projections: Summer Low Flow

The table below shows model median values of historical and projected change in summer low flows (7Q2) in cubic feet per second (cfs) at a location on the Willamette River. Summer low streamflow for the Willamette River is projected to decrease throughout the century for both a high (RCP 8.5) and low (RCP 4.5) scenario. Values in parenthesis are historical variability (standard deviation) and the model range (model 10th and 90th percentile) for three future periods.

Years	Scenario	Low Flow (7Q2)
1981-2010	Historical	737 cfs (416 to 1057)
2011-2040	High (RCP 8.5)	-14% (-49 to -5)
2041-2070	High (RCP 8.5)	-23% (-62 to -10)
2071-2100	Low (RCP 4.5)	-24% (-60 to -7)
2071-2100	High (RCP 8.5)	-31% (-71 to -11)

The State of Climate Adaptation Science for Ecosystems in the Northwest U.S.

AQUATIC ECOSYSTEMS



Recommended Citations by Section:

Alexander Fremier & Amanda Stahl (2024) Climate Effects for Aquatic Ecosystems: Overview. In: The State of Climate Adaptation Science for Ecosystems in the Northwest U.S. [Crystal L. Raymond & Emily J. Fusco eds.]

Amanda Stahl & Alexander Fremier (2024) Climate Effects for Aquatic Ecosystems: <Ecoregion> Fact Sheet. In: The State of Climate Adaptation Science for Ecosystems in the Northwest U.S. [Crystal L. Raymond & Emily J. Fusco eds.]

Amanda Stahl & Alexander Fremier (2024) Climate Adaptation for Aquatic Ecosystems. In: The State of Climate Adaptation Science for Ecosystems in the Northwest U.S. [Crystal L. Raymond & Emily J. Fusco eds.]

Photo: Forest River, Olympic National Park, Washington. Credit: Photo by Jachan DeVol on Unsplash

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AQUATIC ECOSYSTEM DESCRIPTION

Northwest (NW) aquatic ecosystems are diverse, ranging from coastal lowlands to inland alpine rivers, streams, lakes, reservoirs, wetlands, and associated riparian areas. Climate-driven stressors vary across regional elevation gradients and span maritime-to-continental precipitation and temperature patterns. NW ecoregions can be grouped into four zones to summarize climate-related stressors for aquatic ecosystems, while also considering major factors such as migration distance for salmon and human modification: Coastal Mountains and Lowlands, Inland Mountains, Continental Mountains, and High Inland Plateaus (Table 1, Figure 1). Conditions and ecological responses to climate and existing human stressors will vary by watershed and site location within each zone (Staudinger et al. 2021).

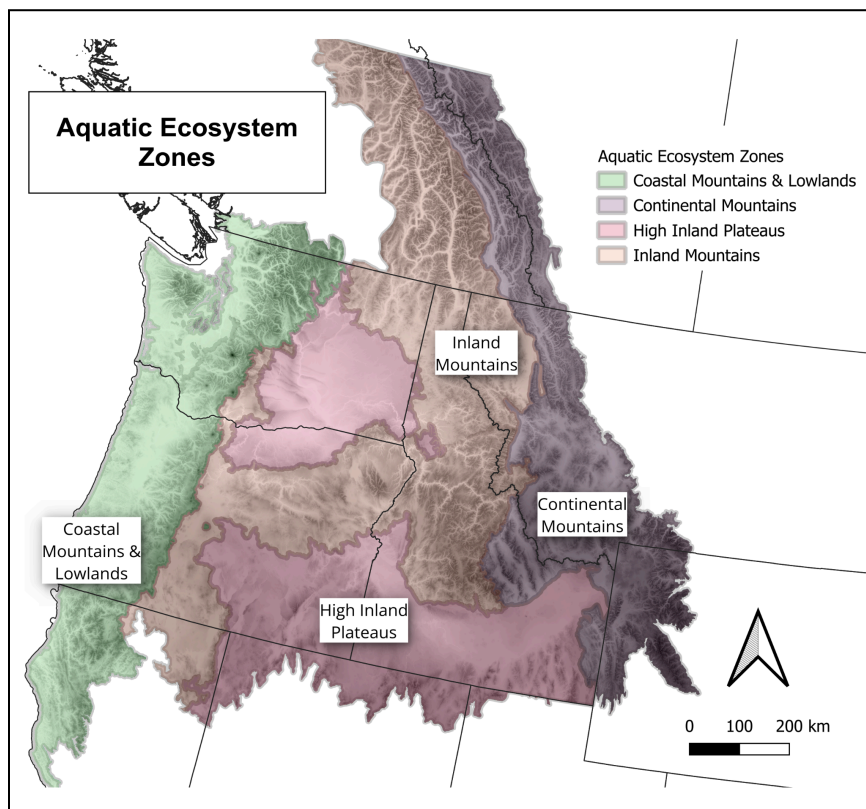


Figure 1. Groupings of Northwest ecoregions into four aquatic ecosystem zones. Data Source: Elevation data from Copernicus DEM, accessed in Google Earth Engine.

CLIMATE EFFECTS: AQUATIC ECOSYSTEMS OVERVIEW

Table 1. Northwest aquatic ecoregions grouped into four larger aquatic ecosystem zones. The ecoregions in each zone share key climate characteristics and stressors.

Aquatic ecosystem zone	Ecoregions - Level III	Description
Coastal Mountains and Lowlands	Coast Range, Puget Lowlands, Northern Cascades, Willamette Valley, Klamath Mtns., Cascades	These ecoregions have a strong maritime-influenced wet climate, span a wide range of elevations and have a similar geologic makeup. Increased temperatures over the next century will influence the rain-dominated flow regimes at low elevations and decreasing snowpack will influence snow-dominated regimes in all but the highest watersheds. Urbanization, dams, agriculture, and habitat alteration are the main existing human impacts.
Inland Mountains	Eastern Cascades, Blue Mtns., Northern Rockies, Idaho Batholith	These ecoregions include high-elevation areas that span a gradient of maritime to continental climates. Ranges here are drier (esp. summer) and colder than the Coastal Mountains, but still have more maritime influence than the Continental Mountains. Climate-altered flow regimes are shifting from snow- to more rain-dominated in the lower watersheds. Dams, habitat alteration, logging and grazing are the main existing human impacts.
Continental Mountains	Canadian Rockies, Middle Rockies	These ecoregions include high elevation areas with cold continental climates. Mountain ranges here are drier with a pronounced dry summer season and late snow melt. Climate-altered flow regimes are becoming less snow-dominated. Dams, habitat alteration, logging and grazing are the main existing human impacts. This zone has some of the best protected and well studied high mountain ecosystems in the region.
High Inland Plateaus	Southeast Idaho, Columbia Plateau, Snake River Plain, Northern Basin & Range	These ecoregions are high, relatively flat areas that collectively span a gradient of maritime to continental climates. These areas are drier than surrounding mountains and have a pronounced hot and dry summer season. Aquatic ecosystems rely on water generated upslope. Protected or natural areas are very limited in extent and are surrounded by lands under intensive agricultural use. Dams, agriculture, habitat alteration, and grazing are the main existing human impacts.

INTERACTION OF CLIMATE CHANGE AND ECOSYSTEM STRESSORS

Direct climate impacts on aquatic ecosystems include rising temperatures, elevated pCO_2 , increased UV radiation, altered flow regimes, and interactions among them (Perry et al. 2012; Hasler et al. 2016; Birrell et al. 2020; Rose et al. 2023). Temperature and precipitation intensity are expected to increase in the region, with declining summer precipitation (see Climate Projections Overview of this report). Gradual warming and extreme temperature events, particularly in spring and summer, will alter snow storage and stream flow magnitudes, as well as the timing, duration, and frequency of key events of aquatic ecosystems (see Hydrology Overview of this report). Elevated ambient temperatures will increase water temperatures, with specific thermal responses varying spatially depending on landscape characteristics, interactions with groundwater or meltwater, hydrologic connectivity, riparian shading, and degree of flow regulation (Isaak et al. 2020).

The complexity of indirect effects of changing temperature and precipitation in aquatic ecosystems are at the forefront of research (Figure 2; Rose et al. 2023). Researchers are building a mechanistic understanding of (1) how rising water temperatures influence ecosystem processes and organismal responses (e.g. Staudinger et al. 2021), (2) how watershed-scale processes, particularly wildfire, influence flow regime and water quality (e.g. Gordon et al. 2022), and (3) the interactive effects with existing ecological stressors on freshwater biodiversity (e.g. Reid et al. 2019). Aquatic organisms are particularly vulnerable to climate stress because they are dependent on thermal and flow regimes, with limited capacity to disperse (Woodward et al. 2010). The specific ecological response and scale of response vary from the genetic to ecosystem level (Woodward et al. 2010). Observed responses are now increasing in scope from shifts in individual behavior, physiology, population dynamics, phenology and range into larger-scale responses, such as evolutionary adaptation, complex interspecific interactions, and entire ecosystem change (Scheffers et al. 2016).

CLIMATE EFFECTS: AQUATIC ECOSYSTEMS OVERVIEW

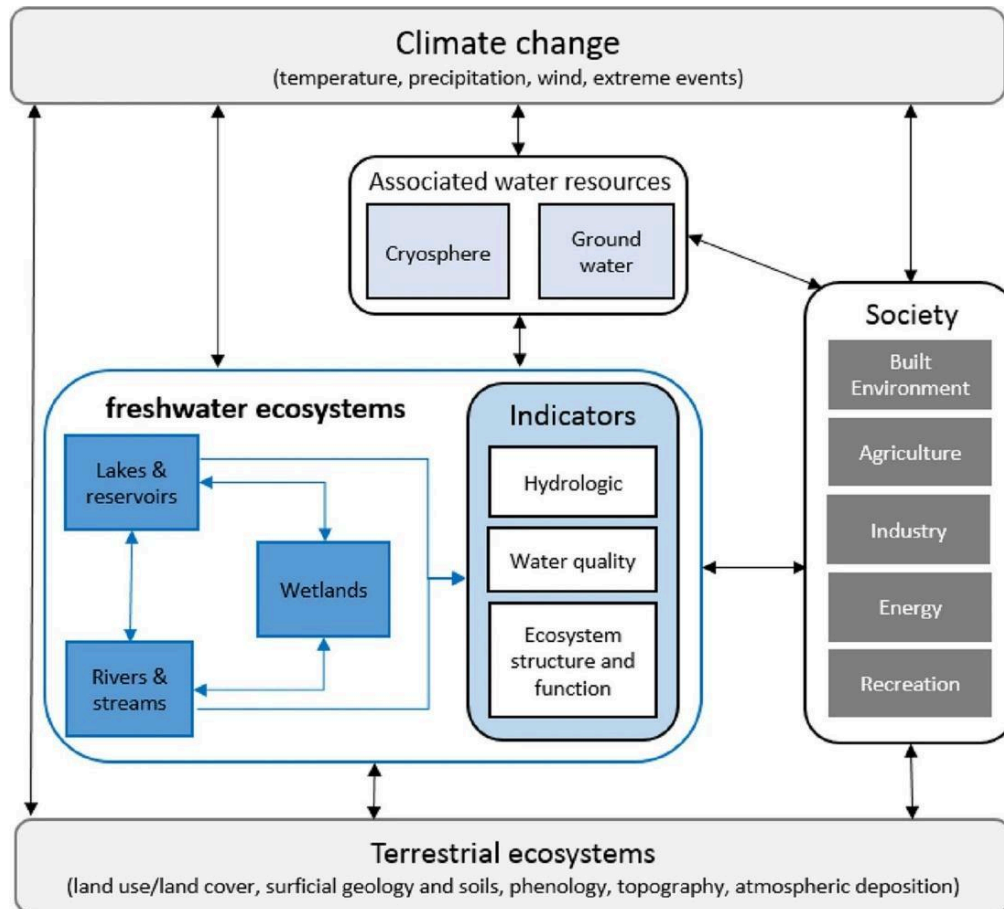


Figure 2. Stressors to aquatic ecosystems are shaped by the cumulative effects of direct (temperature, precipitation, etc.) and indirect (associated water resources and society, terrestrial ecosystem) climate impacts. Reprinted with permission from Rose et al. 2023.

RISING TEMPERATURES AND ALTERED FLOW EFFECTS ON ORGANISMS

Changes in thermal regime and flow regime

Climate change will alter both the flow and thermal regime of stream ecosystems, although thermal sensitivities vary with elevation (Isaak et al. 2017, 2020). Research continues to document the ecological impacts of flow alteration with increased sophistication, such as longer, lower summer low flows with snow-to-rain transitions and their impact on stream temperature regimes. This includes empirical and modeling studies to advance understanding of both the expected thermal shifts and potential ecosystem responses.

Aquatic and Semi-Terrestrial Vertebrates. Previous research shows that many vertebrate populations will be harmed by warming stream temperatures, increasing winter peak flows, and decreasing summer low flows (Mantua et al. 2010; Pound et al. 2021). In some areas, lower flows and warmer temperatures contribute to more extensive stream drying,

CLIMATE EFFECTS: AQUATIC ECOSYSTEMS OVERVIEW

which decreases aquatic habitat area and connectivity (Ward et al. 2020). Wetlands, riparian areas, and the amphibians dependent on them are particularly vulnerable to warmer winters and longer, drier summers (Kissel et al. 2019). The specific impact of climate change across the NW depends on species functional or life-history traits that interact with watershed characteristics. New research highlights the specific relationships between climate stressors and organisms' or populations' responses.

Aquatic invertebrates. Aquatic insects are sentinels of climate change (Birrell et al. 2020). High elevation insect populations are at high risk (Giersch et al. 2017; Hotaling et al. 2017); yet, some cold-water taxa have shown more resilience to warming than expected (Muhlfeld et al. 2020; Hotaling et al. 2020) and icy seeps may persist as cold-water refugia (Tronstad et al. 2020). At a given site, climate impacts to aquatic insects will depend on their sensitivity to individual or cumulative effects of warming.

Resilience to climate change varies among species and depends on the current conditions. Aquatic species have adapted with an array of strategies for surviving in dynamic environments. Recent research highlights species' unexpected and complex responses to climate-related change.

- Species distributional expansions outpaced contractions across 23 aquatic vertebrate taxa with a homogenization of these communities in response to multiple environmental variables (Elliott et al. 2022).
- Tailed frogs and sculpin showed more climate impacts than two salmon species over a similar time period (Hossack et al. 2023), marking the importance of considering multiple species in conservation planning (Wang et al. 2020), particularly, habitat connectivity's role in species' survival (LeMoine et al. 2020).
- Some coldwater taxa (bulltrout, cutthroat trout, rocky mountain tailed frog) might be buffered from increasing ambient temperatures, if high elevation streams less sensitive to increasing air temperatures can serve as refugia (Isaak & Luce 2023).

Functional traits indicate climate responses by salmon and other fish. Considering the ways organisms use their environment for survival helps in assessing climate impacts and adaptation strategies. Some life stages will experience direct climate impacts, while others may be indirectly impacted through changes to habitat and/or the food web.

- Salmon and other fish (cutthroat trout, bull trout, dace, sculpin) are thermally sensitive and shift migration patterns (phenology and range) in response to environmental change (Lee et al. 2020; Wilson et al. 2023). Shifts are *not* consistent across either species or populations (Elliott et al. 2022). Drivers of phenological change can include changes in temperature across seasons, habitat, population density, and flow conditions (Sorel et al. 2023).
- Within a population, climate change impacts can differ by life stage/event and can be complex. Examples include a negative impact on spawning but limited or even positive impact on rearing (Reeder et al. 2021). Prespawn mortality is of concern in

CLIMATE EFFECTS: AQUATIC ECOSYSTEMS OVERVIEW

spring spawning populations as warming continues (Bowerman et al. 2021), particularly in female salmon (Hinch et al. 2021).

- Diverse age structure in salmon populations may be more resilient to climate change by diversifying migration timing across years, even for populations within the same basin (Nicol et al. 2022). Additionally, natural-origin Chinook are spawning later in warming rivers but hatchery fish earlier, influencing adaptation to warming waters (Austin et al. 2021).
- Ocean temperatures and productivity interact with freshwater conditions over the salmon life cycle. Salmon populations are expected to decline during the marine stages due to warming seas (Crozier et al. 2021). Observed phenological shifts have not correlated with environmental or geographic patterns, and importantly, have not tracked ocean productivity, which might lead to mismatches in ocean arrival and food production (Wilson et al. 2023).
- Salmonids' options/access to food sources may diminish with homogenization of flow regimes (Bellmore et al. 2022). Different feeding strategies across fish will be impacted differently based on the food sources – terrestrial versus aquatic (Benjamin et al. 2022). Increases in secondary productivity (stream macroinvertebrates) could offset the loss of other food sources, but could have other implications for diversity and resilience (Dunkle et al. 2024).
- Adaptation is limited by usable habitat area and connectivity, which can be reduced by decreased flows due to snow loss (Tonina et al. 2022), stream drying and habitat loss (Ward et al. 2020), or flow regime changes that affect habitat characteristics for key life stages, such as spawning and incubation (bull trout) (Kaeding & Mogen 2023).

The effects of warming on hydrologic regimes are expected to have a greater effect than direct exposure to higher temperatures. Reduced snowpack, retreating glaciers, lower summer flows, and altered meltwater volume and timing can have multivariate effects on insect performance and species composition. Organisms respond not only to temperature changes but also to temperature-associated changes such as lower dissolved oxygen concentrations and ionic toxicity (Orr & Buchwalter 2020; Jacobsen 2020).

- Driving mechanisms of climate impacts to aquatic insects are intertwined. For example, reduced habitat area due to lower water levels alters connectivity (Giersch et al. 2017), lower water levels compound temperature increases and fewer snow cover days can lead to increased UV-B exposure (Birrell et al. 2020).
- Warmer waters have lower capacity for dissolved oxygen and lead to increased rates of metabolism. Metabolic oxygen demand thus increases with temperature. Oxygen depletion can alter insects' physiology or exceed tolerances, potentially causing range shifts to higher elevations with warming (Jacobsen 2020).
- Increases in temperature can drive ion transport increases which can make water toxic to aquatic organisms (Orr & Buchwalter 2020). This impact is likely

compounded by higher salinity of freshwaters due to human impacts, such as fracking, road de-icing, etc.

Climate stress produces a range of biological responses. The diversity of ways insects survive in changing environments provides valuable insight into the complexity of predicting ecosystem response to climate change. The cumulative effect on organisms varies across levels of biological organization, including impacts on species distributions, decoupled interspecific interactions, and survival at specific life stages.

- To understand either stressors or organismal responses, it is necessary to define the scope and importance of potential responses across levels of biological organization (Birrell et al. 2020) and the timing of life-history stages or cues in relation to climate stressors (Finn et al. 2022).
- Insect phenology is affected by climate change in complex ways (including biotic interactions) that vary by population or species and timeframe, influencing lab study design and modeling assumptions (Finn et al. 2022).
- Cold-sensitive taxa may tolerate higher temperatures than expected (Muhlfeld et al. 2020) but can become more susceptible to biotic interactions such as competition with other taxa that are expanding their ranges into former coldwater habitats (Hotaling et al. 2020). However, the sensitivity to thermal stress might be better understood by long rather than peak exposures. For example, the threatened meltwater stonefly (*Lednia tumana*) shows resilience to short term peak temperatures (Hotaling et al. 2020) but sensitivity to longer chronic exposures across life stages, illustrating a complex multi-trait response to climate change (Shah et al. 2023).
- Wetland macroinvertebrates show sensitivity to temperature and precipitation, particularly in warm-dry wetlands where entire families of insects are at risk (Epele et al. 2022).

Climate impacts to riparian and wetland vegetation are both direct and indirect, such as altered flow regimes, drier soil conditions, and increased atmospheric CO₂ (Perry et al. 2012). Changing climate conditions induce plant heat and water stress, reduce biomass and increase seedling mortality, alter phenology and range shifts, and disrupt interspecific interactions (Garssen et al. 2014). Compositional changes are varied but generally favor more drought-tolerant species, reduce habitat quality for animals, and alter numerous ecosystem functions (Perry et al. 2012).

- Mountain streams fed by meltwater are becoming homogenized with warming due to the loss of high-disturbance events associated with melting ice or snow. Resulting changes to the form and dynamics of the stream channel and floodplain may trigger shifts in riparian community composition to fewer shrubs and more herbaceous species (McKernan et al. 2018).
- Peak streamflow events from snowmelt are shifting earlier with warming, decoupling phenological stages, such as seed release from peak flows and reducing

seedling recruitment (Perry et al. 2020). At a regional scale, such decoupling could cause major shifts in the composition of early successional species.

- As summer droughts become longer and more frequent, highly drought-stressed, ephemeral riparian and wetland areas are projected to disappear; others will become drier (Garssen et al. 2014), causing shifts in species composition (Stromberg et al. 2017; Dwire et al. 2018). Vegetation communities are expected to generally shift in composition to more upland and later serial species (Perry et al. 2012).

EXTREME EVENTS

Studies of climate impacts on ecosystems commonly focus on long term averages of directional change, rather than short-duration extremes (Adrian et al. 2012; Nadeau et al. 2017). Research is emerging on the potential impact of discrete, short-duration peak events on ecosystems, particularly organisms.

- Peak discharge increases are expected throughout the NW with contrasting longitudinal patterns of increases in west-side versus east-side basins (Queen et al. 2021). Both the magnitude and timing of hydrological events have implications for aquatic organisms.
- Predators can buffer the destabilizing impacts of extreme heat events in aquatic communities (Ross et al. 2022). This suggests conserving trophic structure can foster ecological resilience surrounding extreme events.
- Flow regime and water temperature of neighboring streams show contrasting hydrologic response to glacier melting caused by heat waves (Pelto et al. 2022). Aquatic communities might be buffered by the effects of short-term glacier melting (higher discharges and lower temperature increases).
- Time step influences the degree of impact in life-cycle models of coho salmon (Bellmore et al. 2023). Models of climate impact that do not represent extreme events might inadvertently minimize stressors on aquatic ecosystems.

ELEVATED CARBON DIOXIDE

Riparian and aquatic responses to rising CO₂ are not straightforward, reflecting the complexity of disentangling ecosystem responses to multiple climate drivers and cascading impacts.

- In riparian ecosystems, elevated atmospheric CO₂ will likely stimulate photosynthesis, growth and water use efficiency. Yet, drier floodplain conditions might offset gains in plant productivity (Frelich & Reich 2010; Perry et al. 2012).
- Aquatic ecosystems have *not* shown consistent changes in dissolved CO₂ (pCO₂), altered ecosystem function nor organismal responses (Hasler et al. 2016, 2018; Toavs et al. 2023). Documented ecological impacts include altered stoichiometry (Urabe et al. 2003), nutritional quality, plankton community structure, photosynthesis, macrophyte distribution (Hasler et al. 2016; Reitsema et al. 2020),

freshwater mussels (Jeffrey et al. 2018), to fish (Ou et al. 2015; Treanor et al. 2020), as well as studies showing no impact (Traynor et al. 2023).

CHANGING FIRE REGIMES

More frequent and severe wildfires in the Northwest (Abatzoglou & Williams 2016) are causing multiple effects on aquatic and riparian ecosystems.

- Stressors range from the direct damage or removal of riparian vegetation by wildfires to long-term post-fire watershed conditions that alter water quality and quantity. More severe fires may be more impactful on aquatic/riparian ecosystems in the future (Minshall et al. 2001; Jager et al. 2021) because removal of riparian vegetation negatively impacts both riparian and aquatic habitat. Loss of riparian vegetation reduces shading effects on streams, making water more susceptible to warming (Koontz et al. 2018; Warren et al. 2022).
- Although the moisture in riparian ecosystems can increase their resilience to direct impacts of fire compared to neighboring uplands (Jager et al. 2021), the indirect impacts of wildfires in the watershed can threaten water quality and supply and thus aquatic/riparian habitat and ecosystem services (Robinne et al. 2020, 2021).
- Changing fire regimes cause changes in upland vegetative cover and exposed soil, which can rapidly alter hydrology as well as pathways of sediment and nutrients (such as nitrogen) entering aquatic systems (Gustine et al. 2022). Excess nitrogen in post-fire runoff pollutes water bodies and can deprive upslope soils of nutrients that would be needed for vegetative regrowth, potentially inhibiting post-fire recovery and prolonging effects on aquatic ecosystems. Initial results from intermittent streams suggest that we have an incomplete understanding of the effect of fire on stream water chemistry (MacNeille et al. 2020).
- Wildfire impacts are affecting aquatic and semi-terrestrial species' distributions and assemblages, although the impacts can be species specific (Pilliod et al. 2022)

CLIMATE IMPACTS ON LAKES AND ECOSYSTEM PROCESSES

Ongoing climate warming can alter the transport and processing of key nutrients (carbon, oxygen, nitrogen, etc.) in watersheds and freshwater ecosystems. Altered nutrient processing will impact the basal resources in aquatic food webs. Lake research provides key insights for climate impacts on freshwater processes.

- Warmer climates are expected to alter the timing of lake stratification in northern hemisphere lakes (Woolway et al. 2021). An approximately 1-month-longer period of stratification per year will lead to accelerated deoxygenation, which can impact nutrient mineralization, phosphorus release from sediments and potentially decouple basal resource production from organismal phenologies.
- Lakes receive the bulk of their carbon budget from terrestrial sources. Warming climates can impact the hydrological connectivity between the two ecosystems and either increase ('lake browning') or decrease basal carbon delivery to lake ecosystems depending on environmental context (Johnston et al. 2020). Decreases

in lake transparency from deglaciation (increase in organic carbon) can have similar ecosystem impacts (Olson et al. 2018). Altered carbon cycling can have large ecosystem-level ramifications, such as effects to heat transfers between Earth and atmosphere, photochemical reactions in water, phytoplankton productivity, and entire ecosystem functioning.

- Warming waters and increases in nutrient fluxes have already increased the scale of harmful algal blooms globally, although some climate signals are weakened by interactions with management gains (Ho et al. 2019). Recent evidence suggests that cyanobacteria blooms can also occur in cold water, muddying a simple climate prediction of more algal blooms in persistently warm reservoirs (Reinl et al. 2023).

CUMULATIVE EFFECTS OF CLIMATE AND EXISTING STRESSORS

Climate impacts can be buffered or compounded with existing anthropogenic stressors, such as flow alteration, land-use change, and invasive species (e.g., Comte et al. 2021). Attributing ecological change to climate drivers and recommending management actions requires considering the interaction of multiple ecological stressors.

Warming conditions compound existing impacts on fish. Warming waters can induce physiological stress or habitat loss, trigger phenological or range shifts in coldwater adapted species, and may cause increasing interactions with warm water adapted invasive species such as smallmouth bass.

- Smallmouth bass populations are expected to increasingly overlap with critical habitat of multiple native salmon and trout species which will continue to limit conservation and recovery efforts of endangered salmonid species (Rubenson & Olden 2020; Winkowski et al. 2024).
- Cutthroat trout are likely to be impacted both by warming and related biotic interactions (Heinle et al. 2021). Shifts in emergence and outmigration timing of Chinook salmon will experience different predation by pressures from largemouth bass under warmer conditions (Hawkins et al. 2020).

Multiple climate drivers and existing management influence riparian vegetation. Riparian vegetation is adapted to variability in changing atmospheric and stream flow conditions. Riparian vegetation in the NW is heavily impacted by flow regulation, grazing, and clearing.

- Large dams can remove the climate signature of downstream flow regimes, thereby decoupling atmospheric and shallow groundwater elevations on floodplains. Riparian vegetation on regulated floodplains is buffered from drought with elevated groundwater, yet their natural resilience is undermined by relaxing the hydrological variation they are adapted to (Rohde et al. 2021).
- Livestock grazing can create drier wetland and riparian conditions, and shift species assemblages (Kauffman et al. 2022). Removal of riparian grazing can reduce the climate impact of drying floodplain conditions.

Studies increasingly analyze climate impacts in relation to anthropogenic alterations, such as reservoir management, hydrological response to wildfire and timber management, and mining. Environmental management increasingly needs to address both current and future ecological issues.

- Drought conditions are likely to increase reservoir drawdown frequency and magnitude. Increased reservoir drawdowns reduce kokanee habitat (McLaren et al. 2023).
- Salmon redd locations and egg survival are affected by warming waters or scour depth during high-flow events; yet, in some areas the impacts of events such as wildfire supersede more direct climate impacts (Jacobs et al. 2021).
- Patterns of timber harvest and subsequent forest regeneration over time affect low flows, which can compound or mitigate climate-driven low flows (Coble et al. 2020).
- Mineral mining across western North America impacts salmon populations (Sergeant et al. 2022). Environmental assessments of mining and other stressors do not traditionally incorporate dynamic climate conditions.

AREAS FOR FUTURE RESEARCH

Climate impact research continues to deepen our understanding of ongoing and future ecosystem change related to a complex mix of drivers and responses across biological levels of organization.

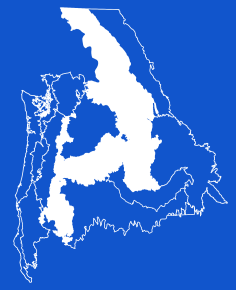
- While climate change is at the forefront of the research agenda, most ecological studies in the NW are either motivated by climate change or report potential implications, with only a smaller subset of studies with study designs to quantify climate impacts. Most of these are laboratory or modeling studies, leaving a gap in observation of the complex ecological responses of climate change, spanning the levels of ecological organization. Empirical studies are necessary to build a complete understanding along with lab and modeling results.
- Long-term datasets of climate drivers are fundamental, such as water temperatures (Isaak et al. 2017). But so are long-term monitoring datasets of ecological responses, including datasets across taxa, elevation, and location.
- Most studies consider gradual shifts in temperature and climate (press disturbances) with fewer studies examining the impacts of extreme events (pulse disturbances). Extreme events may be most critical in determining the future of aquatic and riparian ecosystems.
- Most studies on riparian vegetation in the NW focused on riparian management and not on climate impacts. There are many studies of riparian shading on streams and climate impacts to riparian areas outside the NW, but a limited number focus specifically on riparia.
- Studies of innovative solutions require scientific focus before broad application. Some include restorative aquaculture (Overton et al. 2023), riparian restoration (Beechie et al. 2023), beaver reintroduction (Dittbrenner et al. 2022), highlighting

CLIMATE EFFECTS: AQUATIC ECOSYSTEMS OVERVIEW

coldwater refugia (Mejia et al. 2023), and changing restoration design strategies for ecological resilience (Tullos et al. 2021).

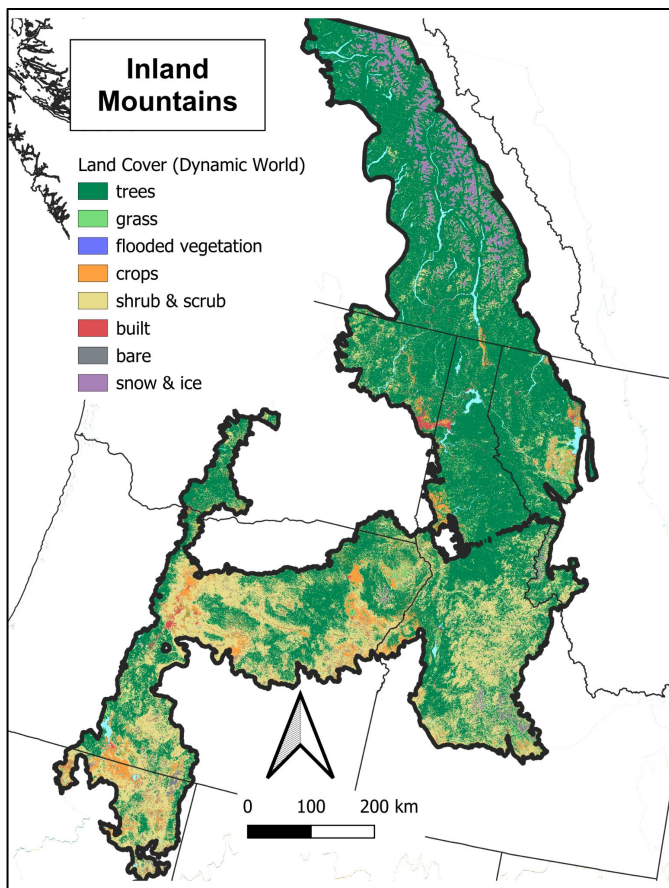
- The physiological tolerances of organisms to change across life stage provides important insights in the species response and to causal mechanisms; yet, these types of studies are limited to a few numbers of taxa, namely alpine insects.
- Separating climate from existing anthropogenic impacts requires specific knowledge of causal mechanism and place. More studies addressing the buffering or compounding interactions among stressors will likely help managers make climate-advised decisions to foster ecological resilience.

Blue Mountains, Eastern Cascades, Northern Rockies, Idaho Batholith Aquatic Ecosystems



Regional Description

The ecoregions listed above have been combined and renamed “Inland Mountains”. They include dry, forested uplands with dry grassland or shrub/scrub in the lowlands. Aquatic and riparian ecosystems here are adapted to colder, drier conditions than the coastal mountains. Salmon and other migratory species face many seasonal temperature- or flow-related barriers to reach inland tributaries and headwater streams. Winter precipitation is shifting from snow to rain, in some cases triggering ecological responses such as shifts in migration timing. Summer water supply is mainly from melting ice and snow or from groundwater seeps or springs. Warmer, longer, and drier summers will contribute to multiple stressors on aquatic and moisture-limited riparian ecosystems.



Map of ecoregions in the Pacific Northwest. Inland Mountains are primarily covered by trees (dry forest). Areas of crops, grass, shrub and scrub are mainly in the lowlands of the southern regional extent. Data: [Dynamic World Land Cover](#)

Management Considerations

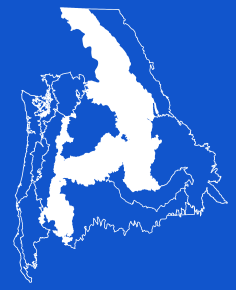
- Uplands with consistent snowpack and moisture availability through summer may be resilient to climate change but still susceptible to wildfire.
- The physiological tolerances of organisms across life stages or during extreme events are important considerations and topics of current research. In particular, the cumulative exposure of coldwater species to higher temperatures over time or at key life stages may be critical.
- Lower flows and warmer temperatures will cause more extensive drying of lowland streams and wetlands, reducing aquatic and riparian habitat area and connectivity.
- Interactions among species (particularly those involving warmwater invasive species) may intensify as populations or species begin to overlap geographically in response to warming. Areas of habitat loss due to lower flows or drying, warming coldwater habitats, and refugia are thus likely to be the sites of multiple, interacting climate and existing stressors.
- Dams, habitat alteration, logging and grazing are the main existing human impacts.

Future Research Areas

- Field studies have been too limited in scope to fully characterize future climate impacts to riparian and aquatic ecosystems.
- Impacts of changing wildfire regime on riparian and aquatic ecosystems are not well understood.
- Climate impacts to riparian and groundwater-dependent ecosystems have major knowledge gaps.
- Multiple stressors and ecological responses interact, making it difficult to predict combined impacts such as warming and competition from nonnative fish on native fish species.

Blue Mountains, Eastern Cascades, Northern Rockies, Idaho Batholith

Aquatic Ecosystems



Managing Ecosystem Stressors



Land Use

Description

Land use impacts habitat and constrains species' survival. Dry conditions are exacerbated by water withdrawals, grazing impacts, degraded water quality, and food web disruptions. Increased wildfire frequency and severity in forests may lead to increased area with post-fire conditions susceptible to rapid runoff, erosion, and pollution of aquatic systems.

Strategy Habitats

- Riparian buffers or native vegetation communities for ecosystem services
- Coldwater fish migration corridors in the mainstem rivers and spawning habitat in the tributary streams
- Wetland complexes and groundwater dependent ecosystems
- Intermittent and drying perennial streams

Management Actions

- Protect riparian areas through managed grazing or forest practices
- Implement forest practices for fuels reduction and to mitigate post-fire impacts throughout watersheds
- Support research to fill the major knowledge gaps for aquatic/riparian species and ecosystems in these ecoregions



Lower Summer Water Levels (Minimum Flows)

Description

Declining snowpack will cause longer and more frequent low water conditions in streams, lakes, wetlands, and groundwater in summer. Intermittent streams and wetlands will increase in area and number and will have more frequent and longer dry periods. Drying changes chemical properties and reduces habitat area and connectivity for aquatic and riparian species.

Strategy Habitats

- Intermittent and drying perennial streams
- Wetland complexes, groundwater dependent ecosystems, and associated habitats for flora and fauna (e.g., tailed frogs)
- Habitat and corridors for bull trout, cutthroat trout, and salmon
- Native riparian vegetation communities
- Coldwater refugia

Management Actions

- Arrange water releases from reservoirs to help support key life stages
- Adjust summer water use in key locations to maintain minimum flows
- Plant and maintain riparian and wetland vegetation, use natural or artificial beaver dams to increase infiltration and ephemeral storage
- Support research to fill knowledge gaps for inland aquatic/riparian ecosystems



Water Quality

Description

Water temperatures in the lowlands are predicted to gradually increase, punctuated with extreme heat events that drastically affect life in and adjacent to water bodies. Warming water temperatures will have compounding effects with sediment and nutrient pollution as combined stressors on aquatic organisms.

Strategy Habitats

- Riparian buffers or native vegetation communities
- Coldwater fish migration corridors in the mainstem rivers and spawning habitat in some tributary streams
- Headwater streams identified as climate refuge for coldwater fish and the cool water influence downstream on other critical habitats

Management Actions

- Pursue integrated management approaches that span private and public lands.
- Plant and maintain vegetation to increase riparian shading and increase upland and floodplain filtration
- Maintain minimum flows to moderate instream temperatures
- Support research to fill the major knowledge gaps

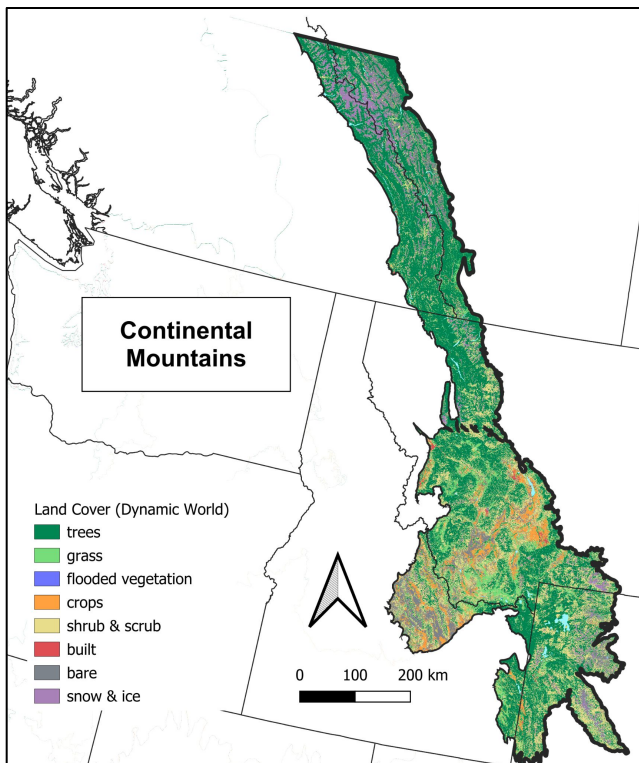
Canadian Rockies, Middle Rockies

Aquatic Ecosystems



Regional Description

The ecoregions listed above have been combined and renamed “Continental Mountains”. Aquatic and riparian ecosystems here are adapted to colder, drier conditions than the coastal mountains. Summer water supply originates from melting ice and snow in late spring-early summer or from groundwater seeps or springs. Vegetation communities in riparian areas and wetlands have been shaped by meltwater patterns and flows and are already showing some impacts of the loss of glaciers, later snowmelt, and loss of headwater storage. At lower elevations, riparian and wetland communities are distinct from adjacent dryland communities and are often moisture-limited during the dry summer season. Warmer, longer, and drier summers are projected, which will contribute to multiple stressors on aquatic and riparian ecosystems.



Map of ecoregions in the interior Pacific Northwest. The Continental Mountains are primarily covered by trees (dry, inland forest). There are some areas of crops, grass, or shrub and scrub, mainly in southwestern Montana and central Idaho. Data: [Dynamic World Land Cover](#)

Management Considerations

- Loss of glaciers and decreasing headwater storage are major concerns. Areas of habitat loss due to loss of snow and ice will likely be the sites of multiple, interacting stressors.
- Warmer temperatures will contribute to changes in species assemblages and vegetation structure in meltwater-influenced habitats. Species interactions may intensify as shifting ranges or phenology cause new overlaps in suitable habitat. Of particular concern are increasing population sizes or expanding ranges of warm water invasive species.
- Lower-elevation areas will likely experience more extensive drying of streams and wetlands, reducing aquatic and riparian habitat area and connectivity. The potential of restoration impacts is influenced by valley configuration, including confined and unconfined reaches.
- Wildfires can compound stressors by removing cover with consequences such as increased erosion and loss of shading effects.
- Physiological tolerances across life stages or during extreme events are important considerations and topics of current research. The cumulative exposure of salmon to higher temperatures over the great migration distances to spawning grounds is a major stressor.
- Dams, habitat alteration, logging and grazing are the main existing human impacts in the region.

Future Research Areas

- Loss of snow and ice drives both gradual and step-change (across threshold) effects that can transform ecological structure and function in meltwater-influenced systems but can be difficult to predict.
- Most field studies occurred in Glacier National Park; the remaining areas are understudied and might have different responses to climate change.
- Little is known about how physiological tolerances vary by species and life stage as well as the intensity and duration of melting or of extreme heat events.

Canadian Rockies, Middle Rockies

Aquatic Ecosystems



Managing Ecosystem Stressors



Loss of Glaciers

Description

Loss of ice and snow will decrease the area and quality of meltwater habitats. While some warming may be mitigated by icy seeps, other coldwater refugia may be lost, reduced in area, or occupied by warmwater-adapted species. Vegetation communities may shift from shrub to more homogeneous, herbaceous species assemblages.

Strategy Habitats

- Meltwater-dependent habitats in headwater streams and riparian areas
- Native riparian vegetation communities
- Coldwater refugia created by icy seeps or groundwater
- Spawning habitat for coldwater-specialized fish

Management Actions

- Support research to fill the major gaps in ecological knowledge of aquatic/riparian species and meltwater dependency in these ecoregions.
- Expand the geographic range of field studies/observations to include areas beyond Glacier National Park



Barriers to Movement

Description

Natural and anthropogenic barriers to fish passage affect climate change vulnerability. Organisms that cannot move to avoid excessive exposure to warming waters or to access coldwater refugia may not survive.

Strategy Habitats

- Streams and tributaries that provide habitat for smaller, less mobile fish species (that are less adaptable)
- Bottlenecks where removal of few barriers or addition of fish passage structures would effectively improve connectivity for fish
- Areas of key habitat for native fish that are vulnerable to invasive species

Management Actions

- Remove anthropogenic fish barriers such as culverts
- Provide options for fish passage to maintain connectivity
- Control invasive species that could benefit from warming waters and increased connectivity
- Consider trade-offs among target and invasive species when connectivity-enhancing actions could result in negative impacts



Loss of Headwater Storage

Description

Loss of ice and snow will decrease headwater storage during the dry season. Melt-driven peak flows will occur earlier in spring and will decrease as glaciers recede. Low flows will be lower, persist longer, and amplify warming in aquatic habitats. Reservoir drawdown for human use will compound water availability challenges.

Strategy Habitats

- Bull trout spawning habitat in headwater streams
- Coldwater refuge habitat for native fish populations
- Critical habitats and migration corridors downstream from reservoirs that could provide cold water during critical periods

Management Actions

- Consider impacts to native fish when defining acceptable reservoir drawdown.
- Address legacy grazing impacts that impede headwater stream ecosystem resilience.
- Support research to fill the major knowledge gaps regarding anticipated flow regime changes and impacts on aquatic/riparian species in these ecoregions.

Cascades, Coast Range, Klamath Mountains, North Cascades, Puget Lowlands, Willamette Valley Aquatic Ecosystems

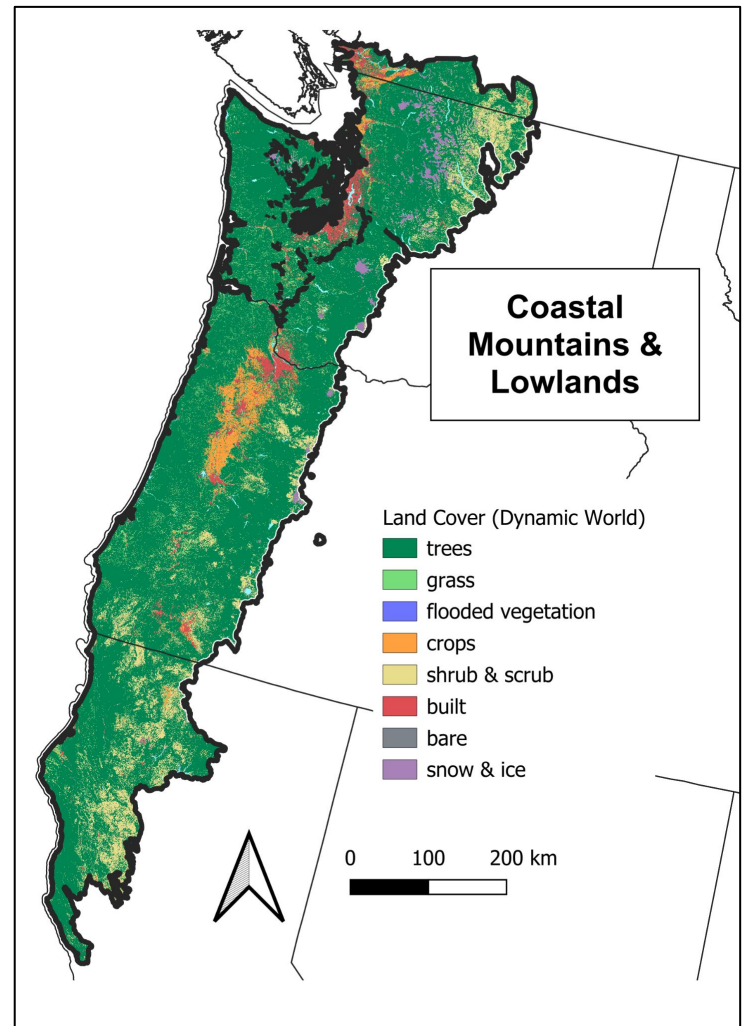


Regional Description

The ecoregions listed above have been combined and renamed “Coastal Mountains and Lowlands” because of their similar climate and headwater connectivity. Aquatic and riparian ecosystems in this maritime-influenced, wet climate span a wide range of elevations. The highest elevation areas may remain snow-dominated and ecosystems there may be buffered against warming and flow regime changes. However, most mountain and lowland ecosystems in these ecoregions will be impacted by climate-driven flow regime changes and existing high population pressures. Direct effects of temperature changes are a concern for some riparian and aquatic organisms but may be less pronounced in these ecoregions than others in the Northwest.

Management Considerations

- The main existing human impacts are urbanization, dams, timber harvest, agriculture, and habitat alteration. Collectively, these human impacts may exacerbate flow extremes and detract from the adaptability of riparian and aquatic species.
- Lower summer low flows reduce aquatic habitat and limit moisture availability for riparian habitat and are thus a concern for organisms throughout this region.
- Amphibians and other organisms that depend on wetlands and riparian areas are vulnerable to warmer winters and warmer, drier summers.
- Extreme events such as high peak flows or heat domes may have significant impacts on organisms' survival, depending on the season (life stage) at which they occur.
- Secondary impacts such as homogenization of flow regimes will likely affect survival of aquatic species
- For salmon, the mismatch in timing between ocean arrival and food production is a concern.



Map of ecoregions in the Pacific Northwest west of the Cascade Crest. Coastal mountains and lowlands are primarily covered by trees (humid forest), crops, and developed areas. Data: [Dynamic World Land Cover](#)

Future Research Areas

- Impacts of changing wildfire regimes on riparian and aquatic systems in these ecoregions are not well characterized.
- The effects of forest management practices on summer low flows are difficult to determine due to the complexity of hydrology.
- The combined impacts of climate stressors are difficult to predict because physiological tolerances vary by species and life stage and in relation to the intensity and duration of extreme temperature or flow events.

Cascades, Coast Range, Klamath Mountains, North Cascades, Puget Lowlands, Willamette Valley Aquatic Ecosystems



Managing Ecosystem Stressors



Peak Water Levels (High Flow Events)

Description

Changes in timing, frequency, and magnitude of peak water levels impact ecosystems differently, based on elevation and snow dependency. Rain-on-snow events cause earlier, higher spring floods with streambed scour that affects salmon egg survival. Floods are flashier when severe wildfires increase impervious surfaces or reduce infiltration in watersheds.

Strategy Habitats

- Salmon spawning habitat, particularly for populations with egg incubation stages during late winter-early spring in tributaries or headwater streams
- Areas impacted by post-fire runoff or erosion
- Areas where restoration can improve hydrology with ecological co-benefits.

Management Actions

- Restore floodplain vegetation and aquatic connectivity to promote resilience by allowing populations to move in response to changing environments.
- Implement forest practices that reduce wildfire severity or mitigate risk of negative post-fire impacts, including fuels reduction and post-fire erosion mitigation.



Lower Summer Water Levels (Minimum Flows)

Description

Lower, longer-lasting summer low flows are exacerbated by water withdrawals. Lower water levels will directly impact aquatic species including salmon with summer migration or rearing stages in amphibians such as the Cascades frog. Adaptability is limited by anthropogenic factors including urbanization, degraded water quality, and food web disruptions by introduced species.

Strategy Habitats

- Salmon migration corridors and rearing habitat
- Amphibian habitat, including riparian or wetland complexes and groundwater-dependent ecosystems
- Forested riparian areas or riparian buffers
- Native riparian vegetation communities located in agricultural areas

Management Actions

- Maintain minimum flows or water levels for species of concern such as salmon with summer migrations
- Increase headwater and floodplain storage via riparian vegetation restoration and floodplain reconnection
- Implement forest and agricultural practices or policies promoting water conservation throughout watersheds.



Water Quality

Description

The water in the lowlands of these ecoregions already has poor water quality due to historical and current land use. Warming water temperatures will have compounding effects with sediment and nutrient pollution as combined stressors on aquatic organisms.

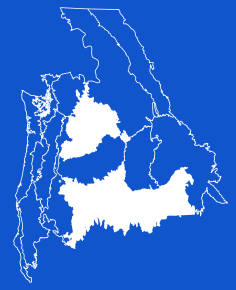
Strategy Habitats

- Riparian buffers or native vegetation communities
- Salmon migration corridors and rearing habitat
- Coastal fish habitat in lowlands
- Headwater streams identified as climate refuge for coldwater fish and the cool water influence downstream on other critical habitats

Management Actions

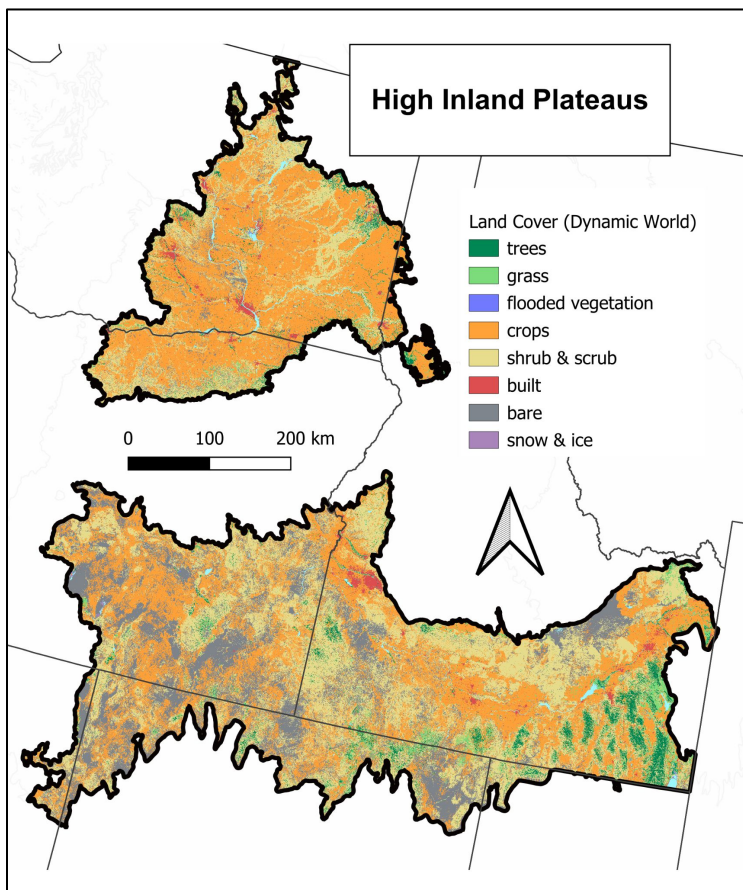
- Moderate water temperatures with vegetated riparian corridors and natural or artificial beaver dams that increase temporary storage
- Maintain minimum flows or water levels to mitigate summer warming
- Implement forest and agricultural practices or policies promoting riparian and water conservation.

Columbia Plateau, Northern Basin and Range, Snake River Plain, Southeast Idaho Aquatic Ecosystems



Regional Description

The ecoregions listed above have been combined and renamed “High Inland Plateaus”. Aquatic and riparian ecosystems in these dryland areas rely on water generated upslope. Summer water supply originates from snowpack in surrounding mountains or from groundwater seeps or springs. Vegetation communities in riparian areas and wetlands are distinct from adjacent dryland communities and are often highly adapted to changing moisture conditions, particularly intra- and interannual variability in water availability. Warmer, longer, and drier summers are projected for this area, which will contribute to multiple stressors on aquatic and riparian ecosystems. Invasive species that benefit from warming may also be of increasing concern in the future.



Map of ecoregions in the Pacific Northwest. The High Inland Plateaus combined region is primarily covered by crops, grass, shrub and scrub. Data: [Dynamic World Land Cover](#)

Management Considerations

- Invasive species have been a persistent problem, particular in lowland (warmwater) aquatic and riparian ecosystems in this region, where non-natives outnumber native species.
- Direct exposure to warmer temperatures and associated factors such as lower dissolved oxygen concentrations are a major concern.
- Lower flows and warmer temperatures will contribute to more extensive drying of streams and wetlands, reducing aquatic and riparian habitat area and connectivity.
- Interactions within and among species may intensify as populations or species begin to overlap geographically in response to warming. Areas of habitat loss due to lower flows or drying, warming coldwater habitats, and refugia are thus likely to be the sites of multiple, interacting climate and existing stressors.
- The physiological tolerances of organisms across life stages or during extreme events are important considerations and research topics. In particular, the cumulative exposure of coldwater species, such as salmon to higher temperatures over time or at key life stages will be critical.
- Riparian vegetation, groundwater or reservoir storage releases may help mitigate impacts on coldwater dependent species.
- Dams, agriculture, habitat alteration, and grazing are the main existing human impacts.

Future Research Areas

- Warming and drying cause multiple, cascading responses ranging from gene to ecosystem in scale.
- Impacts of changing wildfire regime on riparian/aquatic ecosystems are less understood.
- Multiple stressors and ecological responses interact, making it difficult to predict combined impacts or characterize the natural state of these ecosystems, past or future.
- Models and empirical data are being used to better understand stressors and responses for key species throughout the life cycle.
- Ecological studies are limited in these ecosystems.

Columbia Plateau, Northern Basin and Range, Snake River Plain, Southeast Idaho

Aquatic Ecosystems



Managing Ecosystem Stressors



Land Use

Description

Historic land use continues to impact habitat and constrain species' survival. Water withdrawals in the dry season exacerbate dry conditions in aquatic/riparian ecosystems, which are also stressed by the physical impacts of grazing, degraded water quality in streams and wetlands, and food web disruptions by introduced predatory fish species.

Strategy Habitats

- Riparian buffers and native riparian vegetation communities providing ecosystem services
- Salmon migration corridors in mainstem rivers and spawning habitat in tributary streams (albeit limited extent)
- Wetland complexes and groundwater-dependent ecosystems
- Intermittent and drying perennial streams

Management Actions

- Pursue integrated management approaches that span private and public lands
- Restore and maintain riparian vegetation through management (fencing, planting, etc.) and/or policy incentives
- Support research to fill the major knowledge gaps in dryland aquatic/riparian ecosystems.



Lower Summer Water Levels (Minimum Flows)

Description

Declining snowpack will cause longer and more frequent low water conditions in streams, lakes, wetlands, and groundwater in summer. Intermittent streams and wetlands will increase in area and number and will have more frequent and longer dry periods. Drying changes chemical properties and reduces habitat area and connectivity for aquatic/riparian species.

Strategy Habitats

- Intermittent and drying perennial streams
- Wetland complexes, groundwater dependent ecosystems, and associated flora and fauna, such as the Columbia spotted frog
- Mainstem streams support salmon migration with some tributaries supporting spawning and rearing
- Native riparian vegetation communities

Management Actions

- Arrange water releases from reservoirs to support key life stages.
- Maintain minimum flows through the dry season.
- Plant and maintain vegetation to increase upland and floodplain infiltration.
- Support research to fill the major knowledge gaps for dryland aquatic/riparian species, ecosystems, and restoration.



Water Quality

Description

Water temperatures in these ecoregions are predicted to gradually increase with likely extreme heat events affecting life in and adjacent to water bodies. The water in this zone already has poor water quality due to historical and current land use.

Strategy Habitats

- Riparian buffers and native riparian vegetation communities providing sediment/pollutant removal and shading
- Salmon migration corridors in the mainstem rivers and spawning habitat in some tributary streams (Warming waters in these transit zones increase water temperatures in other critical habitats downstream.)

Management Actions

- Pursue integrated management approaches that span private and public lands.
- Plant and maintain vegetation for shading and to increase floodplain filtration.
- Support research to fill the major knowledge gaps for dryland aquatic/riparian ecosystems.

CLIMATE ADAPTATION: Aquatic Ecosystems



Overview

Connectivity and timing are essential considerations for adaptation in aquatic ecosystems. Climate-related stressors operate at site to watershed scales, depend on connectivity, and are cumulative throughout watersheds. Aquatic ecosystems are highly dynamic and adaptation potential varies by species and life stage. Pacific Northwest aquatic settings vary in condition and climate effects and the effectiveness of adaptation strategies will vary. Many watersheds will experience step-changes due to reduced snowpack or ice and shifts in precipitation patterns. Adaptation strategies will need to address potentially significant changes to stream flow and temperature through the year. It is difficult to predict the effects of individual stressors on aquatic ecosystems for a any one time and place. One approach is to implement actions that are likely to promote species' ability to adapt and ecosystem resilience.

Adaptation Options

WHAT IT MEANS: Determine priority areas to restore and protect. Goals may be shaped by species of concern, ecosystem function or resilience. Strategies include restoring riparian vegetation communities, installing instream structures such as beaver dam analogs, and controlling or removing invasive species.

WHY IT WORKS: Process-based restoration aims to promote species' survival by leveraging their adaptability and to enhance ecosystem resilience rather than aim for static targets. Increasing habitat heterogeneity increases options for organisms to respond to stressors such as high flow events by moving to slow water refuges.

FINDING THE SCIENCE:

Beechie et al. 2023

- This study recommends important restoration locations and actions for individual salmon species based on a modeling study in the Chehalis River Basin of Washington.

Nash et al. 2021

- This study presents a process-based framework to guide expectations and effectiveness monitoring of beaver-related restoration actions in 6 case studies across the Western US, including 3 sites in Oregon.

THE METHOW BEAVER PROJECT

DESCRIPTION: The Methow Beaver Project is a local conservation initiative that takes a multifaceted approach to reduce conflict between landowners and beavers and to improve aquatic/riparian habitats throughout the Methow watershed. This group provides education and assistance to landowners to address challenges to co-existence with beavers on their property. They can provide physical assistance with technical solutions or connect the landowner with cost-sharing opportunities. Where conflict is irreconcilable, the group relocates beavers to a more favorable setting on forested public lands higher in the watershed. In some cases, they intervene to restore habitat to sufficient integrity to support beavers before relocation. Habitat restoration actions include installation of beaver dam analogs or post-assisted log structures to capture water, recruit beavers, and assist in beaver establishment at those sites.

AT A GLANCE:

- Goals: to restore natural functions (minimum flows, temperature, habitat) to rivers and streams to promote their resilience to climate-related stressors
- Location: Methow Valley, Washington State
- Timeline: This project is ongoing since 2008
- Strategies: Process-based river restoration using beaver-related restoration techniques
- Project Links: <https://methowbeaverproject.org/>



Close up photograph of a beaver. Photo: Methow Beaver Project

CLIMATE ADAPTATION: Aquatic Ecosystems



WHAT IT MEANS: For decades scientists have understood and managed rivers through the natural flow regime (sensu Poff et al. 1997). Flow regulation, for example, impacts specific parameters of stream hydrology that organisms have adapted to. Management strategies, in some cases, include trying to mimic certain hydrologic parameters to match specific species requirements. Climate change represents a similar, yet broader, challenge. How will climate change alter specific flow parameters and what actions can be implemented to ameliorate the impact for decades to come?

- Downscale climates to streams to identify changing hydrologic parameters to match to sensitive species traits with the goal of identifying conservation concerns and management actions.
- Managing the flow regime in regulated rivers to explicitly include current and expected climate impacts, not only to low flow but peak events.
- Take a watershed approach to understanding climate impacts to streamflow, including the altered fire regimes, forest management, and floodplain reconnection.

WHY IT WORKS: Riverine species are adapted to changing environments within the historic range of variability but are also increasingly being stressed by multiple changing factors. By identifying specific hydrology-species relationships, scientists can identify management targets and strategies to lessen climate impacts at different life stages across taxa, be them at the watershed, floodplain or reach scale.

FINDING THE SCIENCE:

Goode et al. 2013

- This study used climate data and process-based models to explore how predicted stream flow will impact scouring of salmon redds to identify risk and prioritize watersheds for management activities.

Tullos et al. 2021 and Dewey et al. 2022

- These articles highlight important considerations for flow-related restoration in a changing climate, including how to foster dynamism and heterogeneity in river systems.

RESTORING THE TUCANNON RIVER

DESCRIPTION: The Tucannon River in southeastern Washington supports multiple native coldwater fish, including the ESA listed Spring Chinook. Emerging in 2011, a consortium of agencies, tribes, and private landowners joined together to restore the Tucannon River. The primary focus was to restore rearing and spawning conditions and supplement populations with hatchery releases for Spring Chinook; restoration co-benefits have expanded to include other fish, riparia, reduced fire risk and first foods. The recovery plan included forest management plans and floodplain/stream restoration actions over a large portion of the river. Notable for its scale, the restoration floodplain reconfiguration and addition of large, channel and floodplain spanning wood jams are intended to create complex habitat, cool waters through increased hyporheic exchange, and slow water down to increase temporary storage. Much of this work occurred between 2011-2020, with initial positive results. Water temperatures have so far decreased, despite increased ambient temperature, and minimum flows have increased.

AT A GLANCE:

- Goals: Recovery of multiple fish species (spring run Chinook, bull trout, and summer steelhead), with primary focus on ESA listed spring Chinook (1990).
- Location: Tucannon River Basin, southeastern Washington State
- Timeline: This project is ongoing since 2011
- Strategies: Multiple scales of management action from watershed management, floodplain reconnection and riverine restoration of instream habitat and riparian vegetation.
- Project Links: <https://tucannonriver.org/>



Addition of channel spanning wood to increase hyporheic exchange for cooler summer temperatures, decrease stream power, and increased habitat heterogeneity (Photo: AK Fremier Sept 2014)

CLIMATE ADAPTATION: Aquatic Ecosystems



WHAT IT MEANS: Changing climate can alter water temperature patterns through time with varying effects on aquatic organisms. Management actions can help reduce organisms' exposure to extreme temperatures, enabling them to survive and maintain their resilience. Ways to accomplish this strategy include:

- Restore woody riparian vegetation to provide shade that limits warming in adjacent aquatic habitats.
- Pursue beaver-related restoration techniques (natural or artificial) to raise the water table and indirectly moderate instream temperatures.
- Manage dam release that can release cold water to create refuges or remove thermal barriers downstream.

WHY IT WORKS: Keeping water temperatures below critical thresholds at key life stages can reduce mortality or stress for coldwater species. Riparian shading can limit warming in small streams or other small waterbodies. Waters temporarily stored behind dams in cold headwater streams or in groundwater can ameliorate warming downstream where they return to the channel.

FINDING THE SCIENCE:

Noa-Yarasca et al. 2023

- This study quantified and evaluated riparian shade performance, showing potential for watershed-scale estimation of riparian cooling effects.

Fuller et al. 2024

- This study examined relationships between drivers of stream temperature and other variables to inform restoration actions.

Dittbrenner et al. 2022

- This study demonstrated that relocated beavers that build dams can indirectly increase temporary water storage and thus help to moderate downstream water temperatures.

Armstrong et al. 2021

- This article emphasizes the importance of warm water (for productivity, for example) at some life stages, even for species that are thought of as being coldwater dependent.

COLUMBIA COLD WATER REFUGES

DESCRIPTION: The EPA worked with Oregon, Washington, tribes, NOAA Fisheries, and a variety of other groups to identify, describe, and recommend protections for 23 coldwater refuges where cooler tributaries flow into the Lower Columbia River. Salmon that migrate upstream during the warmest conditions (summer-fall) are increasingly using these refuges as temperature increases. There is evidence that the fish benefit by reducing their exposure to high temperatures, suggesting that their use of coldwater refuges is an adaptation to changing climate. The EPA study found that ~80% of steelhead and ~30% of fall Chinook move into the refuges when the temperature exceeds 21°C. Sockeye salmon do not appear to use these refuges, but instead migrate upstream earlier. To comply with the Endangered Species Act and Oregon's clean water standards, EPA recommended specific restoration actions and highlighted key refuges to either maintain or enhance by expanding refuge volume or restoring additional tributaries.

AT A GLANCE:

- Goals: facilitate coordinated aquatic habitat enhancement and protection
- Location: lower 325 miles of the Columbia River
- Timeline: report released in 2021; coordinated implementation is ongoing
- Strategies: provide coldwater refuges for aquatic species to shelter from warming
- Project Links:

<https://www.epa.gov/columbiariver/columbia-river-cold-water-refuges-plan>



The Columbia Cold Water Refuges Program is a report with recommendations for refuges along the lower Columbia River (EPA).

CLIMATE ADAPTATION: Aquatic Ecosystems



WHAT IT MEANS: Adaptive capacity is the ability of a species to cope (persisting in situ) or to respond (range shifting) to a given environmental change (including climate change) (Dawson et al. 2011). Biologists typically discuss adaptive capacity in relation to a species' or population's life-history traits, genetic diversity, and phenotypic plasticity (Nicotra et al. 2015).

WHY IT WORKS: Analyses that focus on adaptive capacity can identify vulnerability among taxa and help design specific management actions to help taxa persist through environmental change (Timpane-Padgham et al. 2017). Taxa naturally vary in their capacity to adapt to changing water temperatures or water availability. Salmon, for example are highly adaptable in that they move into new rivers when conditions change. Removing any physical barriers can help leverage salmon's adaptive capacity, ideally increasing their likelihood of survival.

FINDING THE SCIENCE:

Crozier et al. 2019

- This paper describes a vulnerability analysis of Pacific salmon and steelhead to identify vulnerable populations and suggests plans to address anthropogenic factors limiting their adaptive capacity, such as migration barriers, habitat degradation, and hatchery influences.

Knapp et al. 2016

- This article documents regional increases in hundreds of populations of yellow-legged frog, which were likely due to the cessation of fish stocking and increased resistance to disease. Management actions to reduce existing anthropogenic stressors to increase population size can be viewed as improving a taxa's adaptive capacity to climate change.

Austin et al. 2021

- This article modeled the timing of fall spawning from Chinook salmon redd counts. They compared the spawning time among fish populations in 6 rivers. Generally, spawning dates were later in warmer rivers in the past several decades. However, hatchery-origin Chinook salmon did not show the same shift in spawning timing, suggesting their adaptive capacity may differ from that of wild salmon.

MORE ADAPTATION RESOURCES:

● FLOODPLAINS BY DESIGN

Floodplains by Design (FbD) is a public-private partnership led by the Washington Department of Ecology. FbD aims to protect local communities and support a healthy environment by coordinating and funding integrated projects that reduce flood risks and restore habitat, with communities.

Resource Link: [Floodplains by Design](#)

● BEAVER DAM ANALOG CASE STUDY PUBLICATION

Researchers recently completed a case study in the Bridge Creek watershed of the John Day basin in eastern Oregon. Beaver dam analogues have been installed on both public and private rangelands to improve fish and wildlife habitat in the watershed. This case study focuses mainly on the human dimensions of beaver-related restoration, including the complex policies involved and ranchers' concerns about potential negative impacts.

Resource Link: [Using beaver dam analogues for fish and wildlife recovery on public and private rangelands in eastern Oregon | US Forest Service Research and Development](#)

● PUBLICATION ON TYPES OF THERMAL REFUGES

This article organizes current scientific understanding to provide practical definitions that can help support the recognition and management of thermal refuges and refugia across riverscapes.

Resource Link: [An ecohydrological typology for thermal refuges in streams and rivers](#)

● TREELINE: CLIMATE RESILIENCE & ADAPTATION

Treeline is an emerging network organized by the Bonneville Environmental Foundation to share knowledge and lessons across the Northwest. This community includes restoration practitioners, nursery partners, and researchers working for various groups involved in conservation in the region, including tribes, governmental and nongovernmental organizations.

Resource Link: [Treeline: Climate Resilience & Adaptation - BEF | Sustainability Products and Services](#)

REFERENCES - OVERVIEW

- Abatzoglou JT, Williams AP. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* 113:11770–11775.
- Adrian R, Gerten D, Huber V, Wagner C, Schmidt SR. 2012. Windows of change: temporal scale of analysis is decisive to detect ecosystem responses to climate change. *Marine Biology* 159:2533–2542.
- Austin CS, Essington TE, Quinn TP. 2021. In a warming river, natural-origin Chinook salmon spawn later but hatchery-origin conspecifics do not. *Canadian Journal of Fisheries and Aquatic Sciences* 78:68–77.
- Beechie TJ, Fogel C, Nicol C, Jorgensen J, Timpane-Padgham B, Kiffney P. 2023. How does habitat restoration influence resilience of salmon populations to climate change? *Ecosphere* 14:e4402.
- Bellmore JR, Fellman JB, Hood E, Dunkle MR, Edwards RT. 2022. A melting cryosphere constrains fish growth by synchronizing the seasonal phenology of river food webs. *Global Change Biology* 28:4807–4818.
- Bellmore JR, Sergeant CJ, Bellmore RA, Falke JA, Fellman JB. 2023. Modeling coho salmon (*Oncorhynchus kisutch*) population response to streamflow and water temperature extremes. *Canadian Journal of Fisheries and Aquatic Sciences* 80:243–260.
- Benjamin JR, Dunham JB, Johnson SL, Ashkenas L, Penaluna BE, Bilby RE, Bateman D, Leer D, Bellmore JR. 2022. Pathways of productivity and influences on top consumers in forested streams. *Forest Ecology and Management* 508:120046.
- Birrell JH, Shah AA, Hotaling S, Giersch JJ, Williamson CE, Jacobsen D, Woods HA. 2020. Insects in high-elevation streams: Life in extreme environments imperiled by climate change. *Global Change Biology* 26:6667–6684.
- Bowerman TE, Keefer ML, Caudill CC. 2021. Elevated stream temperature, origin, and individual size influence Chinook salmon prespawn mortality across the Columbia River Basin. *Fisheries Research* 237:105874.
- Coble AA et al. 2020. Long-term hydrological response to forest harvest during seasonal low flow: Potential implications for current forest practices. *Science of The Total Environment* 730:138926.
- Comte L, Olden JD, Tedesco PA, Ruhi A, Giam X. 2021. Climate and land-use changes interact to drive long-term reorganization of riverine fish communities globally. *Proceedings of the National Academy of Sciences* 118:e2011639118.
- Crozier LG, Burke BJ, Chasco BE, Widener DL, Zabel RW. 2021. Climate change threatens Chinook salmon throughout their life cycle. *Communications Biology* 4:1–14. Nature Publishing Group.
- Dittbrenner BJ, Schilling JW, Torgersen CE, Lawler JJ. 2022. Relocated beaver can increase water storage and decrease stream temperature in headwater streams. *Ecosphere* 13:e4168.
- Dunkle MR, Bellmore JR, Fellman JB, Caudill CC. 2024. Glaciers, snow, and rain: Water source influences invertebrate community structure and secondary production

- across a hydrologically diverse subarctic landscape. *Limnology and Oceanography* 69:232–245.
- Dwire KA, Mellmann-Brown S, Gurrieri JT. 2018. Potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon, USA. *Climate Services* 10:44–52.
- Elliott J, Passy SI, Pound KL, Merritt G, Polkowske S, Larson CA. 2022. Strong but heterogeneous distributional responses to climate change are projected for temperate and semi-arid stream vertebrates. *Aquatic Conservation: Marine and Freshwater Ecosystems* 32:1291–1305.
- Epele LB et al. 2022. Perils of life on the edge: Climatic threats to global diversity patterns of wetland macroinvertebrates. *Science of The Total Environment* 820:153052.
- Finn DS, Johnson SL, Gerth WJ, Arismendi I, Li JL. 2022. Spatiotemporal patterns of emergence phenology reveal complex species-specific responses to temperature in aquatic insects. *Diversity and Distributions* 28:1524–1541.
- Frelich LE, Reich PB. 2010. Will environmental changes reinforce the impact of global warming on the prairie–forest border of central North America? *Frontiers in Ecology and the Environment* 8:371–378.
- Garssen AG, Verhoeven JTA, Soons MB. 2014. Effects of climate-induced increases in summer drought on riparian plant species: a meta-analysis. *Freshwater Biology* 59:1052–1063.
- Giersch JJ, Hotaling S, Kovach RP, Jones LA, Muhlfeld CC. 2017. Climate-induced glacier and snow loss imperils alpine stream insects. *Global Change Biology* 23:2577–2589.
- Gordon BL, Brooks PD, Krogh SA, Boisrame GFS, Carroll RWH, McNamara JP, Harpold AA. 2022. Why does snowmelt-driven streamflow response to warming vary? A data-driven review and predictive framework. *Environmental Research Letters* 17:053004.
- Gustine RN, Hanan EJ, Robichaud PR, Elliot WJ. 2022. From burned slopes to streams: how wildfire affects nitrogen cycling and retention in forests and fire-prone watersheds. *Biogeochemistry* 157:51–68.
- Hasler CT, Butman D, Jeffrey JD, Suski CD. 2016. Freshwater biota and rising pCO₂? *Ecology Letters* 19:98–108.
- Hasler CT, Jeffrey JD, Schneider EVC, Hannan KD, Tix JA, Suski CD. 2018. Biological consequences of weak acidification caused by elevated carbon dioxide in freshwater ecosystems. *Hydrobiologia* 806:1–12.
- Hawkins BL, Fullerton AH, Sanderson BL, Steel EA. 2020. Individual-based simulations suggest mixed impacts of warmer temperatures and a nonnative predator on Chinook salmon. *Ecosphere* 11:e03218.
- Heinle KB, Eby LA, Muhlfeld CC, Steed A, Jones L, D'Angelo V, Whiteley AR, Hebblewhite M. 2021. Influence of water temperature and biotic interactions on the distribution of westslope cutthroat trout *Oncorhynchus clarkii lewisi* in a population stronghold under climate change. *Canadian Journal of Fisheries and Aquatic Sciences* 78:444–456.

- Hinch SG, Bett NN, Eliason EJ, Farrell AP, Cooke SJ, Patterson DA. 2021. Exceptionally high mortality of adult female salmon: a large-scale pattern and a conservation concern. *Canadian Journal of Fisheries and Aquatic Sciences* 78:639–654.
- Ho JC, Michalak AM, Pahlevan N. 2019. Widespread global increase in intense lake phytoplankton blooms since the 1980s. *Nature* 574:667–670. Nature Publishing Group.
- Hossack BR, LeMoine MT, Oja EB, Eby LA. 2023. Cryptic declines of small, cold-water specialists highlight potential vulnerabilities of headwater streams as climate refugia. *Biological Conservation* 277:109868.
- Hotaling S, Finn DS, Joseph Giersch J, Weisrock DW, Jacobsen D. 2017. Climate change and alpine stream biology: progress, challenges, and opportunities for the future: Climate change and alpine stream biology. *Biological Reviews* 92:2024–2045.
- Hotaling S, Shah AA, McGowan KL, Tronstad LM, Giersch JJ, Finn DS, Woods HA, Dillon ME, Kelley JL. 2020. Mountain stoneflies may tolerate warming streams: Evidence from organismal physiology and gene expression. *Global Change Biology* 26:5524–5538.
- Isaak D et al. 2017. The NorWeST Summer Stream Temperature Model and Scenarios for the Western US: A Crowd-Sourced Database and New Geospatial Tools Foster a User Community and Predict Broad Climate Warming of Rivers and Streams. *Water Resources Research* 53:9181–9205.
- Isaak DJ, Luce CH. 2023. Elevation-dependent warming of streams in mountainous regions: implications for temperature modeling and headwater climate refugia. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques* 48:167–188.
- Isaak DJ, Luce CH, Horan DL, Chandler GL, Wollrab SP, Dubois WB, Nagel DE. 2020. Thermal Regimes of Perennial Rivers and Streams in the Western United States. *JAWRA Journal of the American Water Resources Association* 56:842–867.
- Jacobs GR, Thurow RF, Buffington JM, Isaak DJ, Wenger SJ. 2021. Climate, Fire Regime, Geomorphology, and Conspecifics Influence the Spatial Distribution of Chinook Salmon Redds. *Transactions of the American Fisheries Society* 150:8–23.
- Jacobsen D. 2020. The dilemma of altitudinal shifts: caught between high temperature and low oxygen. *Frontiers in Ecology and the Environment* 18:211–218.
- Jager HI et al. 2021. Resilience of terrestrial and aquatic fauna to historical and future wildfire regimes in western North America. *Ecology and Evolution* 11:12259–12284.
- Jeffrey JD, Hannan KD, Hasler CT, Suski CD. 2018. Hot and bothered: effects of elevated Pco₂ and temperature on juvenile freshwater mussels. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* 315:R115–R127. American Physiological Society.
- Johnston SE, Striegl RG, Bogard MJ, Dornblaser MM, Butman DE, Kellerman AM, Wickland KP, Podgorski DC, Spencer RGM. 2020. Hydrologic connectivity determines dissolved organic matter biogeochemistry in northern high-latitude lakes. *Limnology and Oceanography* 65:1764–1780.
- Kaeding LR, Mogen JT. 2023. Climate-driven stream-flow impacts on bull trout metapopulation dynamics revealed by quantitative assessment of 22 years of tag-recapture data. *Freshwater Biology* 68:301–311.

- Kauffman JB, Coleman G, Otting N, Lytjen D, Nagy D, Beschta RL. 2022. Riparian vegetation composition and diversity shows resilience following cessation of livestock grazing in northeastern Oregon, USA. *PLOS ONE* 17:e0250136.
- Kissel AM, Palen WJ, Ryan ME, Adams MJ. 2019. Compounding effects of climate change reduce population viability of a montane amphibian. *Ecological Applications* 29:e01832.
- Koontz ED, Steel EA, Olden JD. 2018. Stream thermal responses to wildfire in the Pacific Northwest. *Freshwater Science* 37:731–746.
- Lee S-Y, Fullerton AH, Sun N, Torgersen CE. 2020. Projecting spatiotemporally explicit effects of climate change on stream temperature: A model comparison and implications for coldwater fishes. *Journal of Hydrology* 588:125066.
- LeMoine MT, Eby LA, Clancy CG, Nyce LG, Jakober MJ, Isaak DJ. 2020. Landscape resistance mediates native fish species distribution shifts and vulnerability to climate change in riverscapes. *Global Change Biology* 26:5492–5508.
- MacNeille RB, Lohse KA, Godsey SE, Perdrial JN, Baxter CV. 2020. Influence of Drying and Wildfire on Longitudinal Chemistry Patterns and Processes of Intermittent Streams. *Frontiers in Water* 2:563841.
- Mantua N, Tohver I, Hamlet A. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change* 102:187–223.
- McKernan C, Cooper DJ, Schweiger EW. 2018. Glacial loss and its effect on riparian vegetation of alpine streams. *Freshwater Biology* 63:518–529.
- McLaren JS, Van Kirk RW, Mabaka AJ, Brothers S, Budy P. 2023. Drawdown, Habitat, and Kokanee Populations in a Western U.S. Reservoir. *North American Journal of Fisheries Management* 43:339–351.
- Mejia FH et al. 2023. Closing the gap between science and management of cold-water refuges in rivers and streams. *Global Change Biology* 29:5482–5508.
- Minshall GW, Robinson CT, Lawrence DE, Andrews DA, Brock JT. 2001. Benthic macroinvertebrate assemblages in five central Idaho (USA) streams over a 10-year period following disturbance by wildfire. *International Journal of Wildland Fire* 10:201.
- Muhlfeld CC, Cline TJ, Giersch JJ, Peitzsch E, Florentine C, Jacobsen D, Hotaling S. 2020. Specialized meltwater biodiversity persists despite widespread deglaciation. *Proceedings of the National Academy of Sciences* 117:12208–12214.
- Nadeau CP, Urban MC, Bridle JR. 2017. Coarse climate change projections for species living in a fine-scaled world. *Global Change Biology* 23:12–24.
- Nicol CL, Jorgensen JC, Fogel CB, Timpone-Padgham B, Beechie TJ. 2022. Spatially overlapping salmon species have varied population response to early life history mortality from increased peak flows. *Canadian Journal of Fisheries and Aquatic Sciences* 79:342–351.
- Olson MH, Fischer JM, Williamson CE, Overholt EP, Theodore N. 2018. Landscape-scale regulators of water transparency in mountain lakes: implications of projected glacial

- loss. Canadian Journal of Fisheries and Aquatic Sciences 75:1169–1176. NRC Research Press.
- Orr SE, Buchwalter DB. 2020. It's all about the fluxes: Temperature influences ion transport and toxicity in aquatic insects. *Aquatic Toxicology* 221:105405.
- Ou M, Hamilton TJ, Eom J, Lyall EM, Gallup J, Jiang A, Lee J, Close DA, Yun S-S, Brauner CJ. 2015. Responses of pink salmon to CO₂-induced aquatic acidification. *Nature Climate Change* 5:950–955. Nature Publishing Group.
- Overton K, Dempster T, Swearer SE, Morris RL, Barrett LT. 2023. Achieving conservation and restoration outcomes through ecologically beneficial aquaculture. *Conservation Biology*:e14065.
- Pelto MS, Dryak M, Pelto J, Matthews T, Perry LB. 2022. Contribution of Glacier Runoff during Heat Waves in the Nooksack River Basin USA. *Water* 14:1145.
- Perry LG, Andersen DC, Reynolds LV, Nelson SM, Shafroth PB. 2012. Vulnerability of riparian ecosystems to elevated CO₂ and climate change in arid and semiarid western North America. *Global Change Biology* 18:821–842.
- Perry LG, Shafroth PB, Hay LE, Markstrom SL, Bock AR. 2020. Projected warming disrupts the synchrony of riparian seed release and snowmelt streamflow. *New Phytologist* 225:693–712.
- Pilliod DS, Arkle RS, Thurow RF, Isaak DJ. 2022. Hydroclimatic Conditions, Wildfire, and Species Assemblages Influence Co-Occurrence of Bull Trout and Tailed Frogs in Northern Rocky Mountain Streams. *Water* 14:1162.
- Pound KL, Larson CA, Passy SI. 2021. Current distributions and future climate-driven changes in diatoms, insects and fish in U.S. streams. *Global Ecology and Biogeography* 30:63–78.
- Queen LE, Mote PW, Rupp DE, Chegwiddden O, Nijssen B. 2021. Ubiquitous increases in flood magnitude in the Columbia River basin under climate change. *Hydrology and Earth System Sciences* 25:257–272.
- Reeder WJ, Gariglio F, Carnie R, Tang C, Isaak D, Chen Q, Yu Z, McKean JA, Tonina D. 2021. Some (fish might) like it hot: Habitat quality and fish growth from past to future climates. *Science of The Total Environment* 787:147532.
- Reid AJ et al. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews* 94:849–873.
- Reinl KL et al. 2023. Blooms also like it cold. *Limnology and Oceanography Letters* 8:546–564.
- Reitsema RE, Wolters J-W, Preiner S, Meire P, Hein T, De Boeck G, Blust R, Schoelynck J. 2020. Response of Submerged Macrophyte Growth, Morphology, Chlorophyll Content and Nutrient Stoichiometry to Increased Flow Velocity and Elevated CO₂ and Dissolved Organic Carbon Concentrations. *Frontiers in Environmental Science* 8. Available from <https://www.frontiersin.org/articles/10.3389/fenvs.2020.527801> (accessed November 8, 2023).
- Robinne F et al. 2021. Scientists' warning on extreme wildfire risks to water supply. *Hydrological Processes* 35:e14086.

- Robinne F-N, Hallema DW, Bladon KD, Buttle JM. 2020. Wildfire impacts on hydrologic ecosystem services in North American high-latitude forests: A scoping review. *Journal of Hydrology* 581:124360.
- Rohde MM, Stella JC, Roberts DA, Singer MB. 2021. Groundwater dependence of riparian woodlands and the disrupting effect of anthropogenically altered streamflow. *Proceedings of the National Academy of Sciences* 118. National Academy of Sciences. Available from <https://www.pnas.org/content/118/25/e2026453118> (accessed June 16, 2021).
- Rose KC, Bierwagen B, Bridgham SD, Carlisle DM, Hawkins CP, Poff NL, Read JS, Rohr JR, Saros JE, Williamson CE. 2023. Indicators of the effects of climate change on freshwater ecosystems. *Climatic Change* 176:23.
- Ross SRP -J. et al. 2022. Predators mitigate the destabilising effects of heatwaves on multitrophic stream communities. *Global Change Biology* 28:403–416.
- Rubenson ES, Olden JD. 2020. An invader in salmonid rearing habitat: current and future distributions of smallmouth bass (*Micropterus dolomieu*) in the Columbia River Basin. *Canadian Journal of Fisheries and Aquatic Sciences* 77:314–325.
- Scheffers BR et al. 2016. The broad footprint of climate change from genes to biomes to people. *Science* 354:aaf7671. American Association for the Advancement of Science.
- Sergeant CJ et al. 2022. Risks of mining to salmonid-bearing watersheds. *Science Advances* 8:eabn0929.
- Shah AA, Hotaling S, Lapsansky AB, Malison RL, Birrell JH, Keeley T, Giersch JJ, Tronstad LM, Woods HA. 2023. Warming undermines emergence success in a threatened alpine stonefly: A multi-trait perspective on vulnerability to climate change. *Functional Ecology* 37:1033–1043. John Wiley & Sons, Ltd.
- Sorel MH, Murdoch AR, Zabel RW, Kamphaus CM, Buhle ER, Scheuerell MD, Converse SJ. 2023. Effects of population density and environmental conditions on life-history prevalence in a migratory fish. *Ecology and Evolution* 13:e10087.
- Staudinger MD, Lynch AJ, Gaichas SK, Fox MG, Gibson-Reinemer D, Langan JA, Teffer AK, Thackeray SJ, Winfield IJ. 2021. How Does Climate Change Affect Emergent Properties of Aquatic Ecosystems? *Fisheries* 46:423–441.
- Stromberg JC, Setaro DL, Gallo EL, Lohse KA, Meixner T. 2017. Riparian vegetation of ephemeral streams. *Journal of Arid Environments* 138:27–37.
- Toavs TR, Hasler CT, Suski CD, Midway SR. 2023. A 30-year dataset of CO₂ in flowing freshwaters in the United States. *Scientific Data* 10:20. Nature Publishing Group.
- Tonina D, McKean JA, Isaak D, Benjankar RM, Tang C, Chen Q. 2022. Climate Change Shrinks and Fragments Salmon Habitats in a Snow-Dependent Region. *Geophysical Research Letters* 49:e2022GL098552.
- Traynor EM, DePasquale SW, Hasler CT. 2023. Short-term exposure to near-future CO₂ has limited influence on the energetics and behaviour of young-of-year salmonids. *Canadian Journal of Zoology* 101:991–1003. NRC Research Press.
- Treanor HB, Ray AM, Amberg JJ, Gaikowski MP, Ilgen JE, Gresswell RE, Gains-Germain L, Webb MAH. 2020. Carbon Dioxide-Induced Mortality of Four Species of North American Fishes. *Journal of Fish and Wildlife Management* 11:463–475.

- Tronstad LM, Hotaling S, Giersch JJ, Wilmot OJ, Finn DS. 2020. Headwaters Fed by Subterranean Ice: Potential Climate Refugia for Mountain Stream Communities? *Western North American Naturalist* 80. Available from <https://bioone.org/journals/western-north-american-naturalist/volume-80/issue-3/064.080.0311/Headwaters-Fed-by-Subterranean-Ice--Potential-Climate-Refugia-for/10.3398/064.080.0311.full> (accessed July 12, 2023).
- Tullos D, Baker DW, Crowe Curran J, Schwar M, Schwartz J. 2021. Enhancing Resilience of River Restoration Design in Systems Undergoing Change. *Journal of Hydraulic Engineering* 147:03121001.
- Urabe J, Togari J, Elser JJ. 2003. Stoichiometric impacts of increased carbon dioxide on a planktonic herbivore. *Global Change Biology* 9:818–825.
- Wang CJ, Schaller HA, Coates KC, Hayes MC, Rose RK. 2020. Climate change vulnerability assessment for Pacific Lamprey in rivers of the Western United States. *Journal of Freshwater Ecology* 35:29–55.
- Ward AS, Wondzell SM, Schmadel NM, Herzog SP. 2020. Climate Change Causes River Network Contraction and Disconnection in the H.J. Andrews Experimental Forest, Oregon, USA. *Frontiers in Water* 2:7.
- Warren DR, Roon DA, Swartz AG, Bladon KD. 2022. Loss of riparian forests from wildfire led to increased stream temperatures in summer, yet salmonid fish persisted. *Ecosphere* 13. Available from <https://onlinelibrary.wiley.com/doi/10.1002/ecs2.4233> (accessed September 21, 2022).
- Wilson SM et al. 2023. Phenological shifts and mismatch with marine productivity vary among Pacific salmon species and populations. *Nature Ecology & Evolution* 7:852–861.
- Winkowski JJ, Olden JD, Brown S. 2024. Integrating spatial stream network models and environmental DNA to estimate current and future distributions of nonnative Smallmouth Bass. *Transactions of the American Fisheries Society* 153:180–199.
- Woodward G, Perkins DM, Brown LE. 2010. Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365:2093–2106.
- Woolway RI et al. 2021. Phenological shifts in lake stratification under climate change. *Nature Communications* 12:2318.

REFERENCES - CLIMATE ADAPTATION

- Armstrong, J. B., A. H. Fullerton, C. E. Jordan, J. L. Ebersole, J. R. Bellmore, I. Arismendi, B. E. Penaluna, and G. H. Reeves. 2021. The importance of warm habitat to the growth regime of cold-water fishes. *Nature Climate Change* 11:354–361.
- Austin, C. S., T. E. Essington, and T. P. Quinn. 2021. In a warming river, natural-origin Chinook salmon spawn later but hatchery-origin conspecifics do not. *Canadian Journal of Fisheries and Aquatic Sciences* 78:68–77.
- Beechie, T. J., C. Fogel, C. Nicol, J. Jorgensen, B. Timpane-Padgham, and P. Kiffney. 2023. How does habitat restoration influence resilience of salmon populations to climate change? *Ecosphere* 14:e4402.
- Crozier, L. G., M. M. McClure, T. Beechie, S. J. Bograd, D. A. Boughton, M. Carr, T. D. Cooney, J. B. Dunham, C. M. Greene, M. A. Haltuch, E. L. Hazen, D. M. Holzer, D. D. Huff, R. C. Johnson, C. E. Jordan, I. C. Kaplan, S. T. Lindley, N. J. Mantua, P. B. Moyle, J. M. Myers, M. W. Nelson, B. C. Spence, L. A. Weitkamp, T. H. Williams, and E. Willis-Norton. 2019. Climate vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. *PLOS ONE* 14:e0217711.
- Dewey, C., P. M. Fox, N. J. Bouskill, D. Dwivedi, P. Nico, and S. Fendorf. 2022. Beaver dams overshadow climate extremes in controlling riparian hydrology and water quality. *Nature Communications* 13:6509.
- Dittbrenner, B. J., J. W. Schilling, C. E. Torgersen, and J. J. Lawler. 2022. Relocated beaver can increase water storage and decrease stream temperature in headwater streams. *Ecosphere* 13:e4168.
- Fuller, M. R., N. E. Detenbeck, P. Leinenbach, R. Labiosa, and D. Isaak. 2024. Spatial and temporal variability in stream thermal regime drivers for three river networks during the summer growing season. *JAWRA Journal of the American Water Resources Association* 60:57–78.
- Goode, J. R., J. M. Buffington, D. Tonina, D. J. Isaak, R. F. Thurow, S. Wenger, D. Nagel, C. Luce, D. Tetzlaff, and C. Soulsby. 2013. Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. *Hydrological Processes* 27:750–765.
- Knapp, R. A., G. M. Fellers, P. M. Kleeman, D. A. W. Miller, V. T. Vredenburg, E. B. Rosenblum, and C. J. Briggs. 2016. Large-scale recovery of an endangered amphibian despite ongoing exposure to multiple stressors. *Proceedings of the National Academy of Sciences* 113:11889–11894.
- Nash, C. S., J. S. Selker, G. E. Grant, S. L. Lewis, and P. Noël. 2018. A physical framework for evaluating net effects of wet meadow restoration on late-summer streamflow. *Ecohydrology* 11:e1953.
- Noa-Yarasca, E., M. Babbar-Sebens, and C. Jordan. 2023. An improved model of shade-affected stream temperature in Soil & Water Assessment Tool. *Hydrology and Earth System Sciences* 27:739–759.
- Tullos, D., D. W. Baker, J. Crowe Curran, M. Schwar, and J. Schwartz. 2021. Enhancing Resilience of River Restoration Design in Systems Undergoing Change. *Journal of*

Hydraulic Engineering 147:03121001.

The State of Climate Adaptation Science for Ecosystems in the Northwest U.S.

COASTAL AND MARINE ECOSYSTEMS



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Photo: Oregon coast. Credit: Photo by Emily Fusco

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COASTAL AND MARINE ECOSYSTEM DESCRIPTION

The Pacific Northwest (PNW) coast has a marine-influenced climate characterized by minimal temperature extremes, mild winters and relatively cool summers compared to inland regions in the U.S. West. The region receives abundant precipitation during the extended winter rainy season (November to April). In the southern part of the region, dense fog is prevalent, especially during the summer dry season.

Coastal ecosystems are diverse, encompassing coastal lowlands, coastal uplands, inland coastal systems, and the transition habitat between them. The coastal lowlands include sand dunes, expansive stretches of beach, rocky intertidal zones, and marine terraces below 400 feet (122 m) elevation. Much of the area has been residentially or commercially developed, including recreational developments. Inland coastal systems include the Salish Sea, Puget Sound, and Strait of Juan de Fuca. Tannic streams, marshes, and estuaries are important water features of coastal lowlands and inland coastal systems, with most watercourses flowing directly to the Pacific Ocean. Coastal uplands contain headlands, marine high terraces, and low mountains surrounding the coastal lowlands.

Estuaries are vital habitats, serving as breeding and nursery grounds for economically and culturally important fish such as salmon, sturgeon, and herring. The unique transition from shoreline to forest habitat in a relatively short distance is a distinctive feature of the PNW coast and provides habitat for endemic plant communities and wildlife. People in the PNW are heavily reliant on the ecosystem services coasts provide, including cultural resources, recreation, economic and industry opportunities, food, and protection from natural disasters (e.g., natural storm and flood buffers).

Climate change will continue to alter both atmospheric and oceanic conditions, and the compounded effects will substantially affect PNW coastal ecosystems. Direct effects include increases in air and sea surface temperature (SST). Generally, the PNW coast is projected to warm in all seasons, with the greatest temperature increases in summer (see Climate

Section). Oceans have warmed, absorbing more than 90% of the excess heat produced by rising greenhouse gases, and will continue to warm through the 21st century (IPCC 2019).



Pacific City, Oregon from Cape Kiwanda. (Left) 1930 image of coast pre-development. Wide beach with sand continuing landward, minimal vegetation. (Right) 2012 image of the same area showing coastal development, vegetation, and dune growth. Figure courtesy of S.D. Hacker, OSU

INTERACTION OF CLIMATE CHANGE AND ECOSYSTEM STRESSORS

This section provides an overview of the effects of climate change on coastal ecosystems in the PNW. Climate change will affect coastal ecosystems through increasing temperatures, changes in the frequency and intensity of extreme events, including marine heatwaves and coastal storms. Changes are also expected for long-term, continuous processes such as non-native species invasions, sea level change, and geomorphic processes.

INCREASING AIR AND SEA SURFACE TEMPERATURE

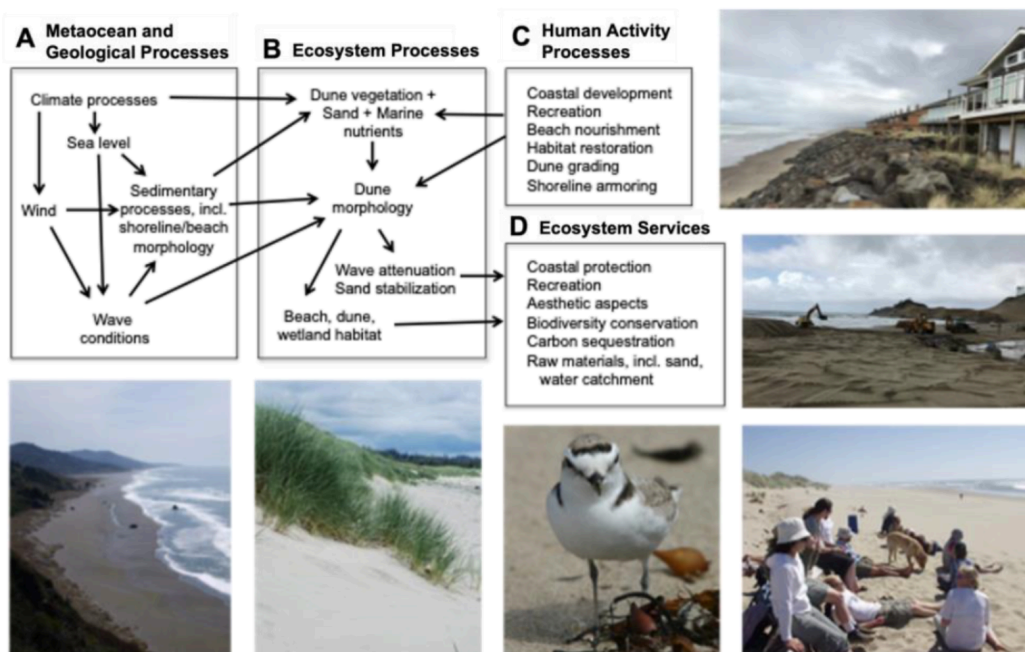
Higher air and sea surface temperatures (SSTs) are expected to affect the abundance and distribution of marine species with cool-water species generally expected to decrease and warm-water species to increase in abundance.

- Higher air temperatures are expected to substantially affect coastal vegetation through increasing evaporative demand and soil moisture depletion, leading to vegetation stress and die-off (Bramwell and Caujapé Castells 2011).
- Higher SSTs are expected to shift the type and quality of prey available for forage fish in the PNW, specifically northern anchovy (*Engraulis mordax*), Pacific sardine (*Sardinops sagax*), jack mackerel (*Trachurus symmetricus*), Pacific herring (*Clupea pallasii*), surf smelt (*Hypomesus pretiosus*), and whitebait smelt (*Allosmerus elongatus*) (Brodeur et al. 2019).
- Changes in the condition and distribution of forage fish, an important link between primary and secondary producers and the upper trophic levels of the marine food web (Pitkitch et al. 2012), will have consequences for ecosystems, such as reduced prey availability for large fish, seabirds, and marine mammals. Given high diversity

CLIMATE EFFECTS: COAST AND MARINE ECOSYSTEMS OVERVIEW

across predatory guilds, changes in forage fish distribution are expected to have variable effects (Thompson et al. 2019).

- Survival rates for Dungeness crab (*Cancer magister*), razor clams (*Siliqua patula*), and red urchins (*Mesocentrotus franciscanus*) are projected to decline by 2100 for a high (RCP 8.5) scenario, compared to historical (1971-2000) conditions (Sunday et al. 2022).
- Due to increasing SSTs and decreasing dissolved oxygen, Alaska pink shrimp (*Pandalus eous*) and anchovy are expected to lose aerobically suitable habitat along the southern portion of their range in the California Current System by the end of the century for a high (RCP 8.5) scenario (Sunday et al. 2022), potentially resulting in northward range shifts.
- Higher temperatures are expected to alter Chinook salmon (*Oncorhynchus tshawytscha*) survival rates in the PNW (Kilduff et al. 2015) and change the distribution and timing of Pacific mackerel (*Scomber japonicus*) and hake (*Merluccius spp.*; Peterson and Schwing 2003).
- Poleward range shifts are expected for salmon, sardine, and other marine fish species in response to warming (Cheung et al. 2015, Morley et al. 2018, Fiechter et al. 2021).
- Throughout the California Current System, seabirds typically associated with colder temperatures are expected to decrease in abundance (Becker et al. 2007, Wolf et al. 2009).



Relationships between physical processes, ecosystem processes, and human activities important to the ecosystem services provided by coastal dunes. Figure courtesy of S.D. Hacker, modified from Ruggerio et al., (2018).

MARINE HEATWAVES

Marine heatwaves (MHWs) have become more frequent, intense, and longer in duration over the past century (1925-2016) (Oliver et al. 2018), and MHWs are expected to increase at an increasing rate with continued warming (DiLorenzo & Mantua 2016, Frolicher et al. 2018, Oliver et al. 2019).

- From 1925 to 2016, global average MHW frequency increased by 34% and duration increased by 17% (Oliver et al. 2018).
- By 2100, under a high (RCP 8.5) scenario, MHWs are expected to be 10 times more intense and occur 50 times more frequently globally than they did historically (1850-1900) (IPCC 2019).

Coastal habitats are especially vulnerable to MHWs, which can have significant direct and indirect effects throughout coastal systems.

- Extreme elevated and prolonged SSTs from MHWs can prompt shifts in weather patterns, altering wind, humidity, and precipitation, and further increasing air temperature (Ibrahim et al. 2021).
- The effects of MHWs are mixed among species (Brodeur et al. 2019). MHWs trigger a bottom-up effect through the food web by directly affecting the abundance and community composition of primary producers such as phytoplankton (Wyatt 2022). Changes in primary production severely affect intermediate trophic levels containing macrozooplankton and micronekton (i.e, large crustaceans and small fish and squid). Changes in prey availability influence the foraging, survival, and reproduction of higher trophic levels, such as marine mammals and seabirds (Piatt 2020).
- Eelgrass beds (*Zostera marina*) and marine ecosystems within estuaries show signs of temperature stress during MHWs, particularly narrower, shallower estuaries that normally have higher water temperatures. These eelgrass beds can have significant eelgrass declines during MHWs (Magel et al. 2022).
- The prevalence of Eelgrass Wasting Disease (EWD) is strongly positively correlated with increases in SST during MHWs, which reduces the resilience of eelgrass species (Groner et al. 2021).
- In the southern portion of the Coast ecoregion, deeper and colder estuaries may act as sanctuaries for eelgrass, but macroalgae may not find refuge in these conditions (Magel et al. 2022).

Marine heatwaves will have varied effects on the survival, abundance, and distribution of different marine organisms.

- An increase in the frequency of MHWs is expected to cause marine organisms to exceed their physiological tolerances, causing range shifts or mortality (Frolicher et al. 2018); however, individual species and system-specific responses to MHWs will be variable.

- In the PNW, MHWs have resulted in widespread mortality of seabirds, including the common murre (*Uria aalge*) (Piatt et al. 2020) and Cassin's auklets (*Ptychoramphus aleuticus*) (Jones et al. 2017).
- A MHW event lasting two to three years can decrease plankton densities (Brodeur et al. 2019) and cause changes in spawning timing and poleward migration of fish populations (Auth et al. 2018). Specifically, Pacific sardine (*Sardinops sagax*) and Pacific hake (*Merluccius productus*) exhibited an unprecedented northward spawning expansion, and increased, continuous spawning duration throughout the 2014-2016 MHW.
- MHWs can negatively affect marine mammals, such as mass strandings of whales, anomalous mortality of pinnipeds (Cavole et al. 2016), and whale entanglements associated with habitat loss (Santora et al. 2020).
- MHWs increase harmful algal blooms, consequently increasing toxicity to marine mammals, as well as people who consume shellfish (Leising et al. 2015, McCabe et al. 2016, Trainer 2020).

EL NIÑO SOUTHERN OSCILLATION (ENSO)

ENSO patterns have direct effects on climate and ecosystems (Box 1), but the effects of climate change on future frequency and intensity of ENSO cycles remain uncertain and is an active area of research (Collins et al. 2010).

- Some studies estimate an increase in the frequency of extreme ENSO events (Cai et al. 2015), with one study projecting a doubling of extreme El Niño events (Cai et al. 2014). However, another study projects ENSO strength will weaken with global warming (Callahan et al. 2021).
- It is uncertain whether the variability in ENSO since 2000 is due to human-caused factors or natural variability, making it more difficult to project future ENSO conditions (Beobide-Arsuaga et al. 2021).
- Specific response to changes in ENSO will continue to vary regionally along the PNW coast depending on where sea-surface temperature anomalies occur.
- Current research aims to strengthen the projection capabilities of future ENSO patterns and its impacts (Tang 2018, Zhou and Zhang 2022).

BOX 1: EL NIÑO SOUTHERN OSCILLATION AND EFFECTS ON ECOSYSTEMS

Within the California Current System, El Niño is associated with reduced upwelling, sea level rise, and anomalously warm temperatures (Lehodey et al. 2020). The PNW experiences extreme changes in SSTs, sea level pressure, and atmospheric forcing (Banard 2017). During El Niño events, the PNW often experiences milder winters, with reduced precipitation and snowpack, which can lead to cascading effects for drought and water supply.

El Niño often affects coastal habitats and wildlife, with consequences for the people who depend on these resources. Reduced precipitation during El Niño reduces water available for habitat, wildlife, and humans (Banard 2017). SSTs and climate anomalies during El Niño are associated with higher likelihood of coastal flooding and erosion along the PNW coast (Olmata Schult et al. 2023). Dramatic changes in the distribution and range expansion of many fish and invertebrate species have been documented during El Niño, including reduced forage fish (Lehodey 2020). Intense El Niño events are strongly linked to decreases in coho and Chinook salmon (*Oncorhynchus kisutch* and *O. tshawytscha*) abundance in California and Oregon (Lehodey et al. 2020).

IMPACTS OF BIOTIC STRESSORS - INVASIVE SPECIES

Throughout the PNW, vegetation plays a key role in dune structure and function, directly affecting the exposure of human populations to storm-wave overtopping and sea level rise (Seabloom 2013, Ruggiero 2018). Many dunes in the PNW have undergone significant changes in structure due to the introduction of two non-native beachgrasses; European beachgrass (*Ammophila arenaria*), and American beachgrass (*A. breviligulata*) (Hacker et al. 2012). The recent emergence of a genetic hybrid beachgrass resulting from the invasive American and European beachgrasses poses concern (Mostow et al. 2021) for dune ecosystems. Over 300 patches of the hybrid have been discovered since 2019 between North Beach, Washington, and Pacific City, Oregon (Askerooth 2023).

Interaction of climate change and invasive beachgrasses will have varied effects on coastal dunes.

- Climate change can influence the structure of dunes through changes in precipitation and storm conditions that are linked to dune vegetation growth and sediment deposition (Ruggiero 2018).
- Increasing temperatures are expected to change the range of invasive beachgrass. Modeling indicates that American beachgrass will have lower biomass with warming, and that warming is expected to restrict the southern limit of its range. European beachgrass has a neutral or positive response to warming and sand burial, and this physiological tolerance suggests the distribution of European beachgrass could expand with warming (Biel and Hacker 2021).

Warming ocean temperatures and El Niño events may increase the persistence and expand the range of the invasive European green crab in coastal estuaries and marshes of the PNW.

- Populations of the European green crab (*Carcinus maenas*), one of the most damaging invasive species globally, have established in coastal estuaries, salt marshes, and mudflats since first observed in the PNW in 1989 (Behrens Yamada

2021). Invasions pose threats to marine food web processes, as green crabs prey on clams, mussels, scallops and oysters, and displace native species.

- The range of the European green crab is expanding in the PNW, with the first occurrences of the crab in the Strait of Juan de Fuca, San Juan Islands, and Padilla Bay, Washington from 2012-2016 (Grason et al. 2018), and Salt Spring Island and Boundary Bay, British Columbia since 2018 (Behrens Yamada 2021, Ens et al. 2022).
- Range expansion of European green crab is expected to continue throughout the Salish Sea, including within marine protected areas, with few northward barriers (Brasseale et al. 2019, Iacarella 2020).
- European green crab recruitment is positively correlated with warm ocean indicators (Behrens Yamada et al. 2021), specifically warm winters ($>10^{\circ}\text{C}$), strong northward coastal water flow during winter, and coastal circulation patterns that keep larvae close to shore.
- Large range expansions and high crab abundance have been linked to strong El Niño events in the PNW (Behrens Yamada et al. 2021).

SEA LEVEL CHANGE

Sea level is rising globally and along much of the PNW coastline, which will have multiple impacts on coastal ecosystems.

- Global mean sea level rise (SLR) has accelerated due to thermal expansion from warming oceans and increased glacial melt. Global mean SLR nearly tripled from a historical (1901-1990) average rate of 0.05 ± 0.01 inches per year (1.2 ± 0.2 mm per year) to an average rate of 0.13 ± 0.02 inches per year (3.4 ± 0.4 mm per year) during the 30-year satellite era (1993-2022) (Beckley et al. 2021).
- Global SLR is projected to accelerate through the 21st century (Sweet et al. 2017, Dangendorf et al. 2019). SLR at specific locations differs from global SLR due to differences in local terrain factors, such as varying tectonic subsidence or uplift, ocean currents, and variations in land height.
- Relative SLR, the change in sea surface height relative to the adjacent land surface, for the PNW coast is rising on average, but less than the average for the US coastline. For 2020 to 2050, the projected range for SLR is 4 inches (102 mm, low scenario) to 12 inches (305 mm, high scenario) relative to the baseline sea level of 2000 (Sweet et al. 2022). Projections of SLR through 2150 show increases at an accelerating rate.
- For the Washington coast specifically, the likely range (83-17% probability) of SLR projections by 2100 is 1.0 - 2.2 ft (0.30 - 0.67 m) for a low (RCP 4.5) scenario and 1.4 - 2.8 ft (0.43 - 0.85 m) for a high (RCP 8.5) scenario (Miller et al. 2018). Locally, relative SLR will vary due to variations in land subsidence and uplift along the Washington coast.

SLR is expected to exacerbate storm surges and flooding, as higher total water levels contribute to flooding further inland during surge events and coastal storms (Miller et al. 2019, Sweet et al. 2022).

- Extreme wave height has increased an average of 0.93 inches (23.5 mm) per year from 1985-2007 on the U.S. West Coast (Menéndez et al. 2008).
- Storm surges and king tides that reach further inland (Miller et al. 2019) are expected to cause loss of coastal habitats, which offer coastal flood protection for coastal communities (Reeder et al. 2013).
- The interaction of storm surges and river discharge can have variable effects on coastal flooding (Bilskie and Hagen 2018), so the extent and magnitude of coastal flooding will be underpredicted if both oceanic and riverine conditions are not accounted for (Serafin et al. 2019).
- Elevated water levels are expected to increase beach erosion and loss of shoreline habitats (Toimil et al. 2019).

SLR is expected to substantially threaten the existence and sustainability of tidal wetlands, marshes, and estuaries in the 21st century.

- The extent of tidal wetlands is expected to change through the century, with increases or decreases locally depending on sedimentation, the rate of SLR, wetland type, and surrounding landward buffers (Schuerch et al. 2018).
- SLR is expected to shrink areas of suitable elevation for tidal wetlands, marshes, and mudflats (Moritsch et al. 2022) and increase the risk of complete submergence of these critical habitats (Thorne et al. 2012, Brophy et al. 2019, Myers et al. 2019).
- One study indicates a complete loss of current tidal wetlands under high SLR scenarios (+55.9 – 65.4 inches; +142-166 cm) in Oregon and California and a 68% loss of tidal wetlands in Washington by 2110 (Thorne et al. 2018). Tidal freshwater marsh area in California, Washington, and Oregon is projected to decrease between 0% and 29% by 2110 relative to 1980-1999 (Thorne et al. 2018).
- Wetland retreat or inland migration is often not possible in the PNW coast, as migration is typically constrained by urban development, steep topography, diked pasturelands, and agricultural lands (Parker and Boyer 2019, Osland et al. 2022), a phenomenon known as “coastal squeeze” (Krosby et al. 2023).

In estuaries of the PNW coast, the rate of SLR compared to the rate of elevation change due to sediment accretion and deposition is important in determining estuarine habitat resilience.

- Tidal marshes and estuaries are more resilient to SLR with sufficient sediment delivery such that sediment accretion rates match or exceed SLR rates (Davis et al. 2022). Rates of vertical accretion that are slower than rates of SLR, can result in soil destabilization and vegetation loss in tidal wetlands (Herbert et al. 2021).
- Marshes at higher initial elevations, with high sediment supply, and with flood-tolerant plant species are expected to have lower near-term vulnerability to submergence (Thorne et al. 2018).

- Throughout the Puget Sound, numerous estuaries are projected to match or surpass expected rates of relative SLR by 2100, suggesting that estuarine ecosystem resilience to SLR is contingent on consistent sediment delivery (Davis et al. 2022).

The loss of estuarine habitats due to SLR threatens the survival of fish and wildlife species.

- Tidal wetlands, marshes, and estuaries in the PNW are important habitat for salmon, forage fish, invertebrates, birds, and culturally significant shellfish beds (Swinomish Tribal Community 2009).
- Many fish species, including juvenile salmon (*Oncorhynchus* spp.), rely on estuaries, salt marshes, and eelgrass meadows as nursery grounds for enhanced prey availability, abiotic and biotic protection from predators, and seasonal nutrient pulses (Davis et al. 2022). For example, in the Skagit River delta, Chinook salmon, Pacific herring, surf smelt, and shiner perch (*Cymatogaster aggregata*) are more abundant in eelgrass habitat than unvegetated areas, highlighting the importance of delta eelgrass habitat (Rubin et al. 2018).
- The combination of higher ocean temperatures and SLR is expected to decrease the quality of estuary habitats for out-migrating salmon and other sensitive fish species (Davis et al. 2022).
- SLR is expected to prevent inland beach migration, causing a significant loss of forage fish spawning habitat. According to one study, by 2100, most spawning habitat in the intertidal zone of Puget Sound will be lost for two ecologically important species, surf smelt and Pacific sand lance (*Ammodytes hexapterus*), assuming SLR of 5.1 - 27.3 inches (12.95 – 69.34 cm) (Krueger et al. 2010).
- Low elevation emergent marsh, high-elevation marsh, and eelgrass habitats provide abundant prey and favorable growth conditions (Kennedy et al. 2018), but these habitats become less suitable during the summer when ocean temperatures are warmer (Davis et al. 2022).
- Implementing target management strategies that restore, maintain, and improve emergent marsh habitats, and improve habitat connectivity throughout the tidal cycle, can support the growth and survival of important fish species.
- Management actions that enhance foraging capacity and the availability of thermal refugia can help sustain fish populations in the face of climate change.

GEOMORPHIC PROCESSES & COASTAL EROSION

Coastal habitat, such as dunes, salt marshes, shellfish beds, and forage fish spawning areas can become eroded by high waves, SLR, and changes in wind direction and power. In the PNW, generally waves and wind exhibit seasonal cyclical patterns, coming from the northwest in the summer and from the southwest in the winter. This causes beaches and dunes to undergo a seasonal pattern of eroding in the winter and rebuilding in the summer, resulting in a nearly balanced sediment budget. These typical patterns of sediment dynamics in coastal habitats are expected to be affected by climate change. In

addition to habitat benefits, these coastal habitats help protect people and infrastructure from climate-related stressors such as coastal erosion and flooding.

Climate change will increase coastal erosion through rising seas. Changes in wave height and direction may also affect coastal erosion, but trends and future projections of waves on the PNW coast remain uncertain.

- Along the Oregon coast, the rate of shoreline erosion has increased in recent decades (2002-2016) relative to historical trends (1967-2002) (Light 2021).
- Wave conditions, short-term wave-driven processes, and swell dominate coastal erosion (Shope et al. 2022, Allan et al. 2006).
- Accelerating SLR is causing chronic coastal erosion directly by landward coastline displacement (Toimil et al. 2020).
- Global wave power has increased approximately 0.4% per year since 1948 due to ocean warming (Reguero et al. 2019). Global studies indicate that climate change is expected to change mean and extreme wave conditions in the future (Toimil et al. 2020).
- El Niño events are associated with 30% larger wave energy (Barnard et al. 2017, Reguero et al. 2019) and 8 – 12 inches (20 – 30 cm) of elevated sea level anomalies (Barnard et al. 2017), when compared to a normal winter on the West coast. Thus, major El Niño events are associated with significant coastal erosion (Allan and Komar 2006, Barnard et al. 2017).
- Recent analyses and measurements of wave heights on the PNW coast suggest that they have been increasing (Ruggiero et al., 2013), but other studies show that these trends may be related to climatic variability (Seymour 2011) or methodology (Gemmrich 2011), so future trends remain uncertain.

AREAS FOR FUTURE RESEARCH

Shoreline erosion monitoring, data, and tools: There is a need for long-term shoreline change monitoring, shoreline-change data in open-source repositories, more frequent airborne LIDAR surveys, and modeling tools to project shoreline erosion from multiple combined stressors.

Sediment movement in estuaries: Further research on regional sediment sinks, sources, and transport pathways in estuaries is needed to inform management decisions (Olmata Schult et al. 2023).

Flood-tolerant plants in estuaries: There is a need to evaluate the tolerance of plant species in estuaries to flooding. Information is limited on the productivity of coastal plants under different CO₂ and temperature scenarios (Parker and Boyer 2019).

Flood risk in wetlands: Research is needed on flood risk reduction provided by natural features and wetland restoration to support planning and management (Janousek et al. 2019). Wetland responses to SLR will vary regionally, so tools are needed that can project

individual outcomes for different sites to estimate the effects of future impacts and restoration planning (Thorne et al. 2018).

Long term-effects of restoration: The long-term effects of revegetation and habitat restoration in dunes, tidal wetlands, salt marshes, and estuarine habitats for reducing SLR impacts are not well understood (Gregg et al. 2018).

Future ENSO projections: Consistent projections of how climate change will affect ENSO dynamics in the coming decades remain a key knowledge gap.

More species-specific and region-specific data collection: Assessment is needed on how different plant and wildlife species will respond to MHWs and SLR. Specifically, knowledge gaps exist in determining how vulnerable marine organisms with reduced mobility will respond to MHWs. Knowledge is also limited on the effects of higher temperatures and salinity on specific plant species (Parker and Boyer 2019).

Interdisciplinary research: Throughout the scientific literature, a common theme is the need for interdisciplinary research to assess the complex ways oceanic and climate processes affect coastal ecosystem structure, function, and the communities that rely on them. Collaboration across scales, institutions, cultures, and disciplines substantially improves planning for coastal resilience.

Coast Range

Coast and Marine Ecosystems



Regional Description

The complex Coast ecoregion stretches along the western edge of northern California, Washington, Oregon, and British Columbia and encompasses a diverse range of ecosystems.

Coastal lowlands are characterized by expansive stretches of beach, coastal dunes, estuaries, and marshes. Coastal uplands contain headlands, high marine terraces, and highly productive coniferous forests. The unique transition from shoreline to forest provides habitat for many local plant species and wildlife.



Dense vegetation is present on the coast of Oregon at Ecola State Park.
Photo Credit: Emily Fusco

Pacific Northwest Observed and Projected Sea Level Rise

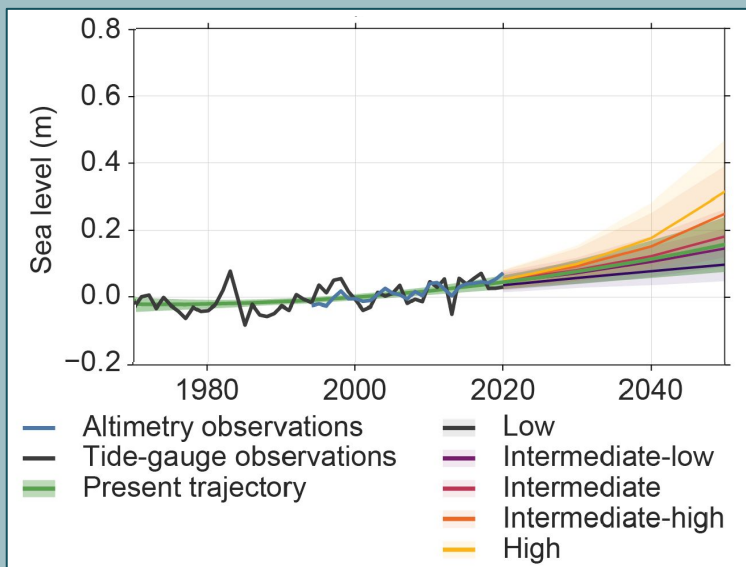


Figure adapted from Sweet et al. 2022, Figure 2.3

Sea level along the Pacific Northwest coastline has risen 2 to 4 inches on average between 1920 and 2020 (Sweet et al. 2022). With continued warming, sea level is projected to rise by 6 in (0.15 m) for an intermediate-low scenario and 10 in (0.25 m) for intermediate-high scenario between 2020 and 2050, relative to the baseline sea level of 2000 (Sweet et al. 2022). This is less than the average for the conterminous US.

Management Considerations

- Humans are interconnected with Pacific Northwest coastal and marine ecosystems, relying on them for economic opportunities, cultural practices, food, and recreation.
- Much of the Coast ecoregion shoreline is developed for residential and commercial uses.
- Coastal dune and beaches support myriad ecosystem process and provide multiple, often competing, ecosystem services to humans such as recreation, aesthetics, and flood protection.
- Ocean forcings, primarily the El Niño Southern Oscillation and the Pacific Decadal Oscillation, will continue to drive interannual variability in sea level along the Pacific Coast and influence ecosystem processes.
- The extent to which the El Niño Southern Oscillation and the Pacific Decadal Oscillation will be affected by human-caused climate change continues to be an active area of research without clear evidence of trends.
- Non-native plant species, such as invasive beachgrasses, are also affecting coastal dune habitats. The effects of climate change on the productivity and distribution of invasive beachgrass is an active area of research.



Managing Ecosystem Stressors



Marine Heatwaves

Description

Marine heatwaves (MHW) have become more frequent, intense, and longer in duration since 1925 (Oliver et al. 2018), and MHW are expected to increase at an increasing rate with future warming (Frolicher et al. 2018, Oliver et al. 2019). MHWs can cause mass mortality of marine species with cascading effects on ocean and coastal ecosystem processes.

Strategy Habitats

- Northeast Pacific Ocean
- Rocky intertidal zone
- These habitats in the Coast ecoregion support species from the foundation of the food web, such as phytoplankton, to fish, to higher trophic level marine mammals.

Management Actions

- Reducing other human-caused stressors, such as pollution and overfishing, can increase the resilience of marine species and habitats to the effects of MHWs.
- Prioritizing critical habitats by establishing marine protected areas can protect habitat for species that are especially vulnerable to MHWs.



Sea Level Rise

Description

Sea level rise (SLR) will vary along the coastline with differences in vertical land movement. Areas with SLR will experience more frequent and deeper coastal floods, with floods extending further inland. Saltwater intrusion into freshwater and brackish marshes will increase.

Strategy Habitats

- Coastal estuaries- important for salmon, benthic invertebrates, birds, shellfish, and plants
- Coastal wetlands- important for fish, amphibians, breeding and stopover grounds for waterfowl

Management Actions

- Land acquisitions for coastal habitat protection and restoration will be more resilient if projects consider future inundation.
- Consider managed retreats to allow for wetland or estuary migration inland where feasible and where barriers can be removed.



Coastal Erosion

Description

With higher sea levels, wave action increases the likelihood and extent of coastal erosion, even without changes in wave energy which are uncertain (Miller et al. 2019, Sweet et al. 2022). Heavier rainfall and riverine flooding also will contribute to coastal erosion that can reduce habitat area and natural flood protection.

Strategy Habitats

- Coastal dunes, beaches, and bluffs
- Salt marshes
- Critical habitat for endangered western snowy plover

Management Actions

- Dune reconstruction and revegetation can reduce the impacts of storms, minimizing erosion and flooding (Fernandez-Montblanc et al. 2020).
- Dune restoration may be more feasible in remote areas where there is less emphasis on protecting coastal communities.

Puget Lowlands

Coast and Marine Ecosystems



Regional Description

Coastal inland systems in the Puget Lowlands ecoregion are characterized by interconnected networks of wetlands, waterways, and riparian areas. Major coastal inland systems include the Salish Sea and Strait of Juan de Fuca, which feature dynamic bays, saltwater estuaries, marshes, and numerous peninsulas and islands. Influenced by the nearby Pacific Ocean and the Olympic and Cascade Mountains, these areas experience mild temperatures and abundant annual precipitation.

Management Considerations

- The Puget Lowlands has a history of high economic productivity, supporting industries such as fishing, shellfish, tourism, and shipping.
- Cultural significance for Indigenous communities is high, further underscoring the importance of the ecosystems for human livelihood.
- Development along the Puget Lowland coastline has altered estuarine habitat, creating barriers to inland migration of habitat as sea level rises.
- Human modification for flood protection and agriculture has changed ecosystem processes affecting the input of saline and fresh water.
- Sediment supply and transport to estuarine habitat has also been heavily modified.

Estuarine Habitats

- Estuarine habitats are diverse and plant associations change quickly with small changes in elevation from just below to just above sea level.
- Estuarine habitats that are sensitive to changes in sea level rise and other climate-related stressors are eelgrass beds, mud flats, tidal marshes (freshwater, saltwater, and brackish), and tidal forests.
- Estuarine habitats are important for fish, shellfish, amphibians, and function as breeding and stopover grounds for waterfowl. For example, in the Skagit River delta, Chinook salmon, Pacific herring, Shiner perch, and surf smelt utilize eelgrass meadows.

Relative Sea Level Rise

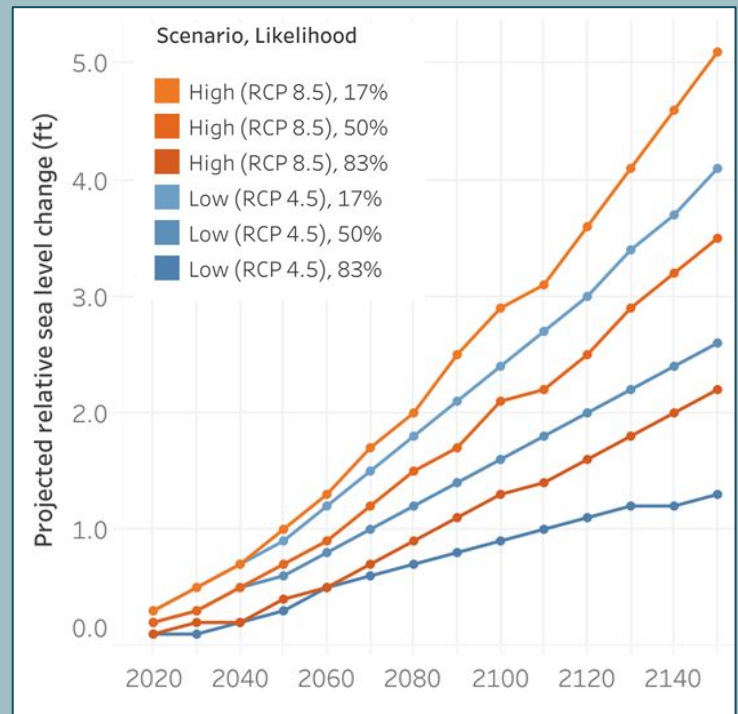


Figure generated with the Interactive Sea Level Rise Data Visualization (Lavin et al. 2019). SLR data (Miller et al. 2018).

For this example location on Puget Sound, the likely range (17% - 83%) of relative sea level rise is about 1.5ft to 3ft (high scenario) compared to the 1991-2009 average (Miller et al. 2018). Sea level is expected to rise along the Puget Lowlands coast as sea surface height increases and land subsides.



Eelgrass can be seen in this aerial view of the Padilla Bay, at the end of the Skagit River Delta. Photo Credit: WA State Dept. of Ecology, Ecology Shoreline Photos. CC BY-NC 2.0

Puget Lowlands Coast and Marine Ecosystems



Managing Ecosystem Stressors



Sea Level Rise

Description

Sea surface height in the Puget Sound and the Strait of Juan de Fuca is projected to increase. Land along the Strait of Juan de Fuca is uplifting, whereas much of the Puget Sound coastline is subsiding, contributing to sea level rise relative to land. Higher seas increase coastal flooding frequency and extend floodwaters further inland. This will modify coastal habitats with cascading effects for wildlife species. Estuarine habitat will contract in some places but could expand where inland migration is not constrained by built or natural barriers.

Management Actions

- Strategic acquisition of coastal habitats for restoration in locations that allow for landward migration of estuarine habitat.
- Topography restoration (such as dredging, excavating, or filling) to remove or add layers of surface material to alter elevations for habitat restoration. Creating irregular topography supports the development of microhabitats as sea level rises (Diefenderfer et al., 2018).



Changes in Salinity

Description

Rising seas and changing streamflows will disrupt the salt to fresh water balance in estuarine habitat. The salinity of groundwater and pore water will increase as denser salt water pushes further into freshwater habitats. Changes in streamflow will affect the amount and timing of freshwater inputs, which will influence the extent of saltwater, brackish, and freshwater marsh habitat. Higher salinity adversely affects plants adapted to a narrow balance of fresh and saline water in estuaries.

Management Actions

- Selecting appropriate plant species for revegetation that reflect the expected rate and amount of sea level rise will increase restoration success despite higher salinity.
- Restoration projects in marsh habitats are more likely to increase recruitment and survival of marsh vegetation when designed to maintain sufficient freshwater input, even as freshwater input declines in summer (Raymond et al., 2018).



Altered Sediment Dynamics

Description

Climate change is expected to alter sediment processes in the Puget lowlands, which are already heavily modified by humans (Grossman et al., 2020). Heavier rainfall will increase sediment transport in rivers (Lee et al., 2015). Greater wave energy is expected to increase sediment mobility leading to bluff, beach, and barrier erosion and sediment loss (Ruggiero, 2013). Estuarine habitat with intact sediment processes that promote vertical accretion will better keep pace with SLR.

Management Actions

- Removing shoreline armor or other structures built to protect shorelines from wave-driven erosion can restore sediment input and transport.
- Removing dikes and berms built to eliminate tidal flooding can reconnect estuarine habitat with tidal waters, and restore sediment supply and transport.
- Focusing restoration in areas with more intact sediment processes can increase success in a changing climate.

CLIMATE ADAPTATION: Coast and Marine Ecosystems



Overview

Resource managers are implementing adaptation strategies in northwest coastal and marine ecosystems. These strategies can be categorized using the Resist, Accept, Direct (RAD) Framework (Schuurman et al. 2020, NPS). Resistance strategies maintain species and habitats in their current conditions. Acceptance involves little intervention, and allows ecological change. Strategies that direct ecological change typically include interventions that encourage less negative, or even desirable, changes to species and habitats.

Adaptation Options

Transform Topography

WHAT IT MEANS: Adaptive topography transformations can include altering elevation, aspect, and slope to promote vegetation growth and increased habitat heterogeneity. Topography can be altered through indirect processes such as revegetation, or direct processes such as dredging or excavating.

WHY IT WORKS: For estuarine systems, steep upland slopes can limit inland migration of species with sea level rise. In outer coastal systems, dune morphology can help mitigate erosion from wave action, or negative effects from sea level rise. Alterations to topography can also create habitat heterogeneity, and therefore microclimates, that act as climate change refugia.

FINDING THE SCIENCE:

- Diefenderer et al. 2018. Ecol. Eng.**
- Creating mounds in tidal and estuarine systems increased habitat heterogeneity through soil moisture microclimates.
- Thorne et al. 2018. Sci. Adv.**
- Steep topography that limits upslope movement of estuarine systems with sea level rise is common in the Pacific Northwest.
- Biel et al. 2017. Ecosphere.**
- Invasive beach grasses are positively associated with dune height and coastal protection, and negatively associated with nesting habitat for the western snowy plover.
 - Tradeoffs for coastal protection and western snowy plover habitat vary across beaches, suggesting that some coastal areas are better candidates for invasive dune grass removal.

NISQUALLY RIVER DELTA RESTORATION

DESCRIPTION: The Nisqually River delta, located at the southern end of the Puget Sound, was leveed in the early 1900s for agricultural purposes. The levees created barriers for migrating fish (including native salmon species) and resulted in a loss of typical estuarine tidal hydrology. To restore these habitats, initial dike removal began in the early 1990s and nearly 4 miles of dike were removed in 2009, making this delta restoration project the largest in the PNW. Key partners included the Nisqually Indian Tribe, the U.S. Fish and Wildlife Service, and Ducks Unlimited. Throughout the course of this project, nearly 1000 acres of salt marsh were restored, and fish habitat connectivity has increased. This restoration project is an example of removing local stressors (dikes), and protecting priority habitat through restoration. Removing barriers also provides opportunities for inland migration of estuarine habitat and can buffer against sea level rise.

AT A GLANCE:

- Goals: Restore estuarine habitats, habitat connectivity, and create resilience to sea level rise
- Location: Nisqually National Wildlife Refuge, Southern Puget Sound
- Timeline: 1990's - 2009, with monitoring ongoing
- Strategies: Protect priority habitat, reduce local stressors, transform topography
- Relevant Link: [Nisqually Delta Restoration](#); [CAKE: Climate Adaptation Knowledge Exchange Case Study](#)



Boardwalk through the Nisqually delta ecosystem at the Billy Frank Jr. Nisqually National Wildlife Refuge. Photo: Emily Fusco

CLIMATE ADAPTATION: Coast and Marine Ecosystems



WHAT IT MEANS: Models, observational study, and expert elicitation can all be used to identify high priority ecosystems and habitats for reaching climate adaptation goals. Once areas are identified, protection efforts may include adding conservation areas through acquisition and alleviating human use stressors through altered use designations and regulations.

WHY IT WORKS: One major adaptation benefit of protecting priority habitat is the potential to increase habitat connectivity, allowing for species dispersal and potential range shifts. By providing species with opportunities to shift into new geographic areas, practitioners can both accept and direct climate effects to ecosystems. For example, adding adjacent upland habitat to currently protected estuarine systems may allow for the landward migration of species with sea level rise. Protecting priority habitats can also be a resistance strategy when used to create climate refugia. This could include prioritizing the protection of tide pools that receive lower levels of solar exposure based on aspect, thereby buffering extreme heat events. Priority areas may also be identified as those with high vulnerability to climate stressors, and protection may include reducing other local stressors to increase resistance. Finally, protected habitats can serve as valuable areas for scientific research and monitoring of climate change effects.

FINDING THE SCIENCE:

Arafeh-Dalmau et al. 2023. One Earth.

- A transboundary approach to identifying climate-smart marine protected areas includes consideration of habitat representation, unique and important areas, longevity, connectivity, and local threats.

Hesketh and Harley, 2022. Glob. Change Biol.

- Barnacle mortality in tidepools in the Salish Sea was lower on steeply sloped and northeast facing tidepools during the 2021 Pacific Northwest Heat Dome.

Robert et al. 2017. PNAS

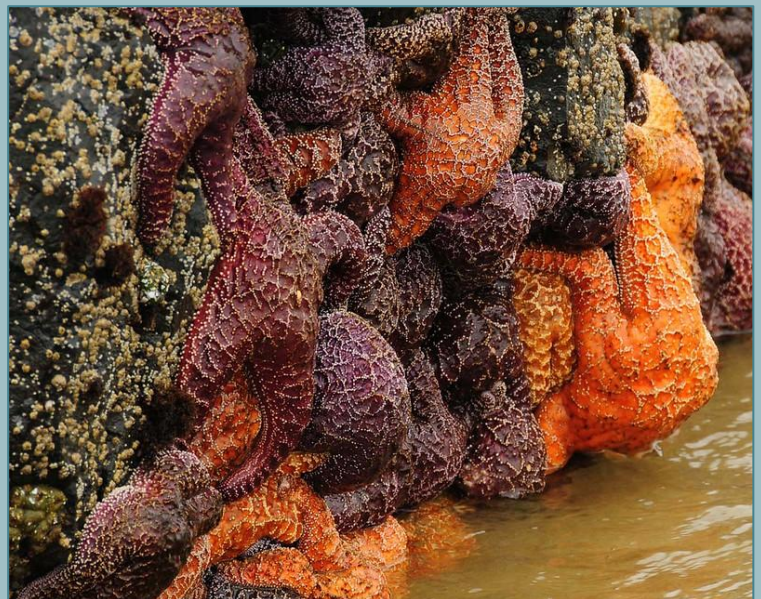
- Reviews climate adaptation benefits marine protected areas, including promoting genetic diversity, providing habitat connectivity, and providing areas of reduced local stressors.

OREGON MARINE RESERVES PROGRAM

DESCRIPTION: The Oregon Marine Reserves consist of five nearshore sites that encompass a variety of habitats, including rocky intertidal zones, kelp beds, and soft sediment areas. The reserve program was established in 2009 and high priority sites were identified based in part on biodiversity and natural features of interest. Monitoring at the sites began in 2010 - 2014, and harvest restrictions at each site began two years after monitoring. Although the goals of the program do not explicitly include climate change adaptation, reserves are meant to conserve local biodiversity by removing harvest and other extraction activities. This could promote genetic diversity in local populations, which is a way to increase species adaptive capacity. These reserves also serve as areas for scientific monitoring which can provide valuable information about climate change effects. To date, the program has been successful in monitoring changes to nearshore environments and collecting data that can be used in nearshore management.

AT A GLANCE:

- Goals: Species/ habitat conservation, scientific study
- Location: Nearshore marine environments in Oregon
- Timeline: 2009 - present
- Strategies: Protect priority habitat, reduce local stressors
- Project Link: [Oregon Marine Reserves Website](#)



Starfish on a rock off the coast of Oregon. Photo: Roy W. Lowe/USFWS CC BY 2.0 DEED

CLIMATE ADAPTATION: Coast and Marine Ecosystems



WHAT IT MEANS: Local stressors include pollution, invasive species, and overexploitation of resources. Reducing these stressors may include identifying and reducing sources of pollution, removing invasive species and restoring native species, or modifying resource use guidelines.

WHY IT WORKS: Ecological theory suggests that organisms' abilities to be resilient in the face of one stressor are often reduced when faced with additional stressors. This is especially true when an organism experiences multiple stressors at the same time, rather than in succession, because there is no time for physiological recovery. Therefore, removing local stressors can promote populations that are more robust to climate related stressors, and provide additional capacity to resist ecological change. Local stressors can also interact with climate change stressors themselves, changing their magnitude or severity. It is important to note that there are exceptions to this depending on the stressors, species, and ecosystems of interest.

FINDING THE SCIENCE:

Gissi et al. 2021. *Sci. Total Environ.*

- The combined effects of climate change and local human stressors are context dependent. At the species level, local human stressors typically intensify negative effects from climate change in marine systems.

Stockbridge et al. 2020. *Sci. Rep.*

- A meta-analysis of seagrass suggests that climate stressors (e.g. increased temperature), combined with other local stressors tend to have negative ecological effects either equal to, or greater than, the sum of their parts.

Clements and Chopin 2017. *Rev. Aquacult.*

- Atmospheric CO₂ is not the only contributor to ocean acidification, particularly in near shore marine areas. By decreasing local stressors, like nutrient runoff that leads to algal blooms and subsequent eutrophication, overall levels of ocean acidification may be mitigated.

Gunderson et al. 2016. *Annu. Rev. Mar. Sci.*

- A review explains the contexts under which multiple stressors may be more, or less, detrimental to organisms in marine systems.

INVASIVE BEACHGRASS REMOVAL

DESCRIPTION: Western snowy plover (*Charadrius nivosus*) and streaked horned lark (*Eremophila alpestris strigata*) require sparsely vegetated sandy areas for nesting, which is at risk due in part to sea level rise and the invasive beachgrasses *Ammophila breviligulata*, *A. arenaria*, and a recently identified hybrid. In 2002, the U.S. Fish and Wildlife Service began removing the invasive beachgrasses from coastal dunes on Willapa National Wildlife Refuge at Leadbetter Point, Washington, using mechanical removal, hand pulling, and herbicide treatments. Employing a resistance strategy, this project reduces local stressors (invasive species), with the aim of restoring priority habitat for native flora and fauna. It also directs ecological transformation by allowing species to migrate inland into new suitable habitats with sea level rise. To date, the project restored over 350 acres (141 ha) of beach habitat, with another 500 acres (202 ha) of restoration underway. Streaked horned lark have increased from a low of five pairs in 2018 to 23 pairs in 2023, with a 10-year average of 10 pairs. Snowy plovers have also increased in number, but less substantially due to several other factors. Native plants have begun to reestablish primarily through natural regeneration and native invertebrates have been documented in the restored ecosystem.

AT A GLANCE:

- Goals: Create resilient habitat for native species by removing invasive grass species
- Location: Leadbetter Point, Willapa National Wildlife Refuge, Washington
- Timeline: 2002 - present
- Strategies: Protect priority habitat, reduce local stressors, transform topography



Restored beach habitat after invasive dune grass removal at Leadbetter Point, Willapa NWR. Photo: William Ritchie/ USFWS

CLIMATE ADAPTATION: Coast and Marine Ecosystems



WHAT IT MEANS: Increasing genetic diversity can increase adaptive capacity, or the ability of species and ecosystems to persist despite climate change. Maximizing genetic diversity can include increasing local population size and adding individuals with new genotypes from non-local populations.

WHY IT WORKS: In theory, increased genetic diversity would increase the likelihood that a species could adapt to changing ecosystem conditions because the species might already have suitable genotypes for new environmental conditions. For example, incorporating individuals from populations in warmer parts of the species' range into local populations could increase adaptive capacity if local populations integrate that genetic material and adapt more quickly. If a local population size is increased (e.g., by reducing predators or changing fisheries management), the local population may also gain higher levels of genetic diversity.

FINDING THE SCIENCE:

Dubois et al. 2022. Glob. Change Biol.

- Populations with genotypes well adapted to higher temperatures can come from the central part of the species range. Here, local populations of eelgrass had variable tolerance to increased temperatures even at fine spatial scales and within the species range interior. It is likely these variations in genotypes were influenced by local stressors.

Thurman et al. 2022. Conserv. Biol.

- Management actions can increase species adaptive capacity directly (e.g. increasing population size), and indirectly (e.g. removing biotic stressors).
- If adaptive capacity cannot be increased, management options can focus on reducing exposure (e.g. providing climate refugia).

Okey et al. 2015. Ocean Coast. Manag.

- Measuring a species adaptive capacity can be difficult. Cumulative impacts from non-climate related stressors can be used as an inverse proxy for adaptive capacity.
- Kelp and seagrass habitats, and shallow and deep rocky reefs were identified as highly vulnerable ecosystems.

MORE ADAPTATION RESOURCES:

● RISING SEAS AND THE COASTAL SQUEEZE DEEP DIVE:

Developed by scientists, managers, and community members, this series of products includes a key findings overview, biophysical, management, and policy syntheses, and a tools database.

Resource Link: [Rising Seas and the Coastal Squeeze Deep Dive | Northwest Climate Adaptation Science Center](#)

● EVALUATING ADAPTATION ACTIONS FOR SEA LEVEL RISE AND COASTAL CHANGE IN THE PACIFIC NORTHWEST

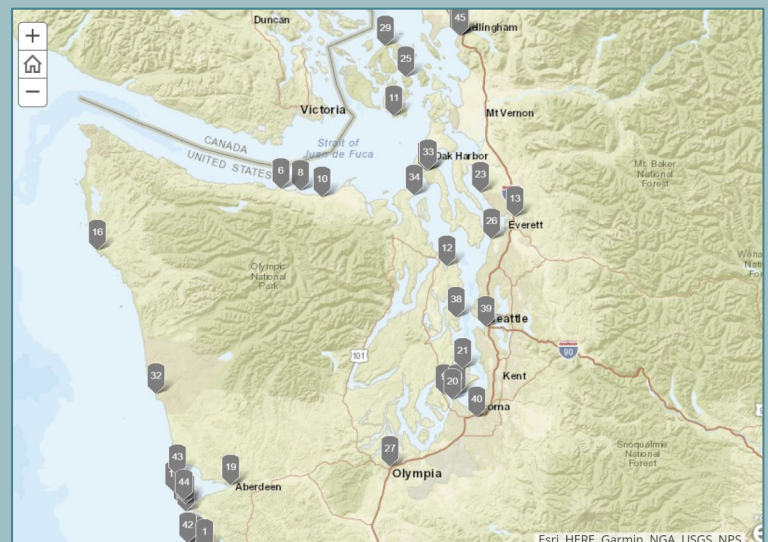
Published in 2018, this assessment provides an overview of adaptation options for sea level rise and includes a tools and literature review database.

Resource Link: [CASC Project Explorer Available Science Assessment Process \(ASAP\)](#)

● WASHINGTON COASTAL HAZARDS AND RESILIENCE NETWORK

This website provides an overview of coastal hazards and a resource library. The associated "Resilience Project Case Studies Mapper" includes 45 examples of coastal resilience projects, many of which relate to sea level rise.

Resource Link: [Washington Coastal Hazards Resilience Network Website](#)



An interactive map from the "Resilience Project Case Studies Mapper" includes information for 45 resilience projects. Image: [Washington Coastal Hazards Resilience Network](#)

REFERENCES - OVERVIEW

- Allan, J. C., and P. D. Komar. 2006. Climate Controls on US West Coast Erosion Processes. *Journal of Coastal Research* 22:511–529.
- Allen, T., D. Eulie, M. Polk, G. McLeod, R. Stuart, A. Garnand, and A. Manning. 2023. Advancing Estuarine Shoreline Change Analysis Using Small Uncrewed Autonomous Systems. *Estuary Research - Recent Advances*.
- Askerooth, R. (n.d.). The Range, Abundance, Spread, and Biophysical Effects of a Novel, Invasive Beachgrass Hybrid, *Ammophila arenaria* × *A. breviligulata*, on U.S. Pacific Northwest Coastal Dunes. Oregon State University.
- Auth, T. D., E. A. Daly, R. D. Brodeur, and J. L. Fisher. 2018. Phenological and distributional shifts in ichthyoplankton associated with recent warming in the northeast Pacific Ocean. *Global Change Biology* 24:259–272.
- Barnard, P. 2017. Extreme oceanographic forcing and coastal response due to the 2015-2016 El niño.
- Barnard, P. L., L. H. Erikson, A. C. Foxgrover, J. A. F. Hart, P. Limber, A. C. O'Neill, M. van Ormondt, S. Vitousek, N. Wood, M. K. Hayden, and J. M. Jones. 2019. Dynamic flood modeling is essential to assess the coastal impacts of climate change. *Scientific Reports* 9:4309.
- Barnard, P. L., D. Hoover, D. M. Hubbard, A. Snyder, B. C. Ludka, J. Allan, G. M. Kaminsky, P. Ruggiero, T. W. Gallien, L. Gabel, D. McCandless, H. M. Weiner, N. Cohn, D. L. Anderson, and K. A. Serafin. 2017. Extreme oceanographic forcing and coastal response due to the 2015–2016 El Niño. *Nature Communications* 8:14365.
- Becker, B. H., M. Z. Peery, and S. R. Beissinger. 2007. Ocean climate and prey availability affect the trophic level and reproductive success of the marbled murrelet, an endangered seabird. *Marine Ecology Progress Series* 329:267–279.
- Beckley, B., R. Ray, N. Zelensky, F. Lemoine, X. Yang, S. Brown, S. Desai, and G. Mitchum. 2021. Integrated Multi-Mission Ocean Altimeter Data for Climate Research TOPEX/Poseidon, Jason-1, 2, & 3 User's Handbook Version 5.
- Behrens Yamada, S., J. L. Fisher, and P. M. Kosro. 2021. Relationship between ocean ecosystem indicators and year class strength of the invasive European green crab (*Carcinus maenas*). *Progress in Oceanography* 196:102618.
- Beobide-Arsuaga, G., T. Bayr, A. Reintges, and M. Latif. 2021. Uncertainty of ENSO-amplitude projections in CMIP5 and CMIP6 models. *Climate Dynamics* 56:3875–3888.
- Biel, R. G., and S. D. Hacker. 2021. Warming alters the interaction of two invasive beachgrasses with implications for range shifts and coastal dune functions. *Oecologia* 197:757–770.
- Bilskie, M. V., and S. C. Hagen. 2018. Defining Flood Zone Transitions in Low-Gradient Coastal Regions. *Geophysical Research Letters* 45:2761–2770.
- Bramwell, D., and J. Caujapé-Castells. 2011. *The Biology of Island Floras*. Cambridge University Press.
- Brasseale, E., E. W. Grason, P. S. McDonald, J. Adams, and P. MacCready. 2019. Larval Transport Modeling Support for Identifying Population Sources of European Green Crab

- in the Salish Sea. *Estuaries and Coasts* 42:1586–1599.
- Brodeur, R. D., T. D. Auth, and A. J. Phillips. 2019. Major Shifts in Pelagic Micronekton and Macrozooplankton Community Structure in an Upwelling Ecosystem Related to an Unprecedented Marine Heatwave. *Frontiers in Marine Science* 6.
- Brodeur, R., M. Hunsicker, A. Hann, and T. Miller. 2018. Effects of warming ocean conditions on feeding ecology of small pelagic fishes in a coastal upwelling ecosystem: A shift to gelatinous food sources. *Marine Ecology Progress Series* View.
- Brophy, L. S., C. M. Greene, V. C. Hare, B. Holycross, A. Lanier, W. N. Heady, K. O'Connor, H. Imaki, T. Haddad, and R. Dana. 2019. Insights into estuary habitat loss in the western United States using a new method for mapping maximum extent of tidal wetlands. *PLOS ONE* 14:e0218558.
- Cai, W., S. Borlace, M. Lengaigne, P. van Rensch, M. Collins, G. Vecchi, A. Timmermann, A. Santoso, M. J. McPhaden, L. Wu, M. H. England, G. Wang, E. Guilyardi, and F.-F. Jin. 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change* 4:111–116.
- Cai, W., G. Wang, A. Santoso, M. J. McPhaden, L. Wu, F.-F. Jin, A. Timmermann, M. Collins, G. Vecchi, M. Lengaigne, M. H. England, D. Domménget, K. Takahashi, and E. Guilyardi. 2015. Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change* 5:132–137.
- Callahan, C. W., C. Chen, M. Rugenstein, J. Bloch-Johnson, S. Yang, and E. J. Moyer. 2021. Robust decrease in El Niño/Southern Oscillation amplitude under long-term warming. *Nature Climate Change* 11:752–757.
- Cavole, L. M., A. M. Demko, R. E. Diner, A. Giddings, I. Koester, C. M. L. S. Pagniello, M.-L. Paulsen, A. Ramirez-Valdez, S. M. Schwenck, N. K. Yen, M. E. Zill, and P. J. S. Franks. 2016. Biological Impacts of the 2013–2015 Warm-Water Anomaly in the Northeast Pacific: Winners, Losers, and the Future. *Oceanography* 29:273–285.
- Cheung, W. W. L., R. D. Brodeur, T. A. Okey, and D. Pauly. 2015. Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. *Progress in Oceanography* 130:19–31.
- Collins, M., S.-I. An, W. Cai, A. Ganachaud, E. Guilyardi, F.-F. Jin, M. Jochum, M. Lengaigne, S. Power, A. Timmermann, G. Vecchi, and A. Wittenberg. 2010. The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience* 3:391–397.
- Dangendorf, S., C. Hay, F. M. Calafat, M. Marcos, C. G. Piecuch, K. Berk, and J. Jensen. 2019. Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change* 9:705–710.
- Davis, M. J., I. Woo, C. S. Ellings, S. Hodgson, D. A. Beauchamp, G. Nakai, and S. E. W. De La Cruz. 2022. A Climate-Mediated Shift in the Estuarine Habitat Mosaic Limits Prey Availability and Reduces Nursery Quality for Juvenile Salmon. *Estuaries and Coasts* 45:1445–1464.
- Diefenderfer, H. L., I. A. Sinks, S. A. Zimmerman, V. I. Cullinan, and A.B. Borde. 2018. Designing topographic heterogeneity for tidal wetland restoration. *Ecological Engineering* 123:212–225.
- Di Lorenzo, E., and N. Mantua. 2016. Multi-year persistence of the 2014/15 North Pacific

- marine heatwave. *Nature Climate Change* 6:1042–1047.
- Ens, N. J., B. Harvey, M. M. Davies, H. M. Thomson, K. J. Meyers, J. Yakimishyn, L. C. Lee, M. E. McCord, and T. G. Gerwing. 2022. The Green Wave: reviewing the environmental impacts of the invasive European green crab (*Carcinus maenas*) and potential management approaches. *Environmental Reviews* 30:306–322.
- Fiechter, J., M. Pozo Buil, M. G. Jacox, M. A. Alexander, and K. A. Rose. 2021. Projected Shifts in 21st Century Sardine Distribution and Catch in the California Current. *Frontiers in Marine Science* 8.
- Frölicher, T. L., E. M. Fischer, and N. Gruber. 2018. Marine heatwaves under global warming. *Nature* 560:360–364.
- Gemmrich, J., B. Thomas, and R. Bouchard. 2011. Observational changes and trends in northeast Pacific wave records. *Geophysical Research Letters* 38.
- Grason, E., S. McDonald, J. Adams, K. Litle, J. Apple, and A. Pleus. 2018. Citizen science program detects range expansion of the globally invasive European green crab in Washington State (USA). *Management of Biological Invasions* 9:39–47.
- Gregg, R. M., W. Reynier, L. Gaines, and J. Behan. 2018. Available Science Assessment Process (ASAP): Sea Level Rise in the Pacific Northwest and Northern California. EcoAdapt (Bainbridge Island, WA) and the Institute for Natural Resources (Corvallis, OR).
- Groner, M. L., M. E. Eisenlord, R. M. Yoshioka, E. A. Fiorenza, P. D. Dawkins, O. J. Graham, M. Winningham, A. Vompe, N. D. Rivlin, B. Yang, C. A. Burge, B. Rappazzo, C. P. Gomes, and C. D. Harvell. 2021. Warming sea surface temperatures fuel summer epidemics of eelgrass wasting disease. *Marine Ecology Progress Series* 679:47–58.
- Hacker, S. D., P. Zarnetske, E. Seabloom, P. Ruggiero, J. Mull, S. Gerrity, and C. Jones. 2012. Subtle differences in two non-native congeneric beach grasses significantly affect their colonization, spread, and impact. *Oikos* 121:138–148.
- Herbert, E. R., L. Windham-Myers, and M. L. Kirwan. 2021. Sea-level rise enhances carbon accumulation in United States tidal wetlands. *One Earth* 4:425–433.
- Hesketh, A.V., and C. D. G. Harley. 2023. Extreme heatwave drives topography-dependent patterns of mortality in a bed-forming intertidal barnacle, with implications for associated community structure. *Global Change Biology* 29:165–178.
- Iacarella, J. C., D. A. Lyons, L. Burke, I. C. Davidson, T. W. Therriault, A. Dunham, and C. DiBacco. 2020. Climate change and vessel traffic create networks of invasion in marine protected areas. *Journal of Applied Ecology* 57:1793–1805.
- Ibrahim, O., B. Mohamed, and H. Nagy. 2021. Spatial Variability and Trends of Marine Heat Waves in the Eastern Mediterranean Sea over 39 Years. *Journal of Marine Science and Engineering* 9:643.
- Ikeda, K., R. Rasmussen, C. Liu, A. Newman, F. Chen, M. Barlage, E. Gutmann, J. Dudhia, A. Dai, C. Luce, and K. Musselman. 2021. Snowfall and snowpack in the Western U.S. as captured by convection permitting climate simulations: current climate and pseudo global warming future climate. *Climate Dynamics* 57:2191–2215.
- IPCC (Intergovernmental Panel On Climate Change), 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M.

- Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)). Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp.
- Janousek, C. N., K. M. Thorne, and J. Y. Takekawa. 2019. Vertical Zonation and Niche Breadth of Tidal Marsh Plants Along the Northeast Pacific Coast. *Estuaries and Coasts* 42:85–98.
- Jones, T., J. Parrish, P. MacCready, W. T. Peterson, E. Bjorkstedt, N. A. Bond, L. T. Ballance, V. Bowes, J. M. Hipfner, K. Lindquist, J. Lindsey, H. M. Nevins, H. K. Burgess, R. Robertson, J. Roletto, L. Wilson, T. W. Joyce, and J. Harvey. 2017. Massive Mortality of a Planktivorous Seabird in Response to a Marine Heatwave: A Citizen Science Case-study 2017:PA23E-02.
- Kennedy, L. A., F. Juanes, and R. El-Sabaawi. 2018. Eelgrass as Valuable Nearshore Foraging Habitat for Juvenile Pacific Salmon in the Early Marine Period. *Marine and Coastal Fisheries* 10:190–203.
- Kilduff, D. P., E. Di Lorenzo, L. W. Botsford, and S. L. H. Teo. 2015. Changing central Pacific El Niños reduce stability of North American salmon survival rates. *Proceedings of the National Academy of Sciences* 112:10962–10966.
- Krueger, K. L., K. B. Pierce, T. Quinn, and D. E. Penttila. (n.d.). Anticipated Effects of Sea Level Rise in Puget Sound on Two Beach-Spawning Fishes.
- Krosby, M., Hasert, R., Kalafatis, S., Askerooth, R., Kuhn, K., and O. Zimmerman. 2023. Rising Seas and the Coastal Squeeze: Managing Inland Migration of Coastal Habitats in Response to Sea Level Rise. Northwest Climate Adaptation Science Center, University of Washington, Seattle
- Lehodey, P., A. Bertrand, A. Hobday, H. Kiyofuji, S. Mcclatchie, C. Menkes, G. Pilling, J. Polovina, and D. Tommasi. 2020. El Niño Southern Oscillation in a Changing Climate. Pages 429–451.
- Leising, A. W., I. D. Schroeder, S. J. Bograd, J. Abell, R. Durazo, G. Gaxiola-Castro, E. P. Bjorkstedt, J. Field, K. Sakuma, R. R. Robertson, R. Goericke, W. T. Peterson, R. Brodeur, C. Barceló, T. D. Auth, E. A. Daly, R. M. Suryan, A. J. Gladics, J. M. Porquez, S. McClatchie, E. D. Weber, W. Watson, J. A. Santora, W. J. Sydeman, S. R. Melin, F. P. Chavez, R. T. Golightly, S. R. Schneider, J. Fisher, C. Morgan, R. Bradley, and P. Warybok. (n.d.). State of the California Current 2014-15: Impacts of the Warm-Water “Blob.” Scripps Institution of Oceanography.
- Light, J. W. (n.d.). Morphodynamic Evolution of Coastal Oregon: Using New Lidar-derived Beach and Sand Dune Morphometrics to Explore Multi-decadal Change. Oregon State University.
- Magel, C. L., F. Chan, M. Hessing-Lewis, and S. D. Hacker. 2022. Differential Responses of Eelgrass and Macroalgae in Pacific Northwest Estuaries Following an Unprecedented NE Pacific Ocean Marine Heatwave. *Frontiers in Marine Science* 9.
- McCabe, R. M., B. M. Hickey, R. M. Kudela, K. A. Lefebvre, N. G. Adams, B. D. Bill, F. M. D. Gulland, R. E. Thomson, W. P. Cochlan, and V. L. Trainer. 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters* 43:10,366-10,376.
- Menéndez, M., F. J. Méndez, I. J. Losada, and N. E. Graham. 2008. Variability of extreme wave heights in the northeast Pacific Ocean based on buoy measurements. *Geophysical*

Research Letters 35.

- Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E. 2018. Projected Sea Level Rise for Washington State – A 2018 Assessment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, University of Oregon, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project. updated 07/2019
- Miller, I.M., Yang, Z., VanArendonk, N., Grossman, E., Mauger, G. S., Morgan, H., 2019. Extreme Coastal Water Level in Washington State: Guidelines to Support Sea Level Rise Planning. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, Pacific Northwest National Laboratory and U.S. Geological Survey. Prepared for the Washington Coastal Resilience Project.
- Moritsch, M. M., K. B. Byrd, M. Davis, A. Good, J. Z. Drexler, J. T. Morris, I. Woo, L. Windham-Myers, E. Grossman, G. Nakai, K. L. Poppe, and J. M. Rybczyk. 2022. Can Coastal Habitats Rise to the Challenge? Resilience of Estuarine Habitats, Carbon Accumulation, and Economic Value to Sea-Level Rise in a Puget Sound Estuary. *Estuaries and Coasts* 45:2293–2309.
- Morley, J. W., R. L. Selden, R. J. Latour, T. L. Frölicher, R. J. Seagraves, and M. L. Pinsky. 2018. Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLOS ONE* 13:e0196127.
- Mostow, R. S., F. Barreto, R. Biel, E. Meyer, and S. D. Hacker. 2021. Discovery of a dune-building hybrid beachgrass (*Ammophila arenaria* × *A. breviligulata*) in the U.S. Pacific Northwest. *Ecosphere* 12:e03501.
- Myers, M. R., P. L. Barnard, E. Beighley, D. R. Cayan, J. E. Dugan, D. Feng, D. M. Hubbard, S. F. Iacobellis, J. M. Melack, and H. M. Page. 2019. A multidisciplinary coastal vulnerability assessment for local government focused on ecosystems, Santa Barbara area, California. *Ocean & Coastal Management* 182:104921.
- Oliver, E. C. J., M. G. Donat, M. T. Burrows, P. J. Moore, D. A. Smale, L. V. Alexander, J. A. Benthuisen, M. Feng, A. Sen Gupta, A. J. Hobday, N. J. Holbrook, S. E. Perkins-Kirkpatrick, H. A. Scannell, S. C. Straub, and T. Wernberg. 2018. Longer and more frequent marine heatwaves over the past century. *Nature Communications* 9:1324.
- Olmata Schult, F. 2023. Oregon Climate Assessment: Coastal Hazards.
- Parker, V. T., and K. E. Boyer. 2019. Sea-Level Rise and Climate Change Impacts on an Urbanized Pacific Coast Estuary. *Wetlands* 39:1219–1232.
- Peterson, C. D., D. J. Pettit, K. Kingen, S. Vanderburgh, and C. Rosenfeld. 2021. Catastrophic beach sand losses due to erosion from predicted future sea level rise (0.5–1.0 m), based on increasing submarine accommodation spaces in the high-wave-energy coast of the Pacific Northwest, Washington, Oregon, and Northern California, USA. *Marine Geology* 439:106555.
- Peterson, W. T., and F. B. Schwing. 2003. A new climate regime in northeast pacific ecosystems. *Geophysical Research Letters* 30.
- Piatt, J. F., J. K. Parrish, H. M. Renner, S. K. Schoen, T. T. Jones, M. L. Arimitsu, K. J. Kuletz, B. Bodenstein, M. García-Reyes, R. S. Duerr, R. M. Corcoran, R. S. A. Kaler, G. J. McChesney,

- R. T. Golightly, H. A. Coletti, R. M. Suryan, H. K. Burgess, J. Lindsey, K. Lindquist, P. M. Warzybok, J. Jahncke, J. Roletto, and W. J. Sydeman. 2020. Extreme mortality and reproductive failure of common murrelets resulting from the northeast Pacific marine heatwave of 2014-2016. *PLOS ONE* 15:e0226087.
- Pikitch, E., P. Boersma, I. L. Boyd, D. Conover, P. Cury, T. Essington, and S. Heppell. 2012. *Little Fish, Big Impact: Managing a Crucial Link in Ocean Food Webs*. Lenfest Ocean Program.
- Reeder, S. 2013. Coasts: Complex Changes Affecting the Northwest's Diverse Shorelines. *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*:67-109.
- Reguero, B. G., I. J. Losada, and F. J. Méndez. 2019. A recent increase in global wave power as a consequence of oceanic warming. *Nature Communications* 10:205.
- Rubin, S. P., M. C. Hayes, and E. E. Grossman. 2018a. Juvenile Chinook Salmon and Forage Fish Use of Eelgrass Habitats in a Diked and Channelized Puget Sound River Delta. *Marine and Coastal Fisheries* 10:435-451.
- Rubin, S. P., M. C. Hayes, and E. E. Grossman. 2018b. Juvenile Chinook Salmon and Forage Fish Use of Eelgrass Habitats in a Diked and Channelized Puget Sound River Delta. *Marine and Coastal Fisheries* 10:435-451.
- Ruggiero, P., S. Hacker, E. W. Seabloom, and P. L. Zarnetske. 2018. *The Role of Vegetation in Determining Dune Morphology, Exposure to Sea-Level Rise, and Storm-Induced Coastal Hazards: A U.S. Pacific Northwest Perspective*. Pages 337-361 *Barrier Dynamics and Response to Changing Climate*. Springer International Publishing.
- Santora, J. A., N. J. Mantua, I. D. Schroeder, J. C. Field, E. L. Hazen, S. J. Bograd, W. J. Sydeman, B. K. Wells, J. Calambokidis, L. Saez, D. Lawson, and K. A. Forney. 2020. Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications* 11:536.
- Seabloom, E. 2013. Invasive grasses, climate change, and exposure to storm-wave overtopping in coastal dune ecosystems. *Global Change Biology*.
- Serafin, K. A., P. Ruggiero, K. Parker, and D. F. Hill. 2019. What's streamflow got to do with it? A probabilistic simulation of the competing oceanographic and fluvial processes driving extreme along-river water levels. *Natural Hazards and Earth System Sciences* 19:1415-1431.
- Seymour, R. J. 2011. Evidence for Changes to the Northeast Pacific Wave Climate. *Journal of Coastal Research* 27:194-201.
- Schuerch, M., T. Spencer, S. Temmerman, M. L. Kirwan, C. Wolff, D. Lincke, C. J. McOwen, M.D. Pickering, R. Reef, A. T. Vafeidis, J. Hinkel, R. J. Nicholls, and S. Brown. 2018. Future response of global coastal wetlands to sea-level rise. *Nature* 561:231-234.
- Shope, J. B., L. H. Erikson, P. L. Barnard, C. D. Storlazzi, K. Serafin, K. Doran, H. Stockdon, B. Reguero, F. Mendez, S. Castanedo, A. Cid, L. Cagigal, and P. Ruggiero. 2022. Characterizing storm-induced coastal change hazards along the United States West Coast. *Scientific Data* 9:224.
- Sunday, J. M., E. Howard, S. Siedlecki, D. J. Pilcher, C. Deutsch, P. MacCready, J. Newton, and T. Klinger. 2022. Biological sensitivities to high-resolution climate change projections in

- the California current marine ecosystem. *Global Change Biology* 28:5726–5740.
- Sweet, W. V., R. E. Kopp, C. P. Weaver, J. Obeysekera, R. M. Horton, E. R. Thieler, and C. Zervas. 2017, January 1. Global and Regional Sea Level Rise Scenarios for the United States.
- Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp.
<https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nostechrpt01-global-regional-SLR-scenarios-US.pdf>
- Swinomish Indian Tribal Community. 2009, October. Swinomish Climate Change Initiative Impact Assessment Technical Report.
https://swinomish-nsn.gov/media/54199/swin_tr_2009_01_cctechreport.pdf.
- Tang, Y., R.-H. Zhang, T. Liu, W. Duan, D. Yang, F. Zheng, H. Ren, T. Lian, C. Gao, D. Chen, and M. Mu. 2018. Progress in ENSO prediction and predictability study. *National Science Review* 5:826–839.
- Thompson, A. R., C. J. Harvey, W. J. Sydeman, C. Barceló, S. J. Bograd, R. D. Brodeur, J. Fiechter, J. C. Field, N. Garfield, T. P. Good, E. L. Hazen, M. E. Hunsicker, K. Jacobson, M.G. Jacox, A. Leising, J. Lindsay, S. R. Melin, J. A. Santora, I. D. Schroeder, J. A. Thayer, B. K. Wells, and G. D. Williams. 2019. Indicators of pelagic forage community shifts in the California Current Large Marine Ecosystem, 1998–2016. *Ecological Indicators* 105:215–228.
- Thorne, K., G. MacDonald, G. Guntenspergen, R. Ambrose, K. Buffington, B. Dugger, C. Freeman, C. Janousek, L. Brown, J. Rosencranz, J. Holmquist, J. Smol, K. Hargan, and J. Takekawa. 2018a. U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise. *Science Advances* 4:eaa03270.
- Thorne, K., G. MacDonald, G. Guntenspergen, R. Ambrose, K. Buffington, B. Dugger, C. Freeman, C. Janousek, L. Brown, J. Rosencranz, J. Holmquist, J. Smol, K. Hargan, and J. Takekawa. 2018b. U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise. *Science Advances* 4:eaa03270.
- Toimil, A., Le Cozannet, G., Camus, P., Idier, D., Maspataud, A., Losada, I., & Menendez, M. 2019. A review of existing modeling frameworks to assess climate change-driven shoreline changes the title of the deliverable.
- Toimil, A., P. Camus, I. J. Losada, G. Le Cozannet, R. J. Nicholls, D. Idier, and A. Maspataud. 2020. Climate change-driven coastal erosion modelling in temperate sandy beaches: Methods and uncertainty treatment. *Earth-Science Reviews* 202:103110.
- Trainer, V. L., S. K. Moore, G. Hallegraeff, R. M. Kudela, A. Clement, J. I. Mardones, and W. P. Cochlan. 2020. Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful Algae* 91:101591.
- Wolf, S. G., W. J. Sydeman, J. M. Hipfner, C. L. Abraham, B. R. Tershy, and D. A. Croll. 2009.

Range-wide reproductive consequences of ocean climate variability for the seabird Cassin's Auklet. *Ecology* 90:742–753.

Wyatt, A. M., L. Resplandy, and A. Marchetti. 2022. Ecosystem impacts of marine heat waves in the northeast Pacific. *Biogeosciences* 19:5689–5705.

Yamada, S. B., S. Schooler, R. Heller, L. Donaldson, G. T. Takacs, A. Randall, C. Buffington, and A. Akmajian. 2021. Status of the European Green Crab, *Carcinus maenas*, in Oregon and Washington coastal estuaries in 2019. Pacific States Marine Fisheries Commission.

Zhou, L., and R.-H. Zhang. 2022. A Hybrid Neural Network Model for ENSO Prediction in Combination with Principal Oscillation Pattern Analyses. *Advances in Atmospheric Sciences* 39:889–902.

REFERENCES - COAST RANGE

- Fernández-Montblanc, T., E. Duo, and P. Ciavola. 2020. Dune reconstruction and revegetation as a potential measure to decrease coastal erosion and flooding under extreme storm conditions. *Ocean & Coastal Management* 188:105075.
- Frölicher, T. L., E. M. Fischer, and N. Gruber. 2018. Marine heatwaves under global warming. *Nature* 560:360–364.
- Miller, I.M., Yang, Z., VanArendonk, N., Grossman, E., Mauger, G. S., Morgan, H., 2019. Extreme Coastal Water Level in Washington State: Guidelines to Support Sea Level Rise Planning. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, Pacific Northwest National Laboratory and U.S. Geological Survey. Prepared for the Washington Coastal Resilience Project.
- Oliver, E. C. J., M. T. Burrows, M. G. Donat, A. Sen Gupta, L. V. Alexander, S. E. Perkins-Kirkpatrick, J. A. Benthuisen, A. J. Hobday, N. J. Holbrook, P. J. Moore, M. S. Thomsen, T. Wernberg, and D. A. Smale. 2019. Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. *Frontiers in Marine Science* 6.
- Oliver, E. C. J., M. G. Donat, M. T. Burrows, P. J. Moore, D. A. Smale, L. V. Alexander, J. A. Benthuisen, M. Feng, A. Sen Gupta, A. J. Hobday, N. J. Holbrook, S. E. Perkins-Kirkpatrick, H. A. Scannell, S. C. Straub, and T. Wernberg. 2018. Longer and more frequent marine heatwaves over the past century. *Nature Communications* 9:1324.
- Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp.
<https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nostechrpt01-global-regional-SLR-scenarios-US.pdf>

REFERENCES - PUGET LOWLANDS

- Diefenderfer, H. L., I. A. Sinks, S. A. Zimmerman, V. I. Cullinan, and A. B. Borde. 2018. Designing topographic heterogeneity for tidal wetland restoration. *Ecological Engineering* 123:212–225.
- Grossman, E. E., A. W. Stevens, P. Dartnell, D. George, and D. Finlayson. 2020. Sediment export and impacts associated with river delta channelization compound estuary vulnerability to sea-level rise, Skagit River Delta, Washington, USA. *Marine Geology* 430:106336.
- Lavin, P., Roop, H.A., Neff, P.D., Morgan, H., Cory, D., Correll, M., Kosara, R., and Norheim, R., 2019. Interactive Washington State Sea Level Rise Data Visualizations. Prepared by the Climate Impacts Group, University of Washington, Seattle. Updated 7/20.
- Lee, S.-Y., A. F. Hamlet, and E. E. Grossman. 2016. Impacts of Climate Change on Regulated Streamflow, Hydrologic Extremes, Hydropower Production, and Sediment Discharge in the Skagit River Basin. *Northwest Science* 90:23–43.
- Miller, I., H. Morgan, G. Mauger, and T. Newton. 2018. Projected Sea Level Rise in Washington State – A 2018 Assessment. Washington Coastal Resilience Project.
- Raymond, C., Conway-Cranos, L., Morgan, H., Faghin, N., Spilsbury Pucci, D., Krienitz, J., Miller, I., Grossman, E. and Mauger, G., 2018. Sea level rise considerations for nearshore restoration projects in Puget Sound. A report prepared for the Washington Coastal Resilience Project.
- Ruggiero, P. 2013. Is the Intensifying Wave Climate of the U.S. Pacific Northwest Increasing Flooding and Erosion Risk Faster Than Sea-Level Rise? *Journal of Waterway, Port, Coastal, and Ocean Engineering* 139:88–97.

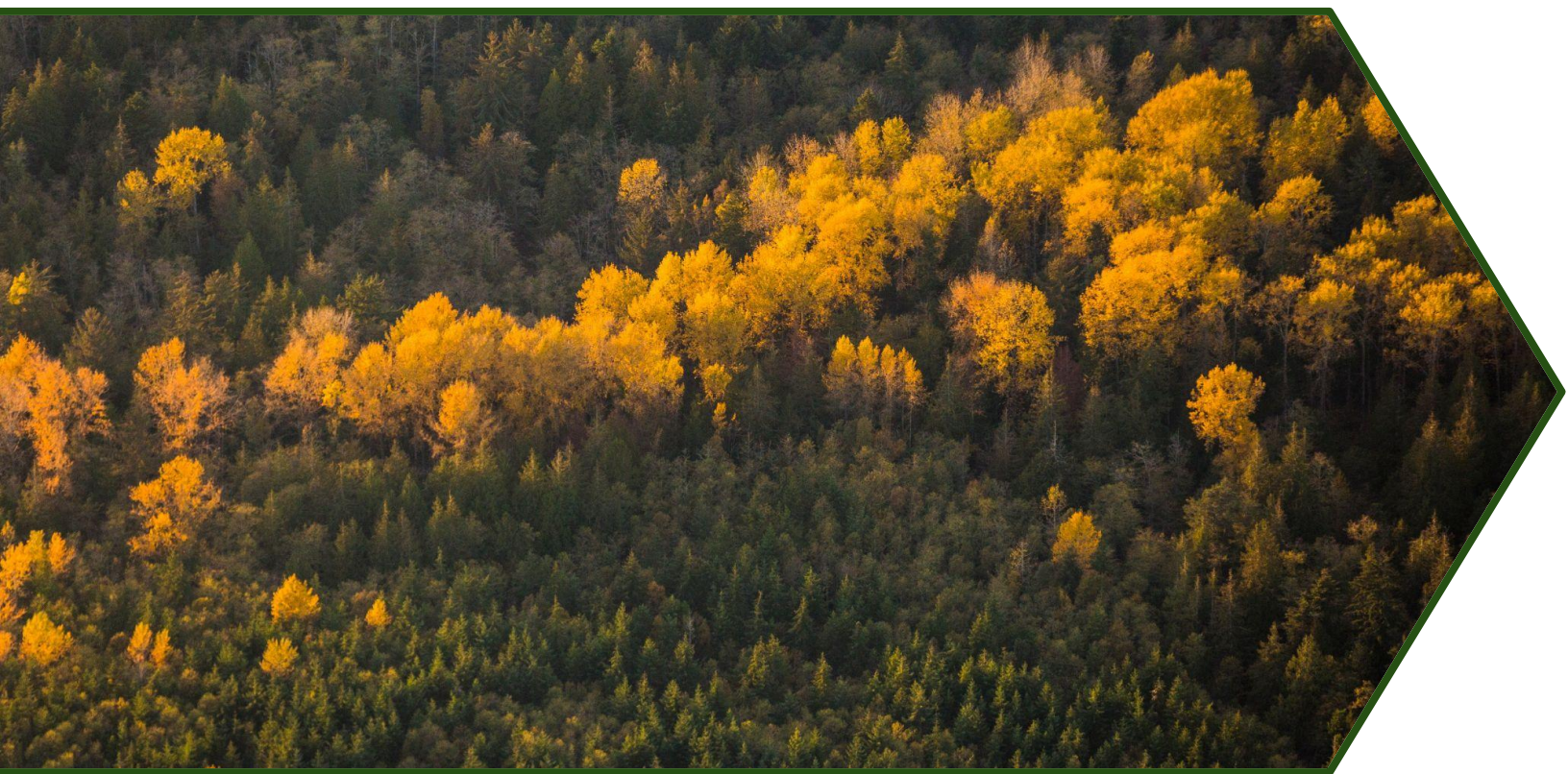
REFERENCES - ADAPTATION

- Arafeh-Dalmau, N., A. et al. 2023. Integrating climate adaptation and transboundary management: Guidelines for designing climate-smart marine protected areas. *One Earth* 6:1523–1541.
- Biel, R. G. 2017. Coastal Dune Ecology, Geomorphology, and Ecosystem Services : How Invasive Beachgrasses, their Interactions, and Sediment Dynamics Shape U.S. Pacific Northwest Dunes. Oregon State University.
- Clements, J. C., and T. Chopin. 2017. Ocean acidification and marine aquaculture in North America: potential impacts and mitigation strategies. *Reviews in Aquaculture* 9:326–341.
- Diefenderfer, H. L., I. A. Sinks, S. A. Zimmerman, V. I. Cullinan, and A. B. Borde. 2018. Designing topographic heterogeneity for tidal wetland restoration. *Ecological Engineering* 123:212–225.
- DuBois, K., K. N. Pollard, B. J. Kauffman, S. L. Williams, and J. J. Stachowicz. 2022. Local adaptation in a marine foundation species: Implications for resilience to future global change. *Global Change Biology* 28:2596–2610.
- Gissi, E., E. Manea, A. D. Mazaris, S. Frascchetti, V. Almpnidou, S. Bevilacqua, M. Coll, G. Guarnieri, E. Lloret-Lloret, M. Pascual, D. Petza, G. Rilov, M. Schonwald, V. Stelzenmüller, and S. Katsanevakis. 2021. A review of the combined effects of climate change and other local human stressors on the marine environment. *Science of The Total Environment* 755:142564.
- Gunderson, A. R., E. J. Armstrong, and J. H. Stillman. 2016. Multiple Stressors in a Changing World: The Need for an Improved Perspective on Physiological Responses to the Dynamic Marine Environment. *Annual Review of Marine Science* 8:357–378.
- Hesketh, A. V., and C. D. G. Harley. 2023. Extreme heatwave drives topography-dependent patterns of mortality in a bed-forming intertidal barnacle, with implications for associated community structure. *Global Change Biology* 29:165–178.
- Okey, T. A., S. Agbayani, and H. M. Alidina. 2015. Mapping ecological vulnerability to recent climate change in Canada's Pacific marine ecosystems. *Ocean & Coastal Management* 106:35–48.
- Roberts, C. M., B. C. O'Leary, D. J. McCauley, P. M. Cury, C. M. Duarte, J. Lubchenco, D. Pauly, A. Sáenz-Arroyo, U. R. Sumaila, R. W. Wilson, B. Worm, and J. C. Castilla. 2017. Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences* 114:6167–6175.
- Schuurman, G. W., D. N. Cole, A. E. Cravens, S. Covington, S. D. Crausbay, C. H. Hoffman, D. J. Lawrence, D. R. Magness, J. M. Morton, E. A. Nelson, and R. O'Malley. 2022. Navigating Ecological Transformation: Resist–Accept–Direct as a Path to a New Resource Management Paradigm. *BioScience* 72:16–29.
- Stockbridge, J., A. R. Jones, and B. M. Gillanders. 2020. A meta-analysis of multiple stressors on seagrasses in the context of marine spatial cumulative impacts assessment. *Scientific Reports* 10:11934.
- Thorne, K., G. MacDonald, G. Guntenspergen, R. Ambrose, K. Buffington, B. Dugger, C.

- Freeman, C. Janousek, L. Brown, J. Rosencranz, J. Holmquist, J. Smol, K. Hargan, and J. Takekawa. 2018. U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise. *Science Advances* 4:eaao3270.
- Thurman, L. L., J. E. Gross, C. Mengelt, E. A. Beever, L. M. Thompson, G. W. Schuurman, C. L. Hoving, and J. D. Olden. 2022. Applying assessments of adaptive capacity to inform natural-resource management in a changing climate. *Conservation Biology* 36:e13838.

The State of Climate Adaptation Science for Ecosystems in the Northwest U.S.

FOREST ECOSYSTEMS



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IN THE OVERVIEW

FOREST ECOSYSTEMS DESCRIPTION

INTERACTION OF CLIMATE CHANGE AND ECOSYSTEM STRESSORS

DIRECT EFFECTS OF CHANGES IN THE CLIMATE

INDIRECT EFFECTS

CHANGES IN FIRE REGIMES

CHANGES IN INSECTS AND PLANT PATHOGENS

CHANGES IN INVASIVE SPECIES DISTRIBUTION AND ABUNDANCE

DISTURBANCE INTERACTIONS

DISTURBANCE AND CLIMATE DRIVER INTERACTIONS

VEGETATION RANGE SHIFTS

FOREST ECOSYSTEMS DESCRIPTION

Forest ecosystems cover much of the Northwest (NW), ranging from highly-productive, wet forests near the Pacific coast to low-productivity, cold forests at high elevations in the Cascade and Rocky Mountain Ranges, and dry woodlands to the south and in the interior plateau (Figure 1). Forests of the NW can be grouped into five types defined by climatic conditions that influence productivity and species composition (Table 1). Fire regimes and biotic disturbances vary among forest types and further influence species composition and structure (Table 1). The influence of human activities on forest is substantial across much of the region and interacts with the effects of climate change.

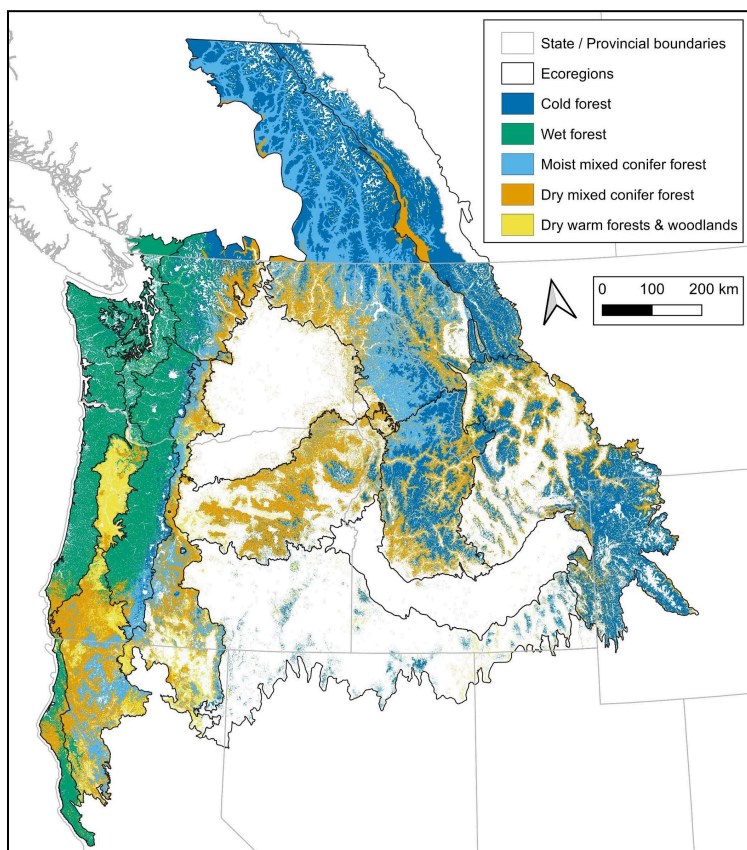


Figure 1. Forest types in the Pacific Northwest and Level III Ecoregions. Data source: Data Sources: [LANDFIRE Biophysical Settings \(BPS\) 2020](#) in the US [Biogeoclimatic Ecosystem Classification \(BEC\) Program](#) in BC.

Table 1: Northwest forest ecosystems grouped into five forest types based on climatic conditions. The forest types share similar species composition, fire regimes, biotic disturbances, and human influences.

Forest type	Climate	Species composition	Disturbance regimes	Human influence
Cold forests: Highest elevational zones throughout the NW. <u>Major ecoregions:</u> Northern Rockies, Idaho Batholith, Middle Rockies, Canadian Rockies, North Cascades	<u>Winters:</u> persistent snow cover from October through June on average <u>Summers:</u> dry with short growing seasons	lodgepole pine, subalpine fir, Engelmann spruce, whitebark pine, mountain hemlock, Alaska yellow-cedar, western white pine, Pacific silver fir, subalpine larch, limber pine <u>Klamath Mountains:</u> red fir	<u>Fire regime:</u> Cool and wet conditions limit fire frequency. Fire regimes range from mixed-severity with fire frequency of approximately 40-70 years in the south, to longer intervals of approximately 100-150 years between severe fires in the North Cascades, to large and severe fires at intervals of approximately 100-300 years in the Rockies. <u>Biotic disturbances:</u> Outbreaks of native bark beetles can be widespread and severe, typically occurring when large-diameter host trees are abundant and sufficiently stressed. Major bark beetle species: mountain pine beetle (pine host trees), western spruce beetle (spruce host trees), western balsam bark beetle (fir host trees).	<u>Cultural fire use:</u> Fire is used by many Indigenous groups to foster culturally important plant species such as huckleberry. <u>Land use change:</u> Due to limited accessibility in high elevations, legacies of post-European settlement land use and management are less pronounced. Effects of fire exclusion and suppression and timber harvesting have likely resulted in modest changes to forest structure.
Wet forests: Lower elevations from the Pacific Ocean to mid-elevations on the west side of the Coast and Cascade mountain ranges (generally sea level to 1,000 m). <u>Major ecoregions:</u> Coast Range, Puget Lowlands, Cascades, North Cascades	<u>Winters:</u> cool, dominated by abundant rainfall and periodic snow from October to June <u>Summers:</u> cool and moist, maintained by ocean moisture and fog along the coast	<u>Coastal margins:</u> Sitka spruce to the north and coast redwood to the south. <u>Low and mid elevations:</u> Douglas-fir, western hemlock, western redcedar, bigleaf maple, red alder	<u>Fire regime:</u> Fire occurrence is constrained by the relatively cool and wet maritime climate, with large episodic fires (e.g., exceeding several hundred thousand hectares) occurring when late summer drought, ignitions, and strong east winds coincide. Smaller fires are more numerous than larger fires in wet forests but account for relatively little area burned, leading to most forested areas experiencing stand-replacing fires at intervals of 250-750 years. <u>Biotic disturbances:</u> Localized outbreaks of native insects and pathogens are less widespread and severe than in drier forests. Major species driving outbreaks include: Douglas-fir beetle, laminated root rot, Swiss needle cast.	<u>Cultural fire use:</u> Indigenous fire use is an important component of fire regimes and supported frequent fire in many locations (e.g., coast redwood stands) prior to European colonization. <u>Timber harvest:</u> Wet forests have been strongly impacted by timber harvesting following European colonization which has generally homogenized stand structure compared with the historical range of variability.
Moist mixed-conifer forests: Mid-montane elevation zone and low elevations in wet positions in the interior of the NW. Transition from cold high-elevation forest to low-elevation dry mixed-conifer forests.	<u>Winters:</u> cold with intermittent to persistent snow cover	Douglas-fir, grand fir, western white pine, western larch, ponderosa pine <u>Klamath Mountains:</u> sugar pine, incense-cedar, Jeffrey pine, knobcone pine	<u>Fire regime:</u> Historical fire return intervals range from approximately 10-100 years. Frequency is greatest on southwest facing slopes and least on northeast facing slopes. Most burned area is of moderate severity with small patches of high severity / stand-replacing fire.	<u>Land use change:</u> Moist mixed-conifer forests have been heavily impacted by historical high-grade logging of the largest fire-resistant trees, fire exclusion, and fire suppression that followed European colonization and settlement. These have

CLIMATE EFFECTS: FOREST ECOSYSTEMS OVERVIEW

Forest type	Climate	Species composition	Disturbance regimes	Human influence
<u>Major ecoregions:</u> Northern Rockies, Idaho Batholith, Eastern Cascades	<u>Summers:</u> warm and dry	<u>Riparian corridors and disturbed sites:</u> bigleaf maple, red alder	<u>Biotic disturbances:</u> Outbreaks of native bark beetles, pathogens, and plant parasites are endemic and increase in prevalence with host tree abundance. Major species: mountain pine beetle, Douglas-fir beetle, laminated root rot, dwarf mistletoe.	collectively resulted in contemporary forests that are homogeneous and composed of more small and shade-tolerant trees, and fewer large and fire-resistant trees, compared to historical conditions.
Dry mixed-conifer forests: Low-montane elevation zone, interior valleys, foothills east sides of the Cascades, Coast Range, and Rockies, drier areas at mid-elevations. <u>Major ecoregions:</u> Eastern Cascades, Northern Rockies, Blue Mountains, Klamath Mountains	<u>Winters:</u> cold with intermittent snow cover <u>Summers:</u> warm and very dry	Species composition overlaps with moist mixed-conifer forests. <u>Drier locations:</u> ponderosa pine, deciduous species such as Oregon white oak.	<u>Fire regime:</u> Historical fire return intervals range from <10 years to 30-50 years. Fires were primarily low intensity, which resulted in high survival rates of thick-barked ponderosa pine and Douglas-fir trees. <u>Biotic disturbances:</u> Relatively sparse tree density limits the occurrence of widespread and severe biotic disturbances.	<u>Cultural fire use:</u> Indigenous fire use has shaped fire regimes and supported forest heterogeneity via frequent and low severity fire prior to European colonization. <u>Land use change and forest structure:</u> To a greater degree than moist mixed-conifer forests, dry mixed-conifer forests are heavily altered from the combination of high-grade logging, fire exclusion, fire suppression, and development in the wildland-urban interface. Many mixed-conifer forests are in a contemporary fire deficit compared to historical rates of annual area burned.
Dry warm forests and woodlands: Low-elevation zone, in broad valleys along major river systems, and on islands in the Salish Sea. <u>Major ecoregions:</u> Willamette Valley, Klamath Mountains	<u>Winters:</u> mild with most precipitation as rain <u>Summers:</u> very warm and dry	ponderosa pine, Douglas-fir, Oregon white oak, black oak, canyon live oak, tanoak, madrone <u>Interior dry and warm forests and woodlands:</u> western juniper	<u>Fire regime:</u> Historical fire return intervals range from 3 to 5 years in woodlands dominated by oak species, and 25-40 years in areas dominated by conifer species. <u>Biotic disturbances:</u> Relatively open and sparse structure (primarily facilitated by frequent fire) limits the occurrence of widespread and severe biotic disturbances, aside from localized native agents (e.g., oak mistletoe).	<u>Cultural fire use:</u> Indigenous fire use is an important component of fire regimes and maintained open conditions via frequent and low severity fire prior to European colonization. <u>Fire exclusion and land use change:</u> Exclusion of Indigenous fire use, fire suppression, and development has led to expansion of juniper woodlands into sagebrush and grassland habitats. <u>Invasive species:</u> Invasive pathogens and annual grasses contribute to novel disturbance regimes in this forest type. Oak species and tanoak have been severely impacted by sudden oak death. Cheatgrass and ventenata establishment has increased fire potential in many areas.

Sources: Agee 1993; Agne et al. 2018; Donato et al. 2020; Donato et al. 2023; Franklin and Dymess 1973; Haugo et al. 2021; Raffa et al. 2008; Reilly et al. 2021

INTERACTION OF CLIMATE CHANGE AND ECOSYSTEM STRESSORS

Climate change is affecting forest ecosystems throughout the NW and impacts are expected to intensify with further warming and changes in precipitation patterns. Changes in the climate will directly affect plant phenology, growth, productivity, regeneration, and mortality. Biotic and abiotic disturbance regimes, themselves altered by a changing climate, will interact with the direct effects of climate change to influence future forest structure and composition over large areas, ultimately changing the distribution of species and the extent of forest cover.

DIRECT EFFECTS OF CHANGES IN THE CLIMATE

The physiological sensitivity of forest vegetation to the direct effects of increasing temperatures and changes in precipitation patterns partially depends on species-specific vulnerability to climate change.

- Higher temperatures, greater evaporation or evapotranspiration, and decreases in summer precipitation are expected to reduce moisture available for tree growth and productivity during some times of the year.
- Dry mixed-conifer forests and dry, warm forests and woodlands are already water-limited and are expected to be more vulnerable to changes in the frequency and severity of drought.
- Higher temperatures in autumn, winter, and spring will decrease snowpack and lead to longer growing seasons. This is expected to increase growth and productivity in energy-limited cold forests and moist mixed-conifer forests where water is generally sufficient during the growing seasons but temperature currently limits growth.

Climate change is affecting plant phenology primarily through earlier onset of spring phenological events, such as flowering and bud break, and delayed autumn phenological events, such as leaf coloring and senescence (Piao et al. 2019).

- Temperature is a primary control of plant phenological processes, particularly accumulated temperature (i.e., growing degree days), for events that are triggered by cold and hot temperatures. Photoperiod also influences phenological events, however, and may limit phenological response to warming (Fu et al. 2015).
- Spring phenology is more responsive to daytime warming than to nighttime warming at both the species and ecosystem levels. Photoperiod regulates phenological events in autumn more than spring, so warming in spring is expected to affect phenological events more compared to warming in autumn (Fu 2015).
- Trends in the earlier onset of phenological events in spring and delay in events in autumn with warming appears to be slowing, but understanding of the mechanisms underlying these phenological responses to climate change remains limited (Piao et al. 2019).

- Changes in the timing of phenological events affect broader ecosystem functions, such as carbon cycling, yet understanding of these functional changes remains limited (Piao et al 2019).

Forest ecosystems demonstrate varying sensitivity to ecological drought as a function of species-specific tolerance of dry conditions, stand composition, and landscape characteristics.

- A lack of available water during drought causes or contributes to tree mortality through the combined effects of carbon starvation and hydraulic failure (Adams et al. 2017).
- The sensitivity of forest ecosystems to drought is a function of multiple factors: plant community composition, forest density, size class distribution, species-specific tolerance of drought stress, and landscape characteristics, such as topography and soils. Local climate mediates the sensitivity of forest ecosystems to drought.
- Ecotones (transitions from forests to non-forest ecosystems such as shrublands and grasslands) in dry, warm forests and woodlands and cold forests of the Rocky Mountains demonstrate high sensitivity to seasonal drought relative to other NW forest ecosystems.
- High elevations (cold forests), forest in drier climates (dry mixed-conifer forests, dry warm forests and woodlands), or forests located in areas with greater soil bulk density exhibit higher drought sensitivity (Cartwright et al. 2020).
- Forests located in valley bottoms and areas with low soil bulk density and soil available water capacity exhibit less drought sensitivity and may function as drought refugia (Cartwright et al. 2020).

Globally, widespread tree mortality in response to drought and heat is well established (Allen et al. 2010). In the NW, recent ecological droughts have reduced forest productivity and tree growth, increased mortality rates, and contributed to diebacks and declines of some species.

- Several tree species in the NW are displaying periods of decline and high rates of mortality in portions of their range, including Douglas-fir in the Klamath Mountains region (Bennett et al. 2023), bigleaf maple (Betzen et al. 2021), and western redcedar in the Coast Range, Cascades and Puget Lowlands regions (Andrus et al. 2024). These declines are preconditioned by ecological drought, in combination with other biotic or abiotic stressors.

The effect of higher atmospheric concentrations of carbon dioxide (CO₂) on forest productivity (i.e. CO₂ fertilization) remains poorly understood; most evidence indicates that the increase is likely to be limited, site specific, and depend on available moisture and nutrients.

- Greater concentrations of atmospheric CO₂ have the potential to increase water use efficiency and drought tolerance of plants by reducing water loss through stomatal conductance.

- Most CO₂ fertilization research relies on biogeochemical models or experiments with highly controlled site conditions, making inferences to the uncontrolled environment difficult. In controlled experiments and modeling studies, higher concentrations of atmospheric CO₂ reduce evapotranspiration, increase soil moisture, photosynthesis, biomass production (Naidu and DeLucia 2001), and offset some negative effects of drought on productivity, but the effects are minor and more pronounced for seedlings than mature trees (DeLucia et al. 2005).

Regeneration and recruitment are sensitive life stages that will influence the trajectory of species range shifts and forest conversion to non-forest vegetation. Climate change effects on recruitment processes will vary by forest type and the associated climatic factors that limit recruitment.

- Juvenile life stages are especially sensitive to climatic conditions because of narrower climatic tolerances relative to mature trees.
- Range shifts for conifer species are expected to lag changes in the climate and range expansion will be limited by constraints on tree regeneration and recruitment including availability of seed sources, availability of microsites for establishment, and climatic conditions in the years following disturbance.
- Seed availability following disturbance is limited by long distances from parent-tree seed sources (Littlefield), and the abundance of parent-trees is especially limiting at the upper elevation edge of conifer species ranges in the NW (Kroiss and HilleRisLambers 2015).
- Availability of suitable microsites will limit seedling germination, but effects will vary by species, complicating projections of range shifts (Kroiss and HilleRisLambers 2015). For example, microsite availability for seed germination is sensitive to the duration of snowpack. The availability of microsites will decrease for low-elevation conifer species as snowpack duration declines but increase for high-elevation species.
- The potential for range shifts is greater following disturbance, and post-disturbance regeneration and recruitment rates are strongly correlated with post-disturbance climatic conditions (Littlefield 2019, Littlefield et al. 2020). In water-limited forests, drought and low soil moisture are expected to reduce tree regeneration following disturbance (Tepley et al. 2017), restricting post-disturbance regeneration to growing seasons with a relatively cool and moist (Littlefield 2019).

INDIRECT EFFECTS

Climate change will influence NW forest ecosystems indirectly by altering disturbance regimes. Disturbances are a major driver of forest structure, composition and function and are expected to shift in frequency, extent, severity and seasonality as the climate changes (Seidl et al. 2017). In the NW, major forest disturbances influenced by climate include wildfires, outbreaks of insects and pathogens, species invasions, and their interactions.

CHANGES IN FIRE REGIMES

Climate change will promote wildfire activity in NW forests (Reilly et al. 2021, Hood et al. 2021), **but changes in fire regimes will be variable** (Hoecker et al. 2023).

- Across the western US, climate change has enhanced fuel aridity and driven increases in fire activity (Abatzoglou & Williams 2016) including extreme fire weather (Abatzoglou et al. 2019, Abatzoglou et al. 2021, Coop et al. 2022), area burned (Westerling 2016, Abatzoglou and Williams 2016), high-severity burn area (Parks and Abatzoglou 2020), fire season length (Jolly et al. 2015), number of large fires (Dennison et al. 2014) and nighttime fire intensity (Balch et al. 2022).
- Future warming is expected to continue to increase fire activity, though trends differ across forest types and are influenced by future patterns of, and feedbacks in, climate, land use, fire suppression and vegetation change (Littell et al. 2018).

In forests where fire is limited by available fuel (dry warm forests and woodlands, mixed-conifer forests), climate change is highly likely to increase fire frequency, extent, and severity (Halofsky et al. 2020), especially in the wildland-urban interface.

- Increasing spring and autumn temperatures and drier summers are expected to increase area burned (Holden et al. 2018, Littell et al. 2018) and lengthen the fire season (Jolly et al. 2015).
- Forests in and near the wildland-urban interface are likely to experience greater impacts due to greater potential for human-caused ignitions (Balch et al. 2017).
- Increases in fire severity and extent will be partially driven by enhanced fuel abundance and connectivity from the legacy of past fire exclusion and suppression (Reilly et al. 2021).
- Over longer time frames, fuel-limited systems may experience reductions in fire frequency and severity if fuel availability is reduced by future declines in vegetation productivity (Reilly et al. 2021).

In forests where fire is limited by flammability (wet and cold forests), future fire activity is less certain due to limited historical data on fire-climate relationships (Donato et al. 2020).

- Area burned is projected to increase more and sooner in flammability-limited systems compared to fuel-limited systems since warming and drying climate conditions promote fuel aridity (Littell et al. 2018).

- Where fuel aridity is primarily moisture-driven (wet forests), climate change is less likely to change fire regime characteristics in the near term. Fire frequency and severity are expected to increase with warming, but frequency will remain relatively low (Halofsky et al. 2020). In the absence of extreme fire weather, the potential for small to moderate size fires may increase (Reilly et al. 2022), though co-occurrence of compounding extremes (e.g., fuel aridity and high winds) are expected to increase the risk of smaller fires becoming large events (Abatzoglou et al. 2021).
- Where fuel aridity is primarily temperature-driven (cold forests), climate change is moderately likely to increase fire frequency and extent (Halofsky et al. 2020). Higher temperatures will promote the flammability of forests at high elevations, forests typically too wet to burn for much of the year (Alizadeh et al. 2021), allowing increased fire activity in lower elevations to spread into subalpine areas.
- Increased vegetation productivity will provide more available fuel in cold forests during dry conditions (Halofsky et al. 2020).

Changing fire regimes are expected to alter postfire forest structure, composition and function. Fire effects will be compounded by legacies of past management, particularly in mixed-conifer forests where fire exclusion and suppression have led to anomalously high fuel amounts (Hagmann et al. 2022).

- Increased fire frequency, severity and extent will decrease forest age and alter landscape heterogeneity within large burn patches (Halofsky et al. 2020, Halofsky et al. 2018f, Harvey et al. 2023, Cassell et al. 2019).
- More frequent large and severe fires will limit postfire regeneration by reducing seed availability (Halofsky et al. 2020, Hoecker et al. 2023, Meigs et al. 2020, Agne et al. 2022) and survival (Davis et al. 2019b, Wolf et al. 2021).
- By removing vegetation and altering soil properties, high-severity fire reduces soil stability and increases debris flows with implications for water quality and quantity (Prichard et al. 2021).

CHANGES IN INSECTS AND PLANT PATHOGENS

Climate change will alter the potential for biotic disturbance outbreaks in NW forests through interacting effects on both biotic agents and their host trees. Effects will vary by site, species and climate scenario (Agne et al. 2018; Fettig et al. 2022a; Simler-Williams et al. 2019).

Shifts in temperature and precipitation will affect the virulence of biotic agents directly through effects on fitness, fecundity and phenology (Fettig et al. 2022a, Agne et al. 2018). **Adaptation to local conditions may limit the extent to which biotic agents can respond to climate variation** (Simler-Williamson et al. 2019).

- Climate change promotes increased likelihood and extent of insect outbreaks. Warming is expected to increase population growth and range expansion for some insect species by promoting greater overwinter survival, faster development, earlier

emergence, completion of more generations in a year and enabling climatic suitability at higher elevations (Pureswaran et al. 2018; Simler-Williamson et al. 2019; Fettig et al. 2022a).

- Fungal development is highly sensitive to precipitation and often favored by cool and moist soil conditions, suggesting that warming may reduce the virulence of some plant pathogens in dry climate scenarios (Agne et al. 2018).

Climate change will influence biotic outbreak dynamics indirectly by influencing host tree susceptibility to insects and plant pathogens.

- Greater drought frequency and severity increase host tree susceptibility to biotic agents by reducing resources available for defense (Pureswaran et al. 2018). However, water stress may also reduce nutritional content and structural properties of host leaves, thus weakening the benefits for foliar pathogens and defoliating insects (Simler-Williamson et al. 2019).
- Trees affected by biotic agents may be more sensitive to direct effects of warming and drought stress on growth and mortality, contributing to increased outbreak severity (Agne et al. 2018; Bell et al. 2020).
- Host susceptibility may be mediated by stand conditions, genetic variation within the host tree population, host tree range shifts and asynchronicity in key host and biotic agent development stages (Agne et al. 2018; Pureswaran et al. 2018; Six et al. 2018; Simler-Williamson et al. 2019).

CHANGES IN INVASIVE SPECIES DISTRIBUTION AND ABUNDANCE

Climate change will promote opportunities for expanded distribution, rate of spread and abundance of invasive species in NW forests.

- Forests of the NW are vulnerable to species invasion due to heterogeneity in climatic and landscape conditions that facilitate diverse habitat niches, importance of international trade of forest products to the regional economy, and rapid human population growth – factors associated with invasive species introductions and establishment (Gervais et al. 2020).
- Effects of climate change on invasive species dynamics will be variable within and among species, and depend on direct effects on individuals, indirect effects on available resources and species interactions, and alteration of environmental conditions by humans and other influences (e.g., management, extreme events, disturbances; Finch et al. 2021; Gervais et al. 2020).
- Increased frequency, duration and intensity of extreme weather events (e.g., floods, droughts) may facilitate dispersal and colonization of invasive species by carrying propagules, reducing existing vegetation, and creating bare soil (Finch et al. 2021).

Shifts in temperature and precipitation will have direct effects on invasive species via climate controls on physiology.

- Many invasive plants have broad climatic tolerances, high phenological plasticity, and can adapt rapidly to local climates which may promote greater survival and

reproductive success under warmer and drier climate conditions than native plant species (Ayres et al. 2014; Finch et al. 2021).

- Warming is likely to benefit invasive insects by increasing movement, dispersal, feeding, growth and survival. Yet, warming may also reduce insect survival and reproduction by disrupting developmental synchrony with their hosts and altering overwintering conditions (Finch et al. 2021).
- Increasing temperatures and shifts in precipitation amount and timing will have direct effects on invasive pathogen spore formation and host infection success, and indirect effects via changes in host stress (Finch et al. 2021).

DISTURBANCE INTERACTIONS

Greater disturbance activity under climate change increases the potential for interactions among disturbances in NW forests. Disturbances may be linked, where the effects of one disturbance alter the likelihood, extent, or severity of a subsequent disturbance (Simard et al. 2011). Disturbance interactions may also produce compound effects on forest structure and function when multiple disturbances occur without sufficient time for recovery between them (Paine et al. 1998, Kleinman et al. 2019).

Climate-driven increases in fire activity will promote the likelihood of reburns – areas where multiple fires overlap. Reburn severity will be influenced by severity of the first fire, climate setting and forest type, interval between fires, and fire weather (Halofsky et al. 2020).

- Reburns may be less severe at shorter intervals and more severe in areas with prolific shrub and tree regeneration (Halofsky et al. 2020).
- In fuel- (dry warm forests and woodlands, mixed-conifer forests) and temperature-limited systems (cold forests), past fires can act as temporary barriers (5–25 years) to subsequent fire occurrence, spread and severity due to consumption of available fuels and changes in vegetation. This effect weakens over time as fuels recover, and can be overcome by extreme fire weather (Halofsky et al. 2020, Hood et al. 2021).
- In moisture-limited systems (wet forests), past fires may not reduce reburn likelihood or severity due to rapid postfire accumulation of live biomass (Halofsky et al. 2020, Reilly et al. 2022).
- When occurring over shortened intervals, reburns may produce abrupt shifts in forest structure and composition — including transition to non-forest vegetation — by eroding resilience mechanisms (Agne et al. 2022, Hood et al. 2021, Hoecker & Turner 2022, Halofsky et al. 2020, Kleinman et al. 2019).
- Reburns may maintain or extend the longevity of structurally complex early-seral habitats characterized by high biodiversity (Reilly et al. 2021).

Occurrence and effects of interactions between fire and biotic disturbances will depend on the order, severity and timing of each disturbance (Fettig et al. 2022b).

- Severe fire may reduce biotic disturbance likelihood by killing host trees over extensive areas (Simler-Williamson et al. 2019). Injury and reductions in vigor caused by lower severity fire can increase tree susceptibility to insects and pathogens (Hood et al. 2021), though in some cases fire may stimulate tree defenses and mitigate biotic disturbance risks (Fettig et al. 2022b).
- Biotic disturbances are unlikely to affect fire likelihood (Meigs et al. 2015) or area burned (Hart et al. 2015). However, tree mortality and shifts in fuel profiles following insect or pathogen outbreaks can influence fire behavior (e.g., Woolley et al. 2019) and severity (Talucci et al. 2020), though extreme fire weather will override these effects (Fettig et al. 2022b). Trees injured or killed by biotic agents are more susceptible to fire-caused damage and mortality (Halofsky et al. 2018a).
- Forest recovery following biotic disturbance and fire interactions will depend on the regeneration mechanisms of the affected trees. Canopy seedbanking species are less affected by compound disturbances, whereas obligate seeding species may experience lower postfire seedling establishment in areas affected by insect outbreaks prior to fire (Halofsky et al. 2020).

Increasing disturbance activity will expand the distribution, spread and abundance of invasive species in NW forests.

- Highly competitive traits allow invasive species to rapidly colonize disturbed areas. Fire and insect outbreaks can enhance invasive species performance by killing native species, decreasing competition, creating bare ground and increasing available resources (Finch et al. 2021, Halofsky et al. 2020).
- Low-elevation dry forests are vulnerable to invasive species establishment following more frequent fires (Halofsky et al. 2020, Finch et al. 2021).
- Invasive annual grasses like cheatgrass and ventenata can alter fire regimes by creating a continuous layer of fine, highly combustible fuels that dry early in the season, increasing both fire likelihood and fire season length and further hindering native species recovery (Kerns et al. 2020, Finch et al. 2021, Halofsky and Peterson 2017, Tortorelli et al. 2023).
- Invasive species can increase insect outbreak severity. For example, in cold forests, heavy infections of invasive white pine blister rust reduce tree defenses against mountain pine beetle (Simler-Williamson et al. 2019).

Increasing insect and plant pathogen activity will promote biotic disturbance hotspots — areas where multiple biotic disturbances overlap — with potential for compounded effects on forest recovery. Effects of biotic disturbance interactions depend on species, time since outbreak and outbreak severity and extent (Harvey et al. 2023b).

- Outbreaks of one biotic agent typically limit successive outbreaks of the same species by removing available hosts, whereas interactions between different biotic agents are more variable (Simler-Williamson et al. 2019).

- Stress from needle loss caused by defoliating insects can predispose trees to bark beetle attack (Halofsky et al. 2018c).
- Fungal pathogens may influence host tree susceptibility to insects by increasing stress and reducing defenses (Halofsky et al. 2020). For example, root diseases can predispose trees to attack and mortality by bark beetles, whereas foliar pathogens often reduce host attractiveness to bark beetles (Agne et al. 2018).
- Plant parasites (e.g., dwarf mistletoe) may increase tree susceptibility to bark beetles, though reductions in tree growth and phloem thickness can decrease bark beetle performance (Halofsky et al. 2018c).

DISTURBANCE AND CLIMATE DRIVER INTERACTIONS

Interactions between direct and indirect climate effects will drive shifts in NW forest structure and function.

- Interactions may result in altered species composition or forest loss, particularly for dry forests and sites on southwest-facing slopes or at lower elevations (Davis et al. 2019a, Halofsky et al. 2020, Kemp et al. 2019).
- Climate conditions prior to and during disturbances can alter disturbance severity (Halofsky et al. 2020). Reduced tree vigor from preceding heat and drought stress may increase the severity of fire and insect outbreaks by enhancing tree mortality probability (Coop et al. 2020, Van Mantgem et al. 2020).

Climate conditions following disturbance can influence forest recovery through effects on regeneration processes.

- Temperature and moisture are important drivers of tree regeneration success, with warmer and drier postfire conditions associated with reduced seedling establishment and growth (Littlefield et al. 2020, Kemp et al. 2019, Hankin et al. 2019, Davis et al. 2019b) and longer regeneration timelines (Agne et al. 2022).
- Unfavorable postfire growing conditions may enhance the risk of regeneration failure following future fires (Stevens-Rumann et al. 2018), though topography and stand-level factors may outweigh short-term effects of postfire climate for some areas (Littlefield 2019, Davis et al. 2023).
- Warmer and drier postfire conditions may facilitate faster spread of invasive species and competitive advantage over native species (Finch et al. 2021).

VEGETATION RANGE SHIFTS

Changes in tree recruitment, growth, and mortality will culminate in changes in species dominance and composition and ultimately the distribution, or range, of some tree species. Species ranges are shifting in the NW due to the direct effects of changes in temperature, precipitation and atmospheric CO₂ on these demographic processes, catalyzed by more frequent and severe disturbances. Range shifts are expected to continue as the climate continues to warm.

CLIMATE EFFECTS: FOREST ECOSYSTEMS OVERVIEW

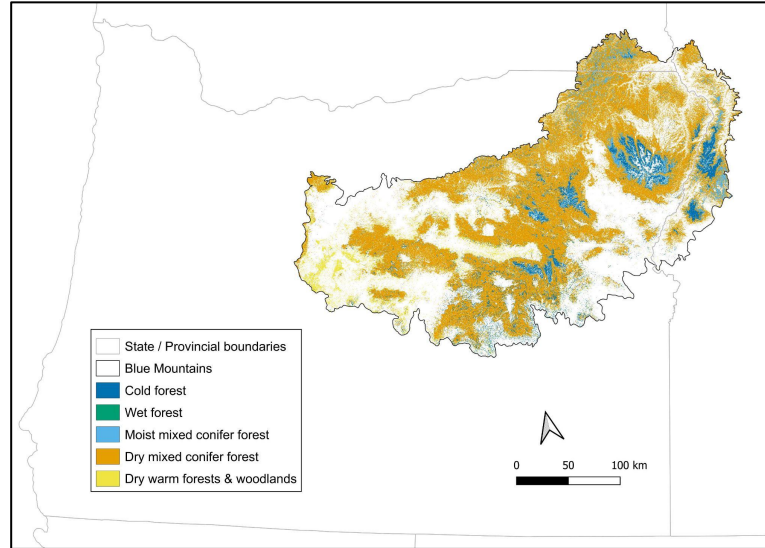
- Simulation modeling of environmental conditions and tree species suitability across the NW suggests that changes in species distribution will be greatest in montane forests (cold forests and moist mixed-conifer forests). Tree species are expected to be most stressed within their current ranges in NW desert ecosystems (i.e. dry, warm forests and woodlands) (Mathys et al. 2017). Species ranges are expected to expand in wet forests and the northern part of the NW.
- More frequent fire will favor species with traits that facilitate fire resistance or rapid postfire recovery over fire-avoidant species (Halofsky et al. 2020, Hoecker et al. 2023). This will catalyze upward shifts in species ranges (e.g., Nigro et al. 2022) and make high-elevation species vulnerable to decline (Cassell et al. 2019).
- Recent warming in forested ecosystems in the NW has shifted community composition towards greater abundance of tree species that are tolerant of heat; this trend is expected to continue with accelerated warming (Rosenblad et al. 2023).
- Changes in the climate are expected to favor species with wider climatic niches and greater physiological tolerances of hot and dry conditions.
- Abrupt shifts to non-forest vegetation may occur where extensive tree mortality and constraints on regeneration compromise forest recovery (Coop et al. 2020). Lower elevation and drier forests will be particularly vulnerable to fire-driven conversion to shrub- or grass-dominated systems (Davis et al. 2019a, Davis et al. 2020, Hoecker et al. 2023, Meigs et al. 2023, Parks et al. 2019).

Blue Mountains Forest Ecosystems



Regional Description

The Blue Mountains ecoregion is generally lower elevation than the Cascade and Rocky Mountains. Forests are primarily dry mixed-conifer forests, with areas of cold and moist mixed-conifer forests and dry warm forests and woodlands. Major tree species in dry mixed-conifer forests include ponderosa pine and Douglas-fir. Major tree species in the maritime-influenced, productive moist mixed-conifer forests include fir Engelmann spruce and fir species. Major tree species in cold forests include subalpine fir, Engelmann spruce and whitebark pine. The major tree species in dry warm forests and woodlands is western juniper, which has expanded its range considerably.



The ecoregion is dominated by dry mixed -conifer forests with cold-moist mixed conifer forests at high elevations and dry warm forests in woodlands at low elevations. Data Source: [LANDFIRE Biophysical Settings \(BPS\) 2020](#).

Management Considerations

- In dry mixed-conifer forests, fire exclusion has increased forest density, and shifted species composition away from ponderosa pine dominance towards shade-tolerant, fire-intolerant species.
- Dense forests with an overabundance of shade-tolerant trees are less resistant to wildfire and increase the potential for uncharacteristically large and severe fire.
- Extensive cattle grazing in dry mixed-conifer forests and non-forest ecosystems has changed plant composition and increased the abundance of invasive species such as cheatgrass.

Managing Ecosystem Stressors



Drought Stress and Declining Forest Productivity

Description

Productivity in dry mixed-conifer forests is limited by moisture availability. Hotter and drier conditions in summer are expected to decrease available soil water, which reduces tree growth and limits recruitment, especially at the forest-steppe ecotone (Halofsky and Peterson 2017). Climatic suitability for Douglas-fir and ponderosa pine is projected to decrease in this ecoregion.

Strategy Habitat

- Vulnerable habitats are ponderosa pine dominant dry mixed-conifer forests, especially where fire exclusion has increased the density of shade-tolerant conifers.
- Older forests with large, fire-resistant trees provide critical wildlife habitat.

Management Actions

- Protect drought-adapted individuals and maintain availability of drought-tolerant tree species and genotypes (Halofsky and Peterson 2017).
- Enhance forest productivity by reducing tree density to maintain tree vigor and growth, with a focus on ecosystem function rather than specific tree species (Sohn et al. 2016).

Blue Mountains Forest Ecosystems



Managing Ecosystem Stressors



Mortality and Range Restriction of Cold-Forest Conifer Species

Description

Longer growing seasons and shorter duration snow cover are expected to enhance growth and recruitment of subalpine species, yet disturbances are expected to increase tree mortality rates (Halofsky and Peterson 2017).

Whitebark pine and limber pine are threatened by white pine blister rust. It is unknown whether climate change will favor blister rust, but a more variable climate may favor infections. Cold forests are slow to recover from fire, so more fire is expected to reduce habitat extent. In recent decades, temperatures have facilitated an upward expansion of the range of mountain pine beetle (Fettig et al. 2022), increasing mortality rates of high-elevation conifers. Encroachment by low-elevation conifers in a warmer climate increases competition, whereas space for upward migration of cold-forest conifers is limited by topography and substrate.

Strategy Habitat

- Conifer species in cold forests of this ecoregion, particularly whitebark pine, limber pine, and mountain hemlock, are especially vulnerable to warming.
- Rare and relic populations of whitebark pine, limber pine, and mountain hemlock are especially vulnerable to loss from biotic and abiotic disturbances that are favored in a warmer climate.
- Whitebark pine is a critical food source for wildlife species and contributes to the character of high-elevation forests.

Management Actions

- Suppress fire or use insecticides and/or semiochemicals (e.g., anti-aggregation pheromones to resist the loss of relic populations of high-elevation conifers (Halofsky and Peterson 2017).
- Monitor abundance and vigor of five-needle pines (Halofsky and Peterson 2017).
- Resist species loss by maintaining genetic diversity within five-needle pine populations with natural regeneration (Six et al. 2021, Six et al. 2018).
- Plant blister rust resistant whitebark pine genotypes to resist species loss (Halofsky and Peterson 2017).



Annual Grass Invasion and Changing Fire Regimes

Description

Nonnative annual grass invasion (e.g. cheatgrass and ventenata) has changed fire regimes by increasing fine fuels that carry wildfire. Following fire, cheatgrass invades low-elevation dry forests where it competes for resources, facilitates future fires, and increases fire season length (Kerns et al. 2020). Cheatgrass range is limited by cold temperatures, but it is expected to spread to higher elevations and into forests in a warming climate. However, more precipitation may offset these effects and limit range expansion (Bradley et al. 2018). Cheatgrass productivity is also enhanced by elevated carbon dioxide (Ziska et al. 2005). Recent increases in ventenata raise concerns for this ecoregion due to its ability to outcompete and replace cheatgrass (Tortorelli et al. 2023).

Strategy Habitat

- Two habitats especially vulnerable to this ecosystem stressor are dry mixed-conifer forests at the ecotone with woodlands and dry warm forests and woodlands at the ecotone with shrublands and grasslands.

Management Actions

- Removal of invasive annual grass is not feasible in areas where it is well established (Halofsky and Peterson 2017), but long-term control can still reduce impacts on ecosystems.
- Control of invasive grasses with chemical and biological methods may be less effective with warming (Halofsky and Peterson 2017).
- Minimize the spread of invasive annual grasses by increasing the resilience of native perennial grasses through the use of prescribed burning (Halofsky and Peterson 2017).

Cascades Forest Ecosystems

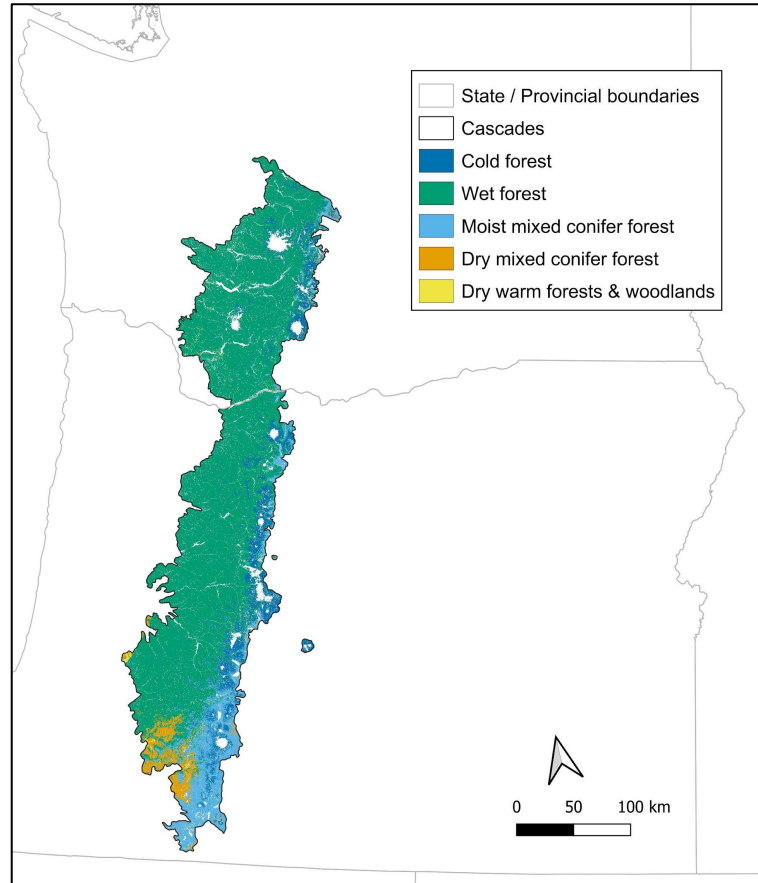


Regional Description

The Cascades ecoregion is dominated by wet forests with cold forests at high elevations. Major tree species in wet forests include Douglas-fir, western hemlock, western redcedar, Pacific silver fir, noble fir, grand fir, red alder, and bigleaf maple. Major tree species in regional cold forests include mountain hemlock, subalpine fir, yellow-cedar, Engelmann spruce and lodgepole pine.

Management Considerations

- Human population and land development is relatively sparse and large areas are publicly-owned wilderness and forest reserves, but population growth creates development pressures.
- Given the long fire return intervals in cold and wet forests in this ecoregion, fire exclusion has had only localized effects on forest composition and structure, primarily in dry mixed-conifer forest.
- Indigenous fire use is a component of fire regimes and supported more frequent fire in some locations prior to European colonization.
- Intensive forest management has decreased early-seral habitat and hardwood species abundance.



Wet forests dominate the Cascades Ecoregion, with dry mixed conifer forest in the south and cold and moist mixed conifer forests at high elevations in the Cascades. Data Source: [LANDFIRE Biophysical Settings \(BPS\) 2020](#).

Managing Ecosystem Stressors



Drought-Related Decline and Mortality

Description

Warmer, drier conditions are reducing growth and contributing to mortality of drought-intolerant species, such as bigleaf maple (Betzen et al. 2021), yellow-cedar (Mercer et al. 2022), western hemlock (Bell et al. 2020), and western redcedar (Andrus et al. 2023). Parasitic plants, e.g., dwarf mistletoe, reduce vigor and intensify direct effects of climatic stress on the growth and mortality of infected trees (Bell et al. 2020). Future warming and drought are expected to accelerate these declines.

Strategy Habitat

- Wet forests, especially tree species that are intolerant of low soil moisture.
- Low elevation wet forest sites in the Cascades ecoregion are most vulnerable to this ecosystem stressor.

Management Actions

- Monitor forest conditions for early detection of signs of decline (Mercer et al. 2022).
- Reducing mistletoe infection rates by removing infected trees or favoring non-host alternate species can slow the spread of infections, but these treatments can be expensive and may not always be ineffective.

Cascades Forest Ecosystems



Managing Ecosystem Stressors



Short-Interval Reburns

Description

Reburns can produce abrupt shifts in forest structure and composition, including transition to non-forest vegetation, when they occur over shortened intervals (Agne et al. 2022, Hoecker & Turner 2022, Halofsky et al. 2020, Kleinman et al. 2019). In wet forests in this ecoregion, past fires may not reduce the likelihood or severity of reburns due to rapid postfire accumulation of live biomass (Halofsky et al. 2020, Reilly et al. 2022). Reburns can maintain or extend the longevity of structurally complex early-seral habitats characterized by high biodiversity (Reilly et al. 2021) and they lengthen the time required to reach mature late-seral habitat conditions.

Strategy Habitats

- Highly productive wet forests dominated by fire-intolerant conifer species are vulnerable to high-severity reburns.
- This ecosystem stressor creates a tradeoff between mature late-seral habitat and complex early seral habitat, both important habitats for wildlife.

Management Actions

- Given the long fire return intervals characteristic of wet forests in this region, suppression of wildfires is an appropriate strategy to resist the effects of more frequent human-caused ignitions and preserve high-value mature forest habitat (Halofsky et al. 2018).
- Fires in wet forests, particularly short-interval reburns, provide opportunities to foster biodiversity and increase landscape heterogeneity through maintenance of early-seral habitats and hardwood species (Donato et al. 2020).
- Treating fuels to reduce small trees and ladder fuels may be an appropriate adaptation strategy for forests in more developed areas and to protect high-value resources and properties (Halofsky et al. 2018).



Douglas-fir Beetle Outbreaks

Description

Douglas-fir beetle attacks stressed and recently fallen trees and is more common in forests affected by wind and fire. It is unknown how climate change will affect the Douglas-fir beetle directly, but moisture stress is expected to increase tree susceptibility to beetle attacks (Agne et al. 2018). More fire and heavier rain events may increase dead and down Douglas-fir trees that attract the beetle (Hudec et al. 2019).

Strategy Habitats

- Wet forests dominated by Douglas-fir, especially where recent fire or wind events have disturbed the overstory canopy, are susceptible to this ecosystem stressor.
- Late-seral Douglas-fir forests are a critical habitat for wildlife in this ecoregion.

Management Actions

- Thinning to remove Douglas-fir host trees with low resistance reduces competition and increases vigor of remaining trees, which can assist forests to adapt to more frequent Douglas-fir beetle outbreaks (Fettig et al. 2022).
- Prompt and thorough applications of sanitation harvests (i.e., removal of infested trees), insecticides and/or semiochemicals (e.g., anti-aggregation pheromones) can reduce mortality caused by current infestations and protect individual high-value trees (Fettig et al. 2022).

Coast Range Forest Ecosystems

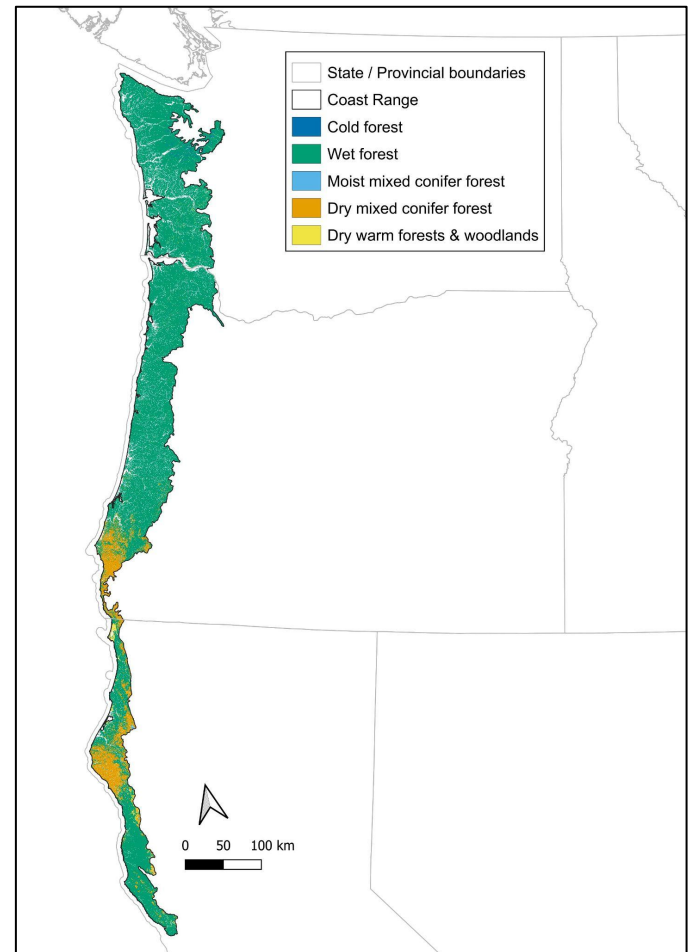


Regional Description

This ecoregion receives substantial precipitation and is dominated by highly productive wet forests. Major tree species in wet forests include Sitka spruce, Douglas-fir, western hemlock and western redcedar. Historically, Sitka spruce dominated the coast with western redcedar, western hemlock and Douglas-fir present in inland areas. Fog is an important climatic factor for redwood forests that dominate the Californian portion of the ecoregion.

Management Considerations

- Timber production is prominent. Many forests are intensively managed with Douglas-fir plantations, especially in the central portion of the ecoregion.
- Recreation and tourism are also prominent in many coastal communities.
- Invasive species and land use change due to development are management considerations for climate adaptation in this ecoregion.
- The characteristic fire regime of wet forests is high-severity, infrequent fire, so fire exclusion is primarily a management consideration for only the dry mixed conifer forests in the ecoregion.



Wet forests dominate the Coast Range Ecoregion, with dry mixed conifer forest in the southern part of the ecoregion in Oregon and California. Data Source: [LANDFIRE Biophysical Settings \(BPS\) 2020](#).

Managing Ecosystem Stressors

Swiss Needle Cast

Description

Swiss needle cast, a fungal plant pathogen that causes foliage disease in Douglas-fir. The disease reduces volume growth and productivity in Douglas-fir plantations. Swiss needle cast is associated with warm winters and high spring and summer precipitation and leaf wetness, so warmer winters are expected to favor pathogen development and increased disease severity. The effects of hotter drier summers on the pathogen are unclear, but could decrease disease severity by reducing leaf wetness (Agne et al. 2018).

Strategy Habitat

- Coastal Douglas-fir and western hemlock forests, especially Douglas-fir plantations

Management Actions

- Thin to remove trees with low disease tolerance (e.g., sparse crowns, small sizes) increases resilience (Shaw et al. 2021).
- Removal of Douglas-fir in severely affected Douglas-fir stands can yield better long-term resilience for western hemlock (Shaw et al. 2021).
- Traditional silvicultural techniques used to reduce foliage disease (e.g., thinning and pruning) are not effective at reducing Swiss needle cast within a plantation (Shaw et al. 2021).

Coast Range Forest Ecosystems



Managing Ecosystem Stressors



Yellow-cedar Decline

Description

Yellow-cedar growth is limited by warm and dry winters that have lower than average snowpack. Warmer winters in recent decades appear to be contributing to stress and decline of yellow-cedar (Mercer et al. 2022). Shallow roots of yellow-cedars are especially susceptible to damage without a persistent snowpack for insulation (Comeau et al. 2019).

Strategy Habitats

- Mature temperate yellow-cedar rainforests have a limited extent and provide critical wildlife habitat.

Management Actions

- Tree-level factors that confer resistance or predisposition to yellow-cedar decline are unknown (Comeau et al. 2019).
- Monitor forest conditions for signs of canopy dieback or tree mortality as winters warm (Mercer et al. 2022).



Douglas-fir Beetle

Description

Douglas-fir beetle, a native bark beetle, feeds on vascular tissue of stressed Douglas-fir and causes tree mortality. Host resistance typically keeps beetle populations at endemic levels, and small diameter trees are rarely attacked. Douglas-fir beetle is associated with windthrow and drought events, as well as localized areas of root disease. Increased host tree stress from hotter drier summers is expected to increase outbreak severity (Agne et al. 2018). Warmer winters may accelerate beetle development (Agne et al. 2018).

Strategy Habitats

- Douglas-fir and western hemlock forests.

Management Actions

- Prevent outbreaks by thinning to remove trees with low resistance, reduce competition and increase vigor of remaining trees (Fettig et al. 2022).
- Suppress outbreaks with prompt and thorough applications of sanitation harvests (i.e., removal of infested trees), insecticides, or semiochemicals (e.g., anti-aggregation pheromones) to address current infestations (Fettig et al. 2022).



Extreme Heat

Description

More frequent and intense heat waves with climate change are expected to increase forest exposure to extreme heat (Thompson et al. 2022). The summer 2021 PNW heat wave caused foliar damage of tree canopies on more than 90,000 ha. Coastal Douglas-fir and western hemlock plantations had the most extensive impacts (Still et al. 2023). Phenological characteristics (e.g., date of budburst), spatial position (e.g., aspect, proximity to exposed edges), water availability, and acclimation all influenced tree susceptibility to scorch, indicating variable vulnerability (Still et al. 2023).

Strategy Habitats

- Wet, cool coastal forests with later dates of budburst (i.e., younger foliage at the time of heat events) are more vulnerable to this stressor than warmer inland and southern forests with earlier dates of budburst.
- Trees on south- and west-facing slopes and along roadsides are especially vulnerable.

Management Actions

- Infrequent deep watering of trees in summer can reduce moisture stress in developed areas.
- Selection of seed mixes with greater proportions of drought-tolerant species and from drought-resistant populations.
- Where acceptable, allow shifts in composition to species more tolerant of warm and dry current and future climate conditions (Andrus et al. 2024).

Eastern Cascades Foothills Forest Ecosystems

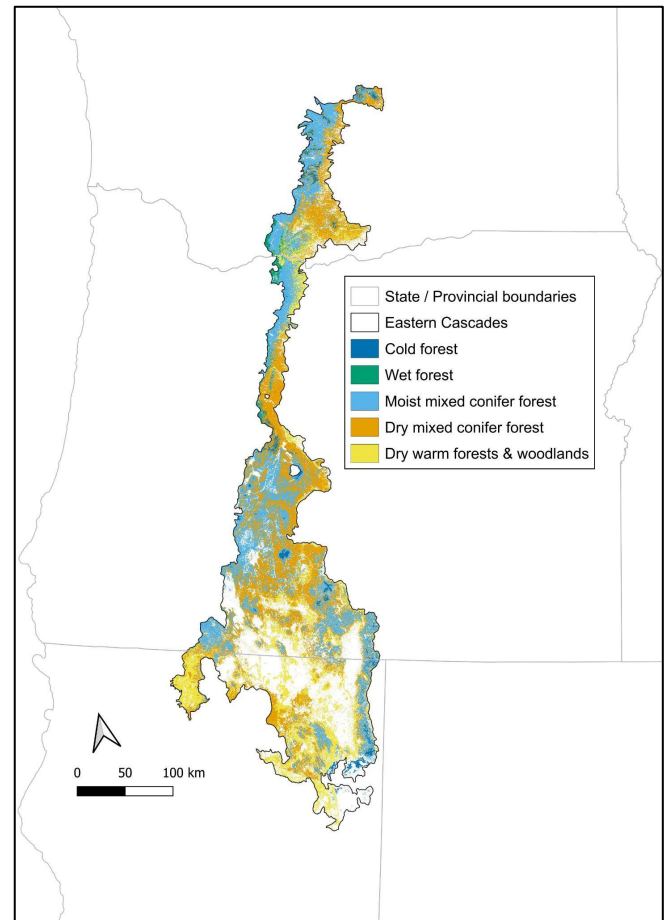


Regional Description

This ecoregion is in the rain shadow of the Cascade Mountains and experiences greater temperature extremes and less precipitation compared to the Cascade ecoregions to the west. At higher elevations, moist mixed-conifer forests include Douglas-fir, western larch, grand fir, white fir, western redcedar, western hemlock. Dry mixed-conifer forests of this region are dominated by ponderosa pine with some Douglas-fir and lodgepole pine. Dry forest and woodlands are dominated by juniper with some oak.

Management Considerations

- Forest management practices, including high-grade and selective harvest of large trees, as well as rural residential development have reduced the extent of dry forests dominated by ponderosa pine.
- Fire exclusion, including indigenous burning practices, has caused fuel accumulation and shifted the fire regime to larger, less frequent fires of higher severity.
- Invasive grass species are altering fire regimes in dry warm forests and woodlands.



The Eastern Cascades Foothills Ecoregion has a diverse mix of forests from moist mixed conifer forests at high elevations and in the north of the ecoregion to dry warm forests & woodlands to the south of the ecoregion in Oregon. Data Source: [LANDFIRE Biophysical Settings \(BPS\) 2020](#).

Managing Ecosystem Stressors

Juniper Woodland Expansion

Description

Western juniper woodlands have expanded into semiarid shrub-steppe ecosystems (Miller et al. 2000) during warmer, wetter periods. Intensive livestock grazing has reduced fine fuels and the frequency of low-severity fire that historically killed young juniper trees. Continued expansion of juniper with climate change depends on precipitation changes. Less precipitation in the growing season is expected to decrease tree establishment and slow expansion; more precipitation in warmer winters is expected to facilitate expansion (Halofsky et al. 2019.)

Strategy Habitat

- Warmer, drier shrub-steppe ecosystems in the region are more vulnerable to juniper expansion than are wetter and colder upland shrub ecosystems (Miller et al. 2013).

Management Actions

- Reduce the invasion of nonnative annual grasses that alter fire regimes.
- Mechanical fuel reduction treatments, grazing management, and prescribed fire can be used to reintroduce low severity fire and slow the expansion of juniper woodlands.

Eastern Cascades Foothills Forest Ecosystems



Managing Ecosystem Stressors



Altered Fire Regimes

Description

With fire exclusion, mixed-conifer forests have experienced increases in stand density and greater vertical and horizontal continuity of fuels relative to natural variability. Because of these altered fuel profiles, fire severity and extent have increased, though many of these forests are still in a contemporary fire deficit (Donato et al. 2023, Haugo et al. 2019). More frequent and severe fire in a warmer, drier climate is expected to further increase tree mortality in large, high-severity patches (Hagmann et al. 2022).

Strategy Habitats

- Habitats especially vulnerable to this ecosystem stressor are dry and moist mixed-conifer forests where fire has been excluded causing an increase in shade-tolerant species and a decrease in fire- and drought-resistant species (e.g., ponderosa pine and western larch) (Hessburg et al. 2022).

Management Actions

- Restore natural fire regimes and reduce fuels using stand density management and prescribed and cultural burning to promote frequent low-intensity fire (Hessburg et al. 2022).
- Use managed wildfire to restore forest structure and frequent low-severity fire by reducing fuel loads, increasing spatial heterogeneity, and promoting survival of large fire-resistant individuals (Laughlin et al. 2023).
- Strategically plant trees postfire, prioritizing cool moist microsites and drought-tolerant species and genotypes to restore species composition (Halofsky et al. 2020).



Shifts to Non-Forest Vegetation

Description

The compounding effects of low soil water availability and fires that burn with large, high-severity patches make dry mixed-conifer forests in this ecoregion vulnerable to potential conversion to grass- or shrub- dominated ecosystems (Coop et al. 2020). Following high-severity fire, recovery of forests is expected to be limited by a combination of low seed availability within large burn patches with limited seed sources (Davis et al. 2020), warm and dry post-fire climatic conditions (Davis et al. 2019), and short-interval reburns that limit tree regeneration (Hagmann et al. 2022).

Strategy Habitats

- Dry mixed-conifer forests have open canopies and lower biomass than mixed-conifer forests in areas with cooler climates and more precipitation.
- Vulnerable habitats include dry mixed-conifer forests at low elevations and on south-facing aspects, also called "trailing edge forests", where conifer regeneration after fire is limited by water availability (Meigs et al. 2023).

Management Actions

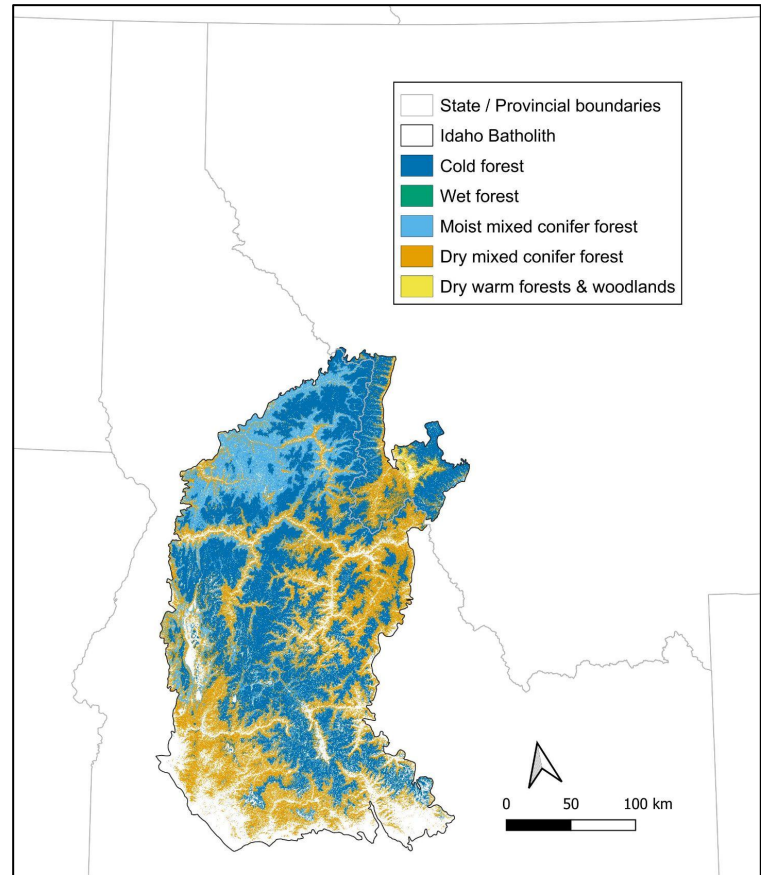
- Implement density- and fuel-reduction treatments that increase resistance to drought and fire via reduced competition and increased tree vigor (Meigs et al. 2023).
- Adjust re-planting approaches to prioritize lower densities of drought-tolerant species arranged spatially using the ICO (i.e., individual trees, clumps, and openings) pattern (North et al. 2019).
- Accept conversion to non-forest vegetation at sites where reforestation is unlikely to be successful due to forest type, topographic setting, and burn patch size (Meigs et al. 2023).
- Plant drought-tolerant non-conifer species (e.g., oak, native shrubs and grasses) to direct vegetation transitions to more drought- and fire-resistant structure and composition (Meigs et al. 2023).

Idaho Batholith Forest Ecosystems



Regional Description

Climate in this ecoregion is only marginally maritime influenced, less so than the Rocky Mountain ecoregions. The Idaho Batholith is dominated by cold and mixed-conifer forests. Major tree species in cold forests are Engelmann spruce and subalpine fir (minor components of whitebark pine, mountain hemlock, subalpine larch, quaking aspen). Major tree species in moist mixed-conifer forests are grand fir, Douglas-fir, lodgepole pine and western larch. Western hemlock is absent and western redcedar is limited to the north. Ponderosa pine and Douglas-fir are the major tree species in dry mixed-conifer forests.



The Idaho Batholith is dominated by cold and mixed-conifer forests. Data Source: [LANDFIRE Biophysical Settings \(BPS\) 2020](#).

Management Considerations

- Timber harvest, grazing and recreation are the major land uses in the Idaho Batholith ecoregion with extensive areas designated as wilderness.
- Soils in forested areas are droughty with limited nutrients and fertility; declining anadromous fish runs have further reduced nutrients.

Managing Ecosystem Stressors



Five-needle Pine Mortality

Description

Whitebark pine and other five-needle pines are experiencing decline across their range. These species are expected to be especially vulnerable to climate change as warming exacerbates existing stressors, including interspecific competition, white pine blister rust and mountain pine beetle outbreaks (Halofsky et al. 2018c). Declines in whitebark pine may have cascading effects on animal species that rely on its seeds as a major food source (e.g., Clark's nutcracker, grizzly bear, black bear) (Tomack et al. 2022).

Strategy Habitat

- Rare and relic populations of whitebark pine, limber pine, and mountain hemlock are especially vulnerable to loss from biotic and abiotic disturbances that are favored in a warmer climate.
- Whitebark pine is a critical food source for wildlife species and contributes to the character of high-elevation forests.

Management Actions

- Plant genetically resistant seedlings to promote blister rust resistance (Halofsky et al. 2018c).
- Enhance natural regeneration to maintain genetic diversity of whitebark pine populations (Six et al. 2021, Six et al. 2018).
- Prioritize restoration of sites that are less likely to be affected by climate change (i.e., refugia) to increase likelihood of restoration success (Halofsky et al. 2018c).

Idaho Batholith Forest Ecosystems



Managing Ecosystem Stressors



Large-scale Bark Beetle Outbreaks

Description

As warming enhances insect population growth and range expansion into higher elevation forests, more frequent and extensive insect outbreaks are expected to increase mortality of host tree species (e.g., lodgepole pine, Engelmann spruce, western white pine, whitebark pine, and subalpine fir) (Fettig et al. 2022; Halofsky et al. 2018). Spatial and temporal co-occurrence of outbreaks by multiple bark beetle species — including mountain pine beetle, spruce beetle, and western balsam bark beetle — and other stressors (e.g., white pine blister rust; Six et al. 2018) may limit forest recovery and promote shifts towards non-forest vegetation by removing multiple host tree species (Harvey et al. 2023).

Strategy Habitat

- Subalpine cold forests at high elevations are vulnerable to bark beetle outbreaks in a warmer climate due to short growing seasons and slow recovery times.
- Five-needle pines will be particularly vulnerable to beetle attack where existing infection by the invasive fungal pathogen that causes white pine blister rust is severe (Six et al. 2021, Tomback et al. 2022).

Management Actions

- Increase species, genetic, and landscape structural diversity to reduce risk of forest cover loss (Halofsky et al. 2018).
- Thin trees to remove host trees with low resistance and to reduce competition and increase vigor of remaining trees (Fettig et al. 2022). This approach may not be appropriate for all tree species (e.g., whitebark pine; Six et al. 2021).
- Promptly and thoroughly apply sanitation harvests (i.e., removal of infested trees), insecticides and/or semiochemicals (e.g., anti-aggregation pheromones) to limit current infestations and protect individual high-value trees (Fettig et al. 2022).



Changing Fire Regimes

Description

Fire occurrence and extent are expected to increase with warming as earlier snowmelt reduces fuel moisture and lengthens the window of flammability across large areas (Alizadeh et al. 2021). Shortened fire intervals may impede forest recovery when the timing between stand-replacing fires is insufficient for trees to mature and produce seed, reducing regeneration and potentially leading to shifts in forest structure and composition (e.g., range expansion of aspen; Nigro et al. 2022), including loss of forest area (Campbell and Shinneman 2017, Hood et al. 2021).

Strategy Habitat

- Subalpine cold forests at high elevations are vulnerable to altered fire regimes in a warmer climate due to short growing seasons and slow recovery times.
- Five-needle pine species will be particularly vulnerable to fire-caused damage and mortality where existing infection by the invasive fungal pathogen that causes white pine blister rust is severe (Loehman et al. 2018).

Management Actions

- Protect fire refugia and persistence of fire-sensitive species (Halofsky et al. 2018a, Keane et al. 2018).
- Suppress fire around culturally important and high-value resources to resist climate- and fire-driven vegetation change (Hoecker and Turner 2022).
- Use assisted migration of drought- and fire-adapted native tree species to enhance resilience to altered disturbance regimes with (Hoecker and Turner 2022).
- Selectively re-plant where populations are declining and prioritize multiple genotypes and species to enhance forest resilience to altered disturbance regimes by (Halofsky et al. 2018, Keane et al. 2018).

Klamath Mountains Forest Ecosystems

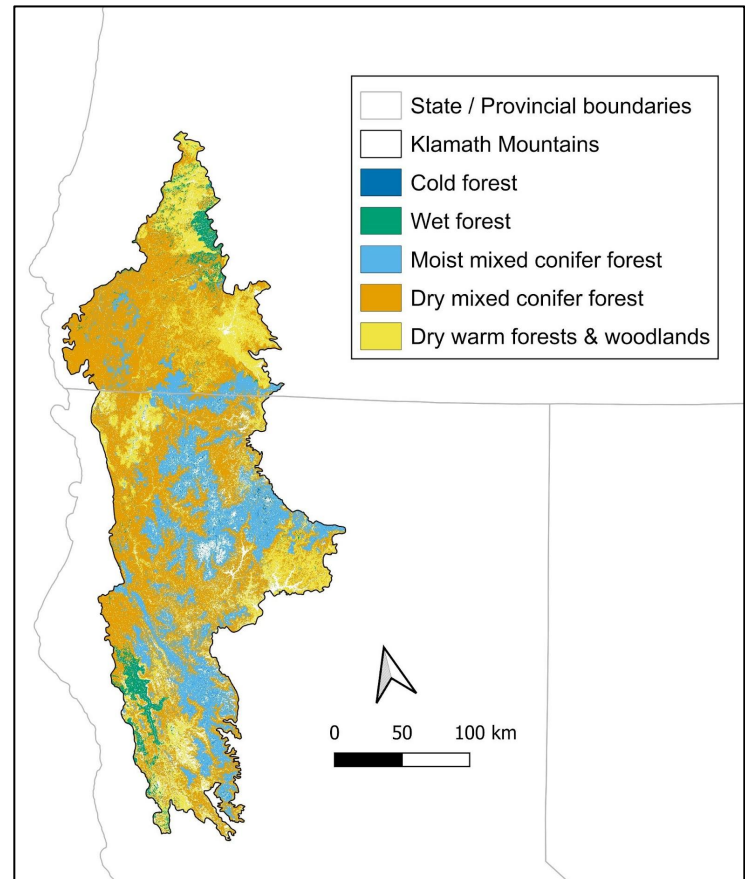


Regional Description

Topography of this ecoregion is dissected ridges, foothills, and valleys of the Klamath and Siskiyou mountains, with substantial relief. The climate is mild, characterized by lengthy summer drought. Dry mixed-conifer forests and dry warm forests and woodlands dominate the ecoregion, with some moist mixed-conifer forest. Oregon white oak, tanoak, and black oak (to the south) are common hardwoods in the dry-mixed conifer forests and dry warm forests and woodlands. Common conifer species include ponderosa pine, Douglas-fir, sugar pine, incense-cedar, white fir and red fir.

Management Considerations

- Habitat has been converted to agriculture, urbanization, and development in rural areas with extensive population growth.
- Fire exclusion, including indigenous burning, has caused fuel to accumulate in dry mixed conifer forests and dry warm forests and woodlands which had frequent low-severity fire historically.
- The ecoregion includes large areas of federally land managed primarily for recreation.



The Klamath Mountains Ecoregion is dominated by dry mixed-conifer forests and dry warm forests and woodlands. Data Source: [LANDFIRE Biophysical Settings \(BPS\) 2020](#).

Managing Ecosystem Stressors



Shift to Non-Forest Vegetation

Description

Projected increases in aridity and more frequent and severe fire are expected to reduce post-fire forest recovery by reducing conifer recruitment (Tepley et al. 2017). Dry areas of the ecoregion may exceed a threshold for which intervals between severe fires are too short to allow for conifer recruitment (Agne et al. 2022). Post-fire regeneration is expected to be low in patches of high-severity fire where seed sources are limited. The vulnerability of conifer forests to conversion to shrub or grass-dominated systems is expected to increase.

Strategy Habitat

- Dry mixed-conifer forests dominated by conifers are especially vulnerable to vegetation type conversion.

Management Actions

- Accept conversions to non-forest vegetation where reforestation success is unlikely. Post-fire patches of deciduous trees and shrubs slow conifer forest recovery, but provide early-seral habitat that contributes to landscape heterogeneity and biodiversity consistent with ecological management objectives (Tepley et al. 2017).
- Prioritize replanting in areas with greater chance of reforestation success to accelerate conifer recovery after high-severity fire and prevent conversion to non-forest (Tepley et al. 2017).

Klamath Mountains Forest Ecosystems



Managing Ecosystem Stressors



Drought and Biotic Disturbance Interactions

Description

Douglas-fir mortality in the Klamath Mountains ecoregion has increased in recent decades due to interacting climatic conditions and bark beetle (e.g., flatheaded fir borer) disturbances (Bennett et al. 2023), with harsh site conditions predisposing trees to mortality. Drought has been identified as an “inciting” factor for this recent mortality. Flatheaded fir borer, a native bark beetle, contributes to mortality on predisposed hot and dry sites. Flatheaded fir borer is expected to be an increasingly important disturbance agent in this ecoregion as drought frequency and severity increase with climate change (Agne et al. 2018).

Strategy Habitat

- Habitats especially vulnerable to this ecosystem stressor are Douglas-fir forests on harsh, dry sites at low elevations. These are sites where Douglas-fir was rare historically but the species has increased in abundance with fire exclusion.

Management Actions

- Thin less vigorous Douglas-fir trees on more favorable sites (low climatic water deficit) to retain more vigorous trees and increase resistance to flatheaded fir borer in the short to medium term (Bennett et al. 2023).
- Thinning Douglas-fir trees on harsh sites (high climatic water deficit) to remove declining trees can shift stand composition towards more drought and fire-resistant species (e.g., ponderosa pine and oaks) and mitigate fuel accumulation associated with Douglas-fir mortality (Bennett et al. 2023).



Sudden Oak Death

Description

Sudden oak death is a non-native protist pathogen that currently occurs in tanoak vegetation in coastal Oregon and California. Black oak and tanoak may become more susceptible to sudden oak death with climate change, constraining oak survival and regeneration and driving changes in canopy cover and vegetation composition (Swiecki and Bernhardt 2016). Warmer, wetter springs favor the expansion of sudden oak death eastward in the region (Standiford and Purcell 2015).

Strategy Habitat

- Oak woodlands are vulnerable to biotic and abiotic ecosystem stressors associated with a warmer climate.
- Mixed-conifer forests are vulnerable to conversion to woodlands as oak species expand with hotter, drier conditions and more frequent high-severity fire that reduces conifer recruitment and promotes persistence of resprouting deciduous species.

Management Actions

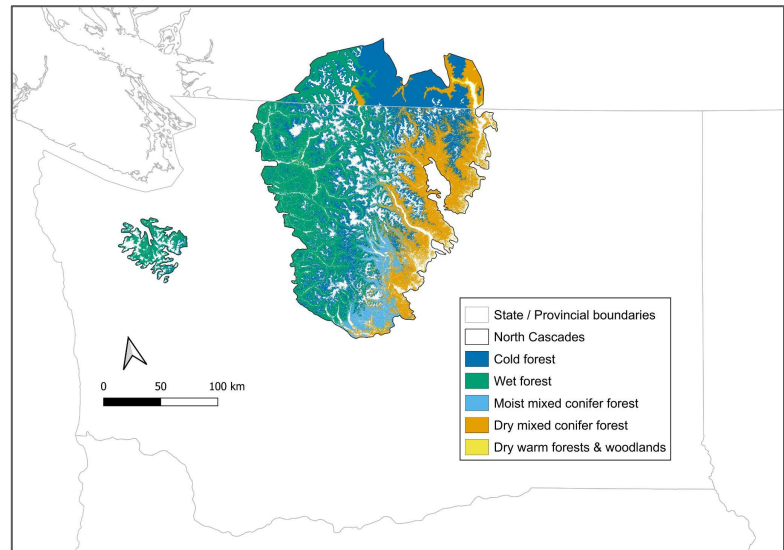
- Prevent sudden oak death establishment through careful inspection of transported material including nursery stock, plant material and soil (Swiecki and Bernhardt 2016).
- Early detection with extensive monitoring can confine new, small infection areas (Filipe et al. 2012).
- Local containment of infection severity and spread via removal of infected host material and surrounding hosts can prevent spread (Filipe et al. 2012).

North Cascades Forest Ecosystems



Regional Description

This ecoregion has distinct forests east and west of the Cascade Mountains. The western portion is dominated by wet and cold forests. Major tree species in wet forests include Douglas-fir, western hemlock, red alder and western redcedar. Major tree species in cold forests include mountain hemlock, Pacific silver fir, subalpine fir and whitebark pine. The eastern portion of the ecoregion is dominated by cold and mixed-conifer forests. Major tree species in eastern cold forests include subalpine fir, Engelmann spruce and subalpine larch. Major species in dry mixed-conifer forests include ponderosa pine, Douglas-fir and western larch.



The North Cascades Ecoregion has cold dry forests to the North and at high elevations, wet forests on the western slopes of the Cascade mountains and dry mixed conifer forests on the eastern slopes. Data Source: [LANDFIRE Biophysical Settings \(BPS\) 2020](#).

Management Considerations

- Much of the ecoregion is publicly owned land, including large areas of National Parks and wilderness.
- Dominant land uses are forestry, recreation, and conservation, which provide opportunities to manage forests for climate adaptation and resilience.
- Whitebark pine in the North Cascades ecoregion has suffered major population declines due to white pine blister rust caused by a nonnative fungus.

Managing Ecosystem Stressors



High-elevation Expansion of Mountain Pine Beetle

Description

Suitable habitat for mountain pine beetle is expected to expand to higher elevations with warming (Fettig et al. 2022), increasing vulnerability of whitebark pine to insect-caused mortality. Historically, the climate in the range of whitebark was too cold to sustain mountain pine beetle populations. Recent increases in mortality of whitebark pine can be attributed to the interacting effects of mountain pine beetle, white pine blister rust, and changes in fire regimes (Rocheffort et al. 2018).

Strategy Habitat

- Whitebark pine is a critical food source for wildlife species and contributes to the character of high-elevation forest, but is highly sensitive to warming because of its narrow climatic niche.
- Whitebark pine forests at high elevations on peaks and ridges are especially vulnerable to upward expansion of mountain pine beetles.

Management Actions

- Plant seedlings selected for resistance to white pine blister rust to reduce species vulnerability to multiple stressors (Six et al. 2021, Six et al. 2018).
- Use insecticides or semiochemicals (e.g., anti-aggregation pheromones) to limit outbreaks and protect individual high-value trees (Fettig et al. 2022).

North Cascades Forest Ecosystems



Managing Ecosystem Stressors



Shifts in Subalpine Forests and Expansion into Alpine Meadows

Description

Cold forests in the alpine ecotone are sensitive to warming and associated declines in spring snowpack and the duration of snow cover. Higher temperatures and a longer growing season are expected to relax climatic constraints on subalpine tree growth and establishment, enabling cold forest species to expand up in elevation. However, competition and range expansion of other species at the low-elevation ecotone of cold forests are expected to reduce total area suitable for subalpine forests (Rogers et al. 2011). More severe fire, especially large patches of high-severity fire, have the potential to limit regeneration of subalpine tree species, but currently post-fire regeneration appears to be resilient, especially when fire is followed by climatic conditions favorable for regeneration (Littlefield 2019).

Strategy Habitats

- Alpine meadows, iconic ecosystems valued for wildlife habitat and aesthetics, are highly sensitive to tree encroachment and vegetation type conversion with warming.
- Growth and productivity of species in subalpine forests, such as subalpine larch and whitebark pine, are limited by temperature and therefore highly sensitive to warming (Case and Lawler 2016).

Management Actions

- Management actions dependent on social and ecological objectives.
- For locations where subalpine meadows and associated plant species are desired, resistance strategies can be used, such as mechanical removal and prescribed burning, to maintain subalpine meadows.
- In other locations, upward expansion of cold forests can compensate for subalpine forest habitat losses at lower elevations or due to high-severity fire.



Changing Fire Regimes

Description

In mixed-conifer forests, stand density and the vertical and horizontal fuel continuity has increased relative to natural variability due to more than a century of fire exclusion. These altered fuel profiles have increased fire severity and extent, though many mixed-conifer forests are in a contemporary fire deficit (Donato et al. 2023, Haugo et al. 2019). More frequent and severe fire in a warmer, drier climate is expected to further increase tree mortality, fire extent, and the size of high-severity patches (Hagmann et al. 2022).

Strategy Habitats

- Dry and moist mixed-conifer forests, especially where fire has been excluded increasing the dominance of shade-tolerant species and decreasing cover of fire-resistant, shade-intolerant species (Hessburg et al. 2022).

Management Actions

- Restore the natural role of fire using mechanical treatments to reduce fuel and prescribed and cultural burning to promote frequent low-intensity fire (Hessburg et al. 2022).
- Manage wildfire to restore forest structure and frequent low-severity fire by reducing fuel, increasing spatial heterogeneity, and promoting survival of large fire-resistant individuals (Laughlin et al. 2023).
- Strategically plant trees post-fire, prioritizing cool moist microsites and drought-tolerant species and genotypes to restore species composition (Halofsky et al. 2020).

Rocky Mountains Forest Ecosystems

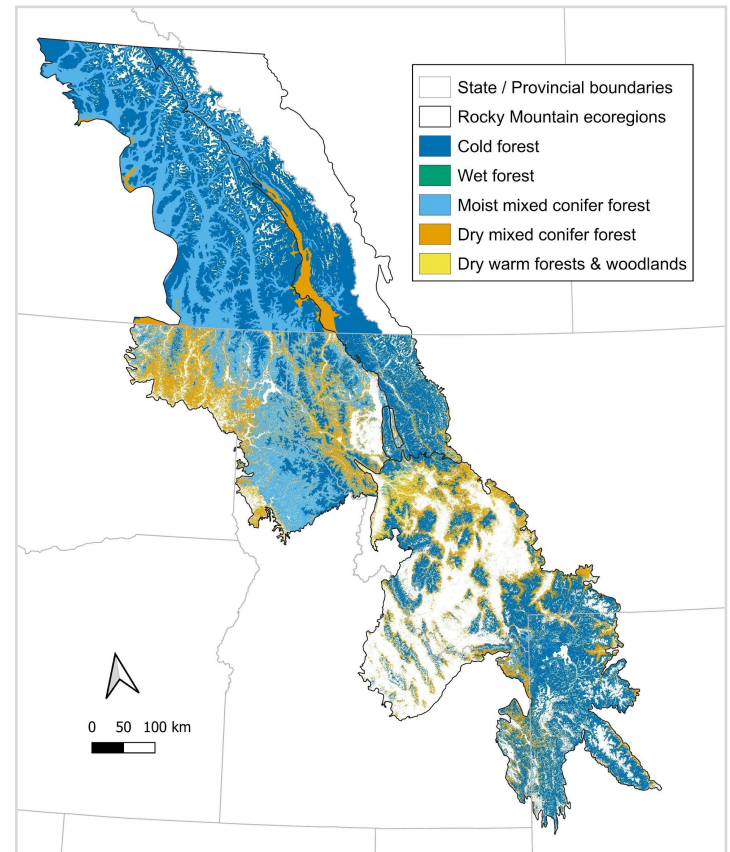


Regional Description

The Rocky Mountain ecoregions (Northern, Middle and Canadian Rockies) are rugged and topographically diverse. The region is dominated by cold and moist mixed-conifer forests. Major tree species in cold forests include subalpine fir, Engelmann spruce and lodgepole pine with minor components of whitebark pine, limber pine, subalpine larch, mountain hemlock, and quaking aspen. Major tree species in moist mixed-conifer forests include western hemlock, western redcedar, Douglas-fir, lodgepole pine and grand fir. Major tree species in regional dry mixed-conifer forests include ponderosa pine and Douglas-fir.

Management Considerations

- The ecoregion includes large areas of functionally intact ecosystems in public management.
- Western white pine was once common but has been greatly reduced by white pine blister rust, timber harvest, and fire exclusion.
- Whitebark pine has suffered major declines due to white pine blister rust.



Cold and moist mixed-conifer forests dominate the Rocky Mountain Ecoregions with areas of dry mixed-conifer forest at low elevations. Data Sources: [LANDFIRE Biophysical Settings \(BPS\) 2020](#) in the US. [Biogeoclimatic Ecosystem Classification \(BEC\) Program](#) in British Columbia, Canada.

Managing Ecosystem Stressors



Shifts to Non-Forest Vegetation

Description

Changes in fuel structure and availability have increased vulnerability of mixed-conifer forests to high severity fire (Higuera et al. 2015). Following high-severity fire, forest recovery is expected to be limited by low seed availability in large burn patches far from live seed sources (Davis et al. 2020) and warm, dry climatic conditions (Davis et al. 2019). These conditions increase the likelihood of regeneration failure and shifts in vegetation (Hankin et al. 2019, Kemp et al. 2019), including conversion to grass- or shrub-ecosystems (Hoecker et al. 2023).

Strategy Habitat

- Mixed-conifer forests where fire exclusion has increased the dominance of fire-intolerant conifers species.
- Low-elevations of the forest range (Higuera et al. 2015) or “trailing edge forests” (Parks et al. 2019) are especially vulnerable to this stressor.

Management Actions

- Plant drought-tolerant species post-fire based on biophysical and microsite conditions (Keane et al. 2018).
- Restore forest structure and reintroduce fire via density- and fuel-reduction treatments (Keane et al. 2018) or managed wildfire (Hessburg et al. 2021).
- Accept shifts to non-forest vegetation where aligned with topo-edaphic spatial patterns (e.g., south-facing slopes) and ecosystem functions in a warmer climate (Hessburg et al. 2021).

Rocky Mountains Forest Ecosystems



Strategy Habitat

- Subalpine forests are especially vulnerable to altered fire regimes and large-scale bark beetle outbreaks due to short growing seasons and slow recovery times.
- Five-needle pine species are especially vulnerable to fire-caused damage and mortality in areas, and in individuals, where existing infection by the invasive fungal pathogen that causes white pine blister rust is severe (Loehman et al. 2018).

Managing Ecosystem Stressors



Changing Fire Regimes

Description

Fire frequency and extent are expected to increase with warming and earlier snowmelt that reduce fuel moisture and lengthen the window of flammability (Alizadeh et al. 2021, Loehman et al. 2018) in this ecoregion. Shorter fire intervals impede forest recovery when the time between stand-replacing fires is insufficient for trees to mature and produce seed (Hoecker and Turner 2022), reducing regeneration and leading to shifts in species composition (e.g., range expansion of aspen; Nigro et al. 2022), and loss of forests (Turner et al. 2019, Hood et al. 2021).

Management Actions

- Protect fire refugia and persistence of fire-sensitive species (Halofsky et al. 2018a, Keane et al. 2018).
- Suppress fire around culturally important and high-value trees to resist climate- and fire-driven vegetation change (Hoecker and Turner 2022).
- Enhance forest resilience to altered disturbance regimes by undertaking assisted migration of drought- and fire-adapted native tree species (Hoecker and Turner 2022).
- Enhance forest resilience to altered disturbance regimes by selectively planting where five-needle pine populations are declining and prioritizing multiple genotypes and species (Halofsky et al. 2018a, Keane et al. 2018).



Large-Scale Bark Beetle Outbreaks

Description

More frequent and extensive bark beetle outbreaks will increase mortality of host tree species (e.g., lodgepole pine, Engelmann spruce, Douglas-fir, and subalpine fir) as warming enhances beetle population growth and range expansion into higher elevation habitat (Fettig et al. 2022a, Loehman et al. 2018). Spatial and temporal co-occurrence of outbreaks by multiple bark beetle species — including mountain pine beetle, spruce beetle, Douglas-fir beetle, and western balsam bark beetle — and other stressors (e.g., white pine blister rust; Six et al. 2018, Tomback et al. 2022) may limit forest recovery and promote species shifts towards non-forest vegetation (Harvey et al. 2023b).

Management Actions

- Increase species, genetic, structural, and seral-stage diversity across large areas to reduce the risk of forest habitat loss (Halofsky et al. 2018a).
- Thin competing species or remove host trees with low resistance to reduce competition and increase vigor of remaining trees (Fettig et al. 2022a). This approach may not work for all species (Six et al. 2021).
- Apply prompt and thorough sanitation harvests (i.e., removal of infested trees), insecticides or semiochemicals (e.g., anti-aggregation pheromones) to reduce current infestations and protect high-value trees (Fettig et al. 2022a), particularly whitepark pine trees known to be resistant to blister rust.

Puget Lowlands Forest Ecosystems

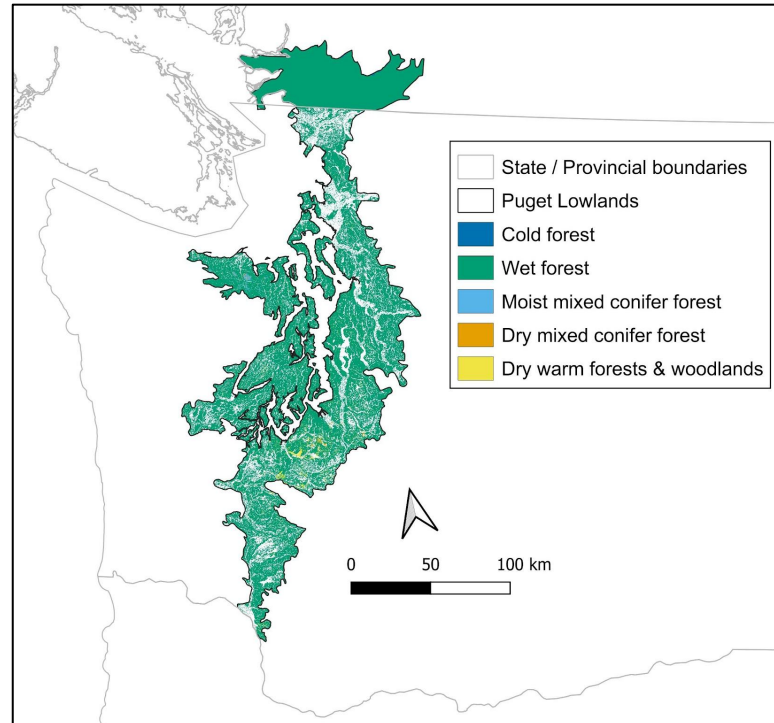


Regional Description

The Puget Lowlands ecoregion includes wet forests and dry warm forests and woodlands. Major tree species in regional wet forests include Douglas-fir, western hemlock, red alder, western redcedar, bigleaf maple and grand fir. Major tree species in regional dry warm forests and woodlands of this ecoregion include Oregon white oak, black oak, Douglas-fir, grand fir and Pacific madrone.

Management Considerations

- This ecoregion is heavily developed and contains 75% of the population of Washington State.
- Development and transportation corridors have caused widespread habitat loss and fragmentation.
- Fire exclusion, due in part to the removal of Indigenous peoples and their traditional burning practices, has contributed to conifer encroachment and the decline of dry warm forests and woodlands.



Wet forests dominate the Puget Lowlands Ecoregion, with dry warm forests and woodlands at the lowest elevations.

Data Sources: [LANDFIRE Biophysical Settings \(BPS\) 2020](#) in the US
[Biogeoclimatic Ecosystem Classification \(BEC\) Program](#) in BC.

Managing Ecosystem Stressors



Shift to Non-Forest Vegetation

Description

Oak woodlands in this ecoregion have been in decline over the last century due to fire exclusion, removal of Indigenous peoples and their burning practices, conifer encroachment, development and other widespread changes in land use. Oak species in the woodlands of this Puget Lowlands ecoregion are vulnerable to climate change due to high sensitivity to changing disturbance regimes (e.g., more severe fire), low adaptive capacity (e.g. limited dispersal ability due to land-use change and short annual dispersal distance), and vulnerability to invasive pathogens (e.g., sudden oak death) (Case and Lawler 2016, Long et al. 2018).

Strategy Habitat

- Oak species, specifically Oregon white oak and Pacific madrone, in woodlands in drier areas of the Puget Lowlands ecoregion are more vulnerable.
- Oak woodland habitat provides unique cultural and ecological benefits and supports biological diversity.

Management Actions

- Restore natural fire regimes using managed wildfire (i.e., allowing wildfires to burn under moderate weather conditions) or mechanical removal of conifer species to help maintain oak woodland habitat (Long et al. 2018, Prichard et al. 2021).
- Use managed wildfire, prescribed fire, and cultural burning to reduce fuels and promote frequent low-intensity fire (Long et al. 2018).

Puget Lowlands Forest Ecosystems



Managing Ecosystem Stressors



Bigleaf Maple Decline

Description

Bigleaf maple is thought to have low vulnerability to climate change because of overall low sensitivity to expected changes in the climate and high adaptive capacity (Case and Lawler 2016). However, recent declines in bigleaf maple in parts of its range suggest it may be more vulnerable than previously thought (Betzen et al. 2021). Bigleaf maple is showing evidence of decline (loss of vigor, loss of transpiration, reduced photosynthesis, leaf loss) that has been associated with warmer summers, in combination with development and urbanization (Betzen et al. 2021). These abiotic stressors are killing trees directly or predisposing trees to biotic agents.

Strategy Habitat

- As one of only a few hardwood species in wet forests primarily dominated by conifer species, bigleaf maple contributes to forest heterogeneity and habitat diversity for wildlife species.
- Habitats that are especially vulnerable and affected by this ecosystem stressor include bigleaf maple forests growing in warm and dry areas, and close to roads and developed sites (Betzen et al. 2021).

Management Actions

- In developed and urbanized areas, use infrequent deep watering of trees in summer to reduce moisture stress and prevent the loss of high-value individuals.



Western Redcedar Dieback

Description

Western redcedar is adapted to the moderate climate of the Puget Lowlands ecoregion. Mortality rates of western redcedar in parts of its range have increased in the last decade. Reduced radial growth is associated with an anomalously warm May and June that lengthens the typical dry summer season (July-September), and mortality tends to follow four to five years of declining radial growth. A warming climate with more frequent and severe drought is expected to increase vulnerability of western redcedar to canopy dieback and mortality (Andrus et al. 2024).

Strategy Habitat

- Western redcedar is a critical species because of its cultural, ecological, and economic importance in the region. The species contributes to wildlife habitat, especially in mature stands which are highly fragmented across the ecoregion by development.
- Habitats that are especially vulnerable and affected by this ecosystem stressor include trees in developed areas and coastal populations that are less tolerant of and adapted to drought.

Management Actions

- In developed and urbanized areas, use infrequent deep watering of trees in summer to reduce moisture stress and prevent the loss of high-value individuals.
- Increase the resilience of coastal populations of western redcedar with assisted population migration via selection of seeds from interior populations that are more tolerant and adapted to drought and resistant to canopy dieback (Andrus et al. 2024).
- Allow shifts in composition towards species that are more tolerant of warm and dry climatic conditions (e.g., Douglas-fir) where acceptable for management and habitat objectives (Andrus et al. 2024).

Willamette Valley Forest Ecosystems

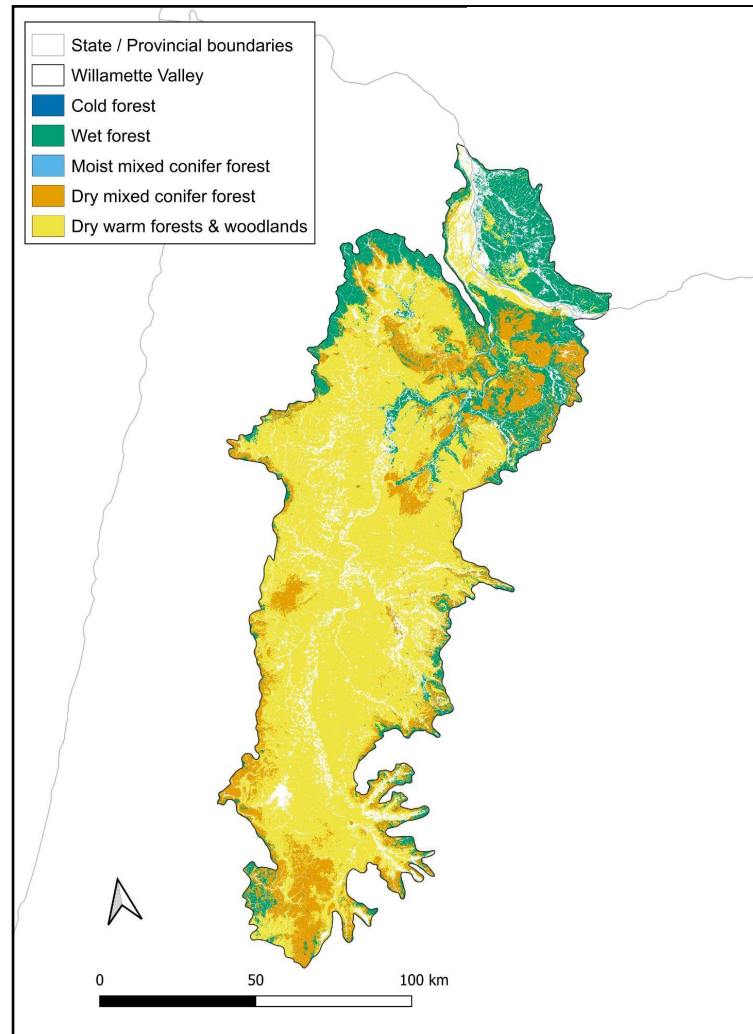


Regional Description

The Willamette Valley ecoregion receives less precipitation than the Coast Range to the west and the Cascades to the east and has much less relief, leading to dry warm forests and woodlands as the dominant forest. Major tree species in dry warm forests and woodlands include Oregon white oak (north), California Black Oak (south), Pacific madrone and Douglas-fir, with minor components of Oregon ash, bigleaf maple, black cottonwood and red alder in riparian areas.

Management Considerations

- Following Euro-American colonization, more than 95% of native oak woodlands have been lost and many remaining woodlands are declining due to urbanization and development, conversion to agriculture, conifer encroachment, exclusion of indigenous burning practices, and invasives.
- As attractive areas for development, the potential for further habitat fragmentation and land use conversion is likely in regional woodlands.
- Warmer, drier conditions are favorable for future expansion of oak woodlands, but habitat fragmentation and altered fire regimes make them highly sensitive to climate change.



Dry warm forests and woodlands are the dominant forest type, but development and agriculture substantially reduced forest area. Data Source: [LANDFIRE Biophysical Settings \(BPS\) 2020](#).

Oak Woodlands

- Oak woodlands are an important habitat throughout the ecoregion.
- They are distributed in small remnant patches and provide important habitat for many threatened, vulnerable, and at risk wildlife species.
- Large and very large hardwood trees are especially important habitat and provide nesting cavities for birds (Long et al. 2018).
- These critical habitats are vulnerable to ecosystem stressors associated with land management practices and a warming climate.



Willamette Valley Oregon White Oak. Photo by Tracy Robillard

Willamette Valley Forest Ecosystems



Managing Ecosystem Stressors



Sudden Oak Death

Description

Black oak and tanoak in the region may become more susceptible to sudden oak death, reducing oak survival and regeneration and driving changes in canopy cover and vegetation composition. Sudden oak death is a non-native protist pathogen that currently occurs in tanoak vegetation in coastal Oregon and California (Swiecki and Bernhardt 2016). Warmer, wetter springs favor the expansion of sudden oak death eastward in the region (Standiford and Purcell 2015).

Management Actions

- Prevent sudden oak death establishment through careful inspection of transported material, including nursery stock, plant material and soil (Swiecki and Bernhardt 2016).
- Detect new and small infected areas early with extensive monitoring (Filipe et al. 2012).
- Contain infection severity and spread via removal of infected host material and surrounding hosts as a preventative buffer (Filipe et al. 2012).



Invasive Annual Grasses

Description

Invasive annual grasses (e.g., cheatgrass), facilitated by cattle overgrazing, have replaced native perennial grasses and compete for soil moisture with oak seedlings. This limits the capacity of oak woodlands to adapt to a changing climate and disturbance regimes (Copes-Gerbitz et al. 2017).

Management Actions

- Enhance native plant communities and protect legacy trees through site preparation, planting, and seeding activities (Halofsky et al. 2022).
- Prevent annual grass invasion through early detection and rapid response with direct eradication treatments (e.g., herbicides) (Halofsky et al. 2022).
- Reduce grazing practices that facilitate spread of invasive annual grasses (Halofsky et al. 2022).



Conifer Encroachment

Description

Removal of Indigenous burning practices, fire exclusion, and timber production have facilitated encroachment by shade-tolerant conifers (e.g., Douglas-fir) into oak woodlands (Copes-Gerbitz et al. 2017). Greater tree density and elevated fuel loads contribute to decreasing habitat area and increase drought sensitivity of mature oaks that must compete with conifers for limited soil moisture (Beckmann et al. 2021). More frequent fire may reduce conifer encroachment and favor expansion of oak woodlands, but high-severity fire due to fuel accumulation can increase oak mortality (Long et al. 2018).

Management Actions

- Clear conifers from near hardwood crowns or restrict planting of conifers to further from hardwood trees (Long et al. 2018).
- Establish new oak woodlands in areas that become more suitable as the climate warms (Long et al. 2018).
- Restore fire at higher frequency and reduced fuel loads (e.g., prescribed fire, thinning) to maintain mosaics of trees, shrubs, and grasses (Long et al. 2018).
- Guide management actions with traditional knowledge used to promote large hardwoods (Long et al. 2018).

CLIMATE ADAPTATION: Forest Ecosystems



Overview

Most climate adaptation strategies for forest ecosystems are based on the theory of ecological silviculture and management, which recognizes change and variability as integral to natural ecosystems. These practices, developed to maintain ecosystem function and process *with change and variability*, are relevant for managing climate change impacts even if their effectiveness for minimizing climatic stressors has not been tested explicitly (Peterson et al. 2011).

Climate adaptation strategies can be categorized using the Resist Accept, Direct (RAD) Framework (Schuurman et al. 2020). *Resistance* strategies maintain species and habitats in their current conditions. *Acceptance* strategies involve little intervention, and allow ecological changes to take place. Strategies that *direct* ecological change typically include interventions that encourage less negative, or even desirable, changes to species and habitats. Appropriate adaptation strategies for any forest depend on the desired outcomes and future objectives, the magnitude of exposure to climate change, and the extent to which human-induced stressors have altered ecosystem function and structure.



Fall colors are vibrant at Jug Creek in the Caribou-Targhee National Forest. Photo Credit: USDA Forest Service.

Adaptation Options

Protect Subalpine Species and Refugia

WHAT IT MEANS: Protect subalpine forests and species in place to resist loss of rare and critical species and habitats that are highly vulnerable to climate change. Strategies include:

- Identifying potential refugia for vulnerable subalpine species.
- Breeding and planting pathogen-resistant seed stock after disturbance, such as whitebark pine resistant to white pine blister rust.
- Thinning and burning mixed-conifer forests adjacent to subalpine forests to buffer these forests from the spread of high-severity fire.

WHY IT WORKS: Subalpine conifers are vulnerable due to narrow climatic niches, competition from low-elevation conifers, more virulent insects and pathogens, and limited migration potential. Although a warmer climate is expected to increase tree growth in these forests, upslope migration of subalpine species is limited by harsh environments where topographic and edaphic controls and short-term climatic variability prevent seedling establishment. Protecting subalpine forests creates high-elevation climate refugia for migration of wildlife species. Forest refugia that includes mature cone-producing trees becomes a seed source post-disturbance, accelerating recovery post-fire and preventing extended periods of habitat loss. Enhancing genetic diversity with pathogen resistant seedlings facilitates regeneration, while conferring resistance to insects and pathogens favored in a warmer climate.

FINDING THE SCIENCE:

Halofsky et al. 2019, 2018, 2017

- Climate vulnerability assessments for national forest regions that include subalpine forests and summarize expected changes and potential adaptation strategies.

Tomback et al. 2022

- Summarizes management practices for restoration and protection of whitebark pine, including the science on which these practices are based and their application to minimize climate impacts.

CLIMATE ADAPTATION: Forest Ecosystems



WHAT IT MEANS: Diversification of tree species and sizes in forests, as well as seral stages across large landscapes, increases resilience by enhancing the potential for recovery from climate-driven disturbance. Strategies include:

- Direct post-fire recovery by aligning species and structure with expected future climate and fire regimes.
- Accept natural regeneration, including variation in conifer regeneration success, to promote complex early seral habitat.
- Assisted population migration of species and genotypes that are expected to be better adapted to the future climate.

WHY IT WORKS: Many forests in the PNW suffer from the homogenizing effects of forest management that reduced species, structural, and seral-stage diversity. Homogeneity increases vulnerability to fire, insect outbreaks, and pathogens by decreasing heterogeneous disturbance effects, such as mixed-severity fire and dispersed tree mortality. Diversity increases resilience to insects and pathogens by establishing natural controls that limit disturbance extent and prevent large patches of tree mortality. As warming enables insect populations to proliferate or creates favorable conditions for pathogens, natural controls on disturbance extent are even more important to keep native insects and pathogens at endemic levels and limit the spread of introduced species.

FINDING THE SCIENCE:

Larson et al. 2022

- Describe practices consistent with ecological forest management that also facilitate post-fire climate adaptation.

Donato et al. 2020

- Quantify the natural range of variability of seral stages for forests with infrequent, severe disturbance regimes and current departures from this range as a guide for managing post-disturbance structural diversity.

Palik et al. 2022

- Although case studies are in the eastern U.S., this is a synthesis of the science of assisted migration and a conceptual framework to operationalize the practice.

NETWORK FOR ASSISTED POPULATION MIGRATION AND SILVICULTURE

DESCRIPTION: The Experimental Network for Assisted Migration and Establishment Silviculture (ENAMES) is implementing assisted migration planting trials to collect information to support operationalizing the practice. Assisted migration has been implemented in individual projects in the NW, but ENAMES is the first systematic study evaluating the practice for a range of forest types across the region. Experiments include planting a selection of seed sources adapted to expected future climates of each site for four time periods from 1961 to 2100. Seed sources are selected using tools such as the Seedlot Selection Tool. The study is also evaluating silvicultural practices to assist seedling survival, such as planting larger seedlings, different seedling stock types, vegetation control to reduce competition, and lower planting densities to increase resources per seedling. Results will be applicable for multiple tree species and post-disturbance conditions and serve as foundational research on assisted population migration, as well as the short- and long-term success of reforestation practices in a changing climate

AT A GLANCE:

- Goals: Develop informat to maximize the effectiveness of reforestation in a changing climate
- Location: A network of 30 sites in OR, WA, CA
- Timeline: Established 2024 and 2025
- Strategies: Assisted migration, silvicultural practices to increase seedling survivals
- Project Link: [ENAMES](#)



The Umpqua National Forest is home to one experimental ENAMES site, Burnt Creek, where Douglas fir is the focal species. Photo Credit: USDA Forest Service.

CLIMATE ADAPTATION: Forest Ecosystems



WHAT IT MEANS: Restore and manage fire to achieve desired ecological benefits and habitat features, while minimizing impacts to human health and communities. Techniques to manage fire depend on species composition and current historical fire regimes. This strategy includes

- Thin and burn mixed-conifer forests where fire exclusion has substantially altered species composition and fuel profiles.
- Restore indigenous burning practices following fuel reduction in woodlands.
- Manage wildfire in subalpine forests, especially wilderness areas where fire poses less risk and fuel profiles have not been altered.
- Suppress fire in wet forests of fire-intolerant species and long-fire return intervals.

WHY IT WORKS: Restoring fire regimes reduces the potential for large, high-severity fires that slow recovery. Large patches of high-severity fire reduce habitat quality in the short term and increase the risk of long-term regeneration failures and conversion to non-forest vegetation. Reintroducing low and mixed-severity fire creates heterogeneity in species composition and forest structure, increasing habitat diversity across scales, from individuals to forests. Species and structural diversity increases resilience to more frequent fire in a warmer climate.

FINDING THE SCIENCE:

Recent reviews summarize the effectiveness of restoring fire as a climate adaptation strategy.

Hagmann et al. 2021

- Reviews the scientific evidence documenting changes in structure and composition in fire-adapted forests due to fire exclusion.

Prichard et al. 2021

- Reviews the effectiveness of techniques to restore fire and manage forests for resilience in a changing climate, including answers to frequently asked questions regarding the application of thinning, prescribed burning, indigenous burning, and managed wildfire.

Halofsky et al. 2018

- Fire suppression as a resistance strategy may be a more effective approach to increase resilience and protect wildlife habitat in the stand-replacing fire regimes of wet forests.

SOUTHERN OREGON OAK WOODLAND RESTORATION PROJECT

DESCRIPTION: The Lomakatsi Restoration Project, in partnership with the US Department of Fish and Wildlife, has restored hundreds of acres of degraded oak woodland habitat in northern California and Southern Oregon. Fire exclusion enabled the encroachment of conifer trees and woody shrubs into open woodlands increasing fuels. Higher temperatures and drier summers increase the likelihood of wildfire, and fuel accumulation causes higher intensity fires that kill the very large oaks that provide important wildlife habitat. Lomakatsi are reducing high-severity fire and promoting development of high-quality woodland habitat by using ecological thinning and prescribed burning to create a mosaic of large oaks and pines, interspersed with open areas and patches of chaparral. Restoring the ecological role of fire slows the decline of oak woodlands and promotes post-fire recovery.

AT A GLANCE:

- Goals: Protect and promote development of oak woodland habitat for wildlife
- Location: Southern Oregon and northern California
- Timeline: Oak restoration began in 1995 and continues with more funding and partners. In 2014, the Wildlife Conservation Society Climate Adaptation Fund supported restoration of 400 acres.
- Strategies: remove non-native plants that compete with native oak species, selectively thin conifer trees and woody shrubs, prevent the conversion of oak woodlands to cropland and residential development.
- Project Links: [Oak Habitat Restoration Program](#)



An Oregon white oak grows in a prairie setting in Oregon. Photo Credit: George Gentry/U.S. Fish and Wildlife Service

CLIMATE ADAPTATION: Forest Ecosystems



WHAT IT MEANS: Silvicultural practices to increase drought resilience can enhance individual tree growth and vigor and reduce mortality. As growing seasons become hotter and drier with more frequent and longer ecological droughts, this practice is expanding. Adaptation strategies include

- Quantify and map spatial variation in drought vulnerability.
- Plant or select for drought-tolerant species.
- Reduce water competition by reducing tree-density and removing invasive species.

WHY IT WORKS: Managing for drought resilience reduces vulnerability and increases defenses against insects and pathogens, enabling forests to maintain ecological processes and functions. The practice has the greatest potential for success in in forests that have been harvested, planted at unsustainable densities, or have high likelihood of being exposed to drought stress. Density management has the co-benefit of accelerating the development of late-successional forest characteristics (e.g., large trees, multiple canopy layers, and overstory canopy gaps).

FINDING THE SCIENCE:

Empirical research is emerging to document and refine silvicultural practices for drought resilience.

Sohn et al. 2016

- Synthesizes results from experiments designed to test thinning approaches for drought resilience. Thinning mitigates growth response during droughts for broadleaved species and improves growth recovery after drought for conifer species. The benefits of thinning decrease with time as trees grow.

Palik et al. 2020

- Provides the scientific theory for ecological silviculture which forms the foundation for why these practices are expected to be effective for climate adaptation despite the difficulty in testing them for this purpose.

D'Amato et al. 2023

- Describes a framework for ecological silviculture design specifically to address climate impacts. Although focused on boreal forests and the eastern US, the general framework is relevant to the northwest.

BEES TO BEARS HABITAT RESTORATION

DESCRIPTION: Idaho Fish and Game and the Yellowstone to Yukon Conservation Initiative restored 250 acres of lowland forest habitat. Restoration reduces the effects of climate and human-induced ecosystem stressors (agriculture development and hydrologic management) on habitat for several Species of Greatest Concern listed in Idaho's State Wildlife Action Plan. The state of Idaho purchased the land in 1999. Past ecosystem alterations reduced habitat quality for aquatic and terrestrial species. Restoration was designed to improve ecological functions and habitat quality for climate-sensitive wildlife species including bees, amphibians, and grizzly bears. Future climate conditions were considered in restoration design by creating areas that provide cold-air refugia, improve soil moisture, and restore ephemeral wetland flooding.

AT A GLANCE:

- Goals: Restoration of lowland forested habitat to assist adaptation for 6 Species of Greatest Conservation Need
- Location: Boundary-Smith Creek Wildlife Management Area, Kootenai Valley, Idaho.
- Timeline: 2018 to 2020
- Strategies: restore ephemeral flood cycles, create topographically altered pollinator habitat, plant native trees and understory plants to provide cover for grizzly bears, improve soil moisture and reduce understory air temperatures
- Project Links: [Idaho Panhandle Bees to Bears Climate Adaptation Project](#)



Northern leopard frog (*Rana pipens*) is a species of greatest conservation need assisted by the project. Photo Credit: Kyle Welsh

CLIMATE ADAPTATION: Forest Ecosystems



MORE ADAPTATION RESOURCES:

● CLIMATE CHANGE ADAPTATION LIBRARY FOR THE WESTERN UNITED STATES

This online resource is compiled from a series of vulnerability assessments conducted by Adaptation Partners for and with U.S. Forest Service and National Park Service land managers in the west. The database includes adaptation strategies that can be filtered by region, resource area, and climate change effect. The website links to the regionally-specific climate change vulnerability assessments.

Resource Link: [Climate Change Adaptation Library](#)

● SEEDLOT SELECTION TOOL

This online GIS-based mapping application allows users to identify seed zones based on future climate projections. The tool can be used to inform assisted migration practices by identifying appropriate locations for seedlots or planting sites based on user-selected climate variables and future time periods. The USFS developed a user guide for the tool that includes case studies for the Northwest.

Resource Link: [Seedlot Selection Tool](#) and [Seedlot Selection Tool Guidebook](#)

● ADAPTIVE SILVICULTURE FOR CLIMATE CHANGE

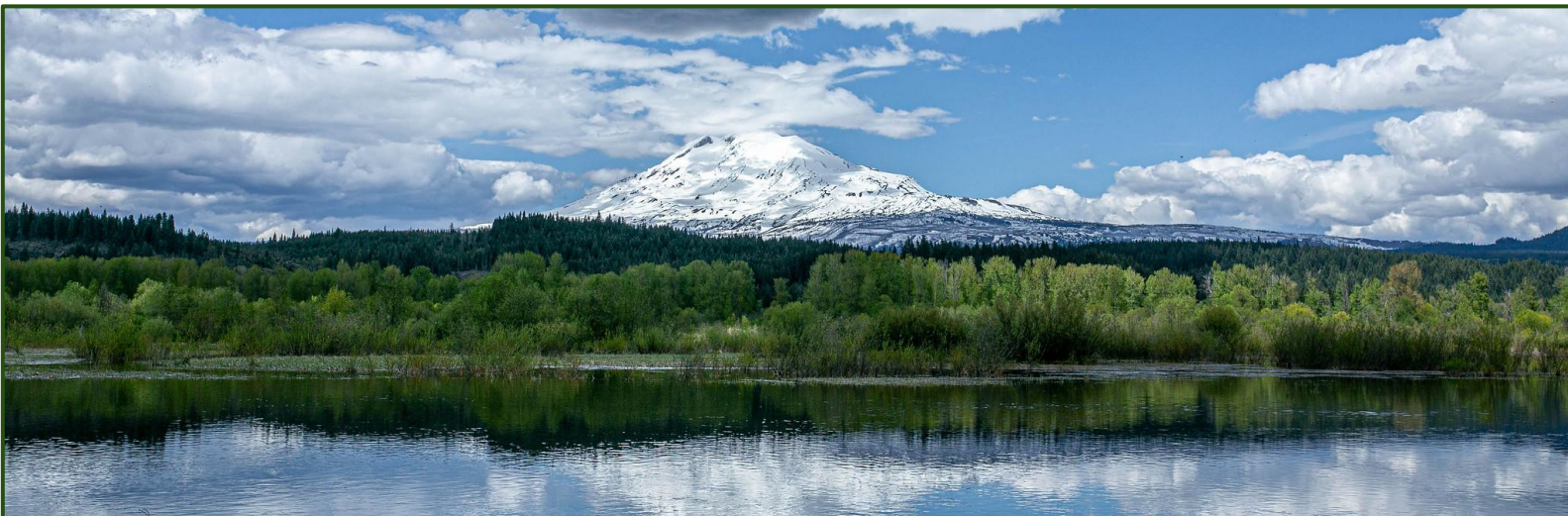
This series of experiments is designed to test a range of locally appropriate silvicultural practices for climate adaptation. Experiments are implemented in a network of forest types mostly in the eastern US, but also in a larch mixed-conifer forest in the Northern Rocky Mountains. The project is producing information and tools to help resource managers integrate climate change into decision making.

Resource Link: [Adaptive Silviculture for Climate Change](#)

● ADAPTATION GUIDES FOR SMALL FOREST LANDOWNERS IN WASHINGTON

These guides pair forest-specific climate impacts with potential adaptation actions. Although they are developed for private landowner audiences in Washington, other forest managers may find the concise impacts summaries and list of actions useful. Adaptation actions for forests in Washington are relevant to other similar NW forest types elsewhere.

Resource Link: [Small Forest Landowner Adaptation Guidance](#)



Trout Lake is surrounded by forest, with Mt. Hood in the background. Photo Credit: Amanda Brewer - USDA Forest Service.

REFERENCES - OVERVIEW

- Abatzoglou, J. T., C. S. Juang, A. P. Williams, C. A. Kolden, and A. L. Westerling. 2021. Increasing Synchronous Fire Danger in Forests of the Western United States. *Geophysical Research Letters* 48:e2020GL091377.
- Abatzoglou, J. T., and A. P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* 113:11770–11775.
- Abatzoglou, J. T., A. P. Williams, and R. Barbero. 2019. Global Emergence of Anthropogenic Climate Change in Fire Weather Indices. *Geophysical Research Letters* 46:326–336.
- Adams, H.D., Zeppel, M.J.B., Anderegg, W.R.L. et al. 2017. A multi-species synthesis of physiological mechanisms in drought-induced tree mortality. *Nat Ecol Evol* 1, 1285–1291.
- Agne, M. C., P. A. Beedlow, D. C. Shaw, D. R. Woodruff, E. H. Lee, S. P. Cline, and R. L. Comeleo. 2018. Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. *Forest Ecology and Management* 409:317–332.
- Agne, M. C., J. B. Fontaine, N. J. Enright, and B. J. Harvey. 2022. Fire interval and post-fire climate effects on serotinous forest resilience. *Fire Ecology* 18:22.
- Alizadeh, M. R., J. T. Abatzoglou, C. H. Luce, J. F. Adamowski, A. Farid, and M. Sadegh. 2021. Warming enabled upslope advance in western US forest fires. *Proceedings of the National Academy of Sciences* 118.
- Andrus, R. A., L. R. Peach, A. R. Cinquini, B. Mills, J. T. Yusi, C. Buhl, M. Fischer, B. A. Goodrich, J. M. Hulbert, A. Holz, A. J. H. Meddens, K. B. Moffett, A. Ramirez, and H. D. Adams. 2024. Canary in the forest?—Tree mortality and canopy dieback of western redcedar linked to drier and warmer summers. *Journal of Biogeography* 51:103–119.
- Ayres, M. P., J. A. Hicke, B. K. Kerns, D. McKenzie, J. S. Littell, L. E. Band, C. H. Luce, A. S. Weed, and C. L. Raymond. 2014. Disturbance Regimes and Stressors. Pages 55–92 in D. L. Peterson, J. M. Vose, and T. Patel-Weynand, editors. *Climate Change and United States Forests*. Springer Netherlands, Dordrecht.
- Balch, J. K., J. T. Abatzoglou, M. B. Joseph, M. J. Koontz, A. L. Mahood, J. McGlinchy, M. E. Cattau, and A. P. Williams. 2022. Warming weakens the night-time barrier to global fire. *Nature* 602:442–448.
- Balch, J. K., B. A. Bradley, J. T. Abatzoglou, R. C. Nagy, E. J. Fusco, and A. L. Mahood. 2017. Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences* 114:2946–2951.
- Bell, D. M., R. J. Pabst, and D. C. Shaw. 2020. Tree growth declines and mortality were associated with a parasitic plant during warm and dry climatic conditions in a temperate coniferous forest ecosystem. *Global Change Biology* 26:1714–1724.
- Bennett, M., D. C. Shaw, and L. Lowrey. 2023. Recent Douglas-fir Mortality in the Klamath Mountains Ecoregion of Oregon: Evidence for a Decline Spiral. *Journal of Forestry* 121:246–261.

- Betzen, J. J., A. Ramsey, D. Omdal, G. J. Ettl, and P. C. Tobin. 2021. Bigleaf maple, *Acer macrophyllum* Pursh, decline in western Washington, USA. *Forest Ecology and Management* 501:119681.
- Cartwright, J. 2018. Landscape Topoedaphic Features Create Refugia from Drought and Insect Disturbance in a Lodgepole and Whitebark Pine Forest. *Forests* 9:715.
- Cartwright, J. M., C. E. Littlefield, J. L. Michalak, J. J. Lawler, and S. Z. Dobrowski. 2020. Topographic, soil, and climate drivers of drought sensitivity in forests and shrublands of the Pacific Northwest, USA. *Scientific Reports* 10:18486.
- Case, M. J., B. G. Johnson, K. J. Bartowitz, and T. W. Hudiburg. 2021. Forests of the future: Climate change impacts and implications for carbon storage in the Pacific Northwest, USA. *Forest Ecology and Management* 482:118886.
- Case, M. J., and J. J. Lawler. 2016. Relative vulnerability to climate change of trees in western North America. *Climatic Change* 136:367–379.
- Cassell, B. A., R. M. Scheller, M. S. Lucash, M. D. Hurteau, and E. L. Loudermilk. 2019. Widespread severe wildfires under climate change lead to increased forest homogeneity in dry mixed-conifer forests. *Ecosphere* 10:e02934.
- Clark, J. S., R. Andrus, M. Aubry-Kientz, Y. Bergeron, M. Bogdziewicz, D. C. Bragg, D. Brockway, N. L. Cleavitt, S. Cohen, B. Courbaud, R. Daley, A. J. Das, M. Dietze, T. J. Fahey, I. Fer, J. F. Franklin, C. A. Gehring, G. S. Gilbert, C. H. Greenberg, Q. Guo, J. HilleRisLambers, I. Ibanez, J. Johnstone, C. L. Kilner, J. Knops, W. D. Koenig, G. Kunstler, J. M. LaMontagne, K. L. Legg, J. Luongo, J. A. Lutz, D. Macias, E. J. B. McIntire, Y. Messaoud, C. M. Moore, E. Moran, J. A. Myers, O. B. Myers, C. Nunez, R. Parmenter, S. Pearse, S. Pearson, R. Poulton-Kamakura, E. Ready, M. D. Redmond, C. D. Reid, K. C. Rodman, C. L. Scher, W. H. Schlesinger, A. M. Schwantes, E. Shanahan, S. Sharma, M. A. Steele, N. L. Stephenson, S. Sutton, J. J. Swenson, M. Swift, T. T. Veblen, A. V. Whipple, T. G. Whitham, A. P. Wion, K. Zhu, and R. Zlotin. 2021. Continent-wide tree fecundity driven by indirect climate effects. *Nature Communications* 12:1242.
- Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. D. Crausbay, P. E. Higuera, M. D. Hurteau, A. Tepley, E. Whitman, T. Assal, B. M. Collins, K. T. Davis, S. Dobrowski, D. A. Falk, P. J. Fornwalt, P. Z. Fulé, B. J. Harvey, V. R. Kane, C. E. Littlefield, E. Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K. C. Rodman. 2020. Wildfire-Driven Forest Conversion in Western North American Landscapes. *BioScience* 70:659–673.
- Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. M. Ritter, and C. M. Hoffman. 2022. Extreme fire spread events and area burned under recent and future climate in the western USA. *Global Ecology and Biogeography* 31:1949–1959.
- Davis, K. T., S. Z. Dobrowski, P. E. Higuera, Z. A. Holden, T. T. Veblen, M. T. Rother, S. A. Parks, A. Sala, and M. P. Maneta. 2019a. Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences* 116:6193–6198.
- Davis, K. T., S. Z. Dobrowski, Z. A. Holden, P. E. Higuera, and J. T. Abatzoglou. 2019b. Microclimatic buffering in forests of the future: the role of local water balance. *Ecography* 42:1–11.

- Davis, K. T., P. E. Higuera, S. Z. Dobrowski, S. A. Parks, J. T. Abatzoglou, M. T. Rother, and T. T. Veblen. 2020. Fire-catalyzed vegetation shifts in ponderosa pine and Douglas-fir forests of the western United States. *Environmental Research Letters* 15:1040b8.
- Davis, K. T., M. D. Robles, K. B. Kemp, P. E. Higuera, T. Chapman, K. L. Metlen, J. L. Peeler, K. C. Rodman, T. Woolley, R. N. Addington, B. J. Buma, C. A. Cansler, M. J. Case, B. M. Collins, J. D. Coop, S. Z. Dobrowski, N. S. Gill, C. Haffey, L. B. Harris, B. J. Harvey, R. D. Haugo, M. D. Hurteau, D. Kulakowski, C. E. Littlefield, L. A. McCauley, N. Povak, K. L. Shive, E. Smith, J. T. Stevens, C. S. Stevens-Rumann, A. H. Taylor, A. J. Tepley, D. J. N. Young, R. A. Andrus, M. A. Battaglia, J. K. Berkey, S. U. Busby, A. R. Carlson, M. E. Chambers, E. K. Dodson, D. C. Donato, W. M. Downing, P. J. Fornwalt, J. S. Halofsky, A. Hoffman, A. Holz, J. M. Iniguez, M. A. Krawchuk, M. R. Kreider, A. J. Larson, G. W. Meigs, J. P. Roccaforte, M. T. Rother, H. Safford, M. Schaedel, J. S. Sibold, M. P. Singleton, M. G. Turner, A. K. Urza, K. D. Clark-Wolf, L. Yocom, J. B. Fontaine, and J. L. Campbell. 2023. Reduced fire severity offers near-term buffer to climate-driven declines in conifer resilience across the western United States. *Proceedings of the National Academy of Sciences* 120:e2208120120.
- DeLucia, E. H., D. J. Moore, and R. J. Norby. 2005. Contrasting responses of forest ecosystems to rising atmospheric CO₂: Implications for the global C cycle. *Global Biogeochemical Cycles* 19:1–9.
- Dennison, P. E., S. C. Brewer, J. D. Arnold, and M. A. Moritz. 2014. Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters* 41:2928–2933.
- Donato, D. C., J. S. Halofsky, D. J. Churchill, R. D. Haugo, C. Alina Cansler, A. Smith, and B. J. Harvey. 2023. Does large area burned mean a bad fire year? Comparing contemporary wildfire years to historical fire regimes informs the restoration task in fire-dependent forests. *Forest Ecology and Management* 546:121372.
- Donato, D. C., J. S. Halofsky, and M. J. Reilly. 2020. Corraling a black swan: natural range of variation in a forest landscape driven by rare, extreme events. *Ecological Applications* 30:e02013.
- Dong, Z., C. T. Driscoll, S. L. Johnson, J. L. Campbell, A. Pourmokhtarian, A. M. K. Stoner, and K. Hayhoe. 2019. Projections of water, carbon, and nitrogen dynamics under future climate change in an old-growth Douglas-fir forest in the western Cascade Range using a biogeochemical model. *Science of The Total Environment* 656:608–624.
- Fettig, C. J., C. Asaro, J. T. Nowak, K. J. Dodds, K. J. K. Gandhi, J. E. Moan, and J. Robert. 2022a. Trends in Bark Beetle Impacts in North America During a Period (2000–2020) of Rapid Environmental Change. *Journal of Forestry* 120:693–713.
- Fettig, C. J., L. A. Mortenson, B. M. Bulaon, and P. B. Foulk. 2019. Tree mortality following drought in the central and southern Sierra Nevada, California, U.S. *Forest Ecology and Management* 432:164–178.
- Fettig, C. J., J. B. Runyon, C. S. Homicz, P. M. A. James, and M. D. Ulyshen. 2022b. Fire and Insect Interactions in North American Forests. *Current Forestry Reports* 8:301–316.
- Finch, D. M., J. L. Butler, J. B. Runyon, C. J. Fettig, F. F. Kilkenny, S. Jose, S. J. Frankel, S. A. Cushman, R. C. Cobb, J. S. Dukes, J. A. Hicke, and S. K. Amelon. 2021. Effects of Climate Change on Invasive Species. Pages 57–83 in T. M. Poland, T. Patel-Weynand, D. M.

- Finch, C. F. Miniat, D. C. Hayes, and V. M. Lopez, editors. *Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector*. Springer International Publishing, Cham.
- Fleishman, E. 2023. Sixth Oregon Climate Assessment. Oregon Climate Change Research Institute, Oregon State University, Corvallis, OR.
- Fu, Y. H., H. Zhao, S. Piao, M. Peaucelle, S. Peng, G. Zhou, P. Ciais, M. Huang, A. Menzel, J. Peñuelas, Y. Song, Y. Vitasse, Z. Zeng, and I. A. Janssens. 2015. Declining global warming effects on the phenology of spring leaf unfolding. *Nature* 526:104–107.
- Germain, S. J., and J. A. Lutz. 2020. Climate extremes may be more important than climate means when predicting species range shifts. *Climatic Change* 163:579–598.
- Germain, S. J., and J. A. Lutz. 2022. Climate warming may weaken stabilizing mechanisms in old forests. *Ecological Monographs* 92:e1508.
- Gervais, J. A., R. Kovach, A. Sepulveda, R. Al-Chokhachy, J. Joseph Giersch, and C. C. Muhlfeld. 2020. Climate-induced expansions of invasive species in the Pacific Northwest, North America: a synthesis of observations and projections. *Biological Invasions* 22:2163–2183.
- Hagmann, R. K., P. F. Hessburg, R. B. Salter, A. G. Merschel, and M. J. Reilly. 2022. Contemporary wildfires further degrade resistance and resilience of fire-excluded forests. *Forest Ecology and Management* 506:119975.
- Halofsky, J. E., and D. L. Peterson. 2017. Climate change vulnerability and adaptation in the Blue Mountains region. Page PNW-GTR-939. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Halofsky, J. E., D. L. Peterson, S. K. Dante-Wood, L. Hoang, J. J. Ho, and L. A. Joyce. 2018a. Climate change vulnerability and adaptation in the Northern Rocky Mountains - Part 1. Pages 1–273. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Halofsky, J. E., D. L. Peterson, S. K. Dante-Wood, L. Hoang, J. J. Ho, and L. A. Joyce. 2018b. Climate change vulnerability and adaptation in the Northern Rocky Mountains - Part 2. Pages 275–475. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Halofsky, J. E., D. L. Peterson, and R. A. Gravenmier. 2022a. Climate change vulnerability and adaptation in southwest Oregon. Page PNW-GTR-995. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Halofsky, J. E., D. L. Peterson, and R. A. Gravenmier. 2022b. Climate change vulnerability and adaptation in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest. Page PNW-GTR-1001. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Halofsky, J. E., D. L. Peterson, and B. J. Harvey. 2020. Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology* 16:4.
- Halofsky, J. E., D. L. Peterson, and J. J. Ho. 2019. Climate change vulnerability and adaptation in south-central Oregon. Page PNW-GTR-974. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

- Halofsky, J. E., D. L. Peterson, J. J. Ho, N. J. Little, and L. A. Joyce. 2018c. Climate change vulnerability and adaptation in the Intermountain Region [Part 2]. Pages 199–513. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Halofsky, J. E., D. L. Peterson, J. J. Ho, N. J. Little, and L. A. Joyce. 2018d. Climate change vulnerability and adaptation in the Intermountain Region [Part 1]. Pages 1–197. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Halofsky, J. E., D. L. Peterson, and H. R. Prendeville. 2018e. Assessing vulnerabilities and adapting to climate change in northwestern U.S. forests. *Climatic Change* 146:89–102.
- Halofsky, J. S., D. R. Conklin, D. C. Donato, J. E. Halofsky, and J. B. Kim. 2018f. Climate change, wildfire, and vegetation shifts in a high-inertia forest landscape: Western Washington, U.S.A. *PLOS ONE* 13:e0209490.
- Halofsky, J. S., D. C. Donato, J. F. Franklin, J. E. Halofsky, D. L. Peterson, and B. J. Harvey. 2018g. The nature of the beast: examining climate adaptation options in forests with stand-replacing fire regimes. *Ecosphere* 9:e02140.
- Hankin, L. E., P. E. Higuera, K. T. Davis, and S. Z. Dobrowski. 2019. Impacts of growing-season climate on tree growth and post-fire regeneration in ponderosa pine and Douglas-fir forests. *Ecosphere* 10:e02679.
- Hansen, W. D., K. H. Braziunas, W. Rammer, R. Seidl, and M. G. Turner. 2018. It takes a few to tango: changing climate and fire regimes can cause regeneration failure of two subalpine conifers. *Ecology* 99:966–977.
- Hart, S. J., T. Schoennagel, T. T. Veblen, and T. B. Chapman. 2015. Area burned in the western United States is unaffected by recent mountain pine beetle outbreaks. *Proceedings of the National Academy of Sciences* 112:4375–4380.
- Harvey, B. J., M. S. Buonanduci, and M. G. Turner. 2023a. Spatial interactions among short-interval fires reshape forest landscapes. *Global Ecology and Biogeography*:geb.13634.
- Harvey, B. J., S. J. Hart, P. C. Tobin, T. T. Veblen, D. C. Donato, M. S. Buonanduci, A. M. Pane, H. D. Stanke, and K. C. Rodman. 2023b. Emergent hotspots of biotic disturbances and their consequences for forest resilience. *Frontiers in Ecology and the Environment*:fee.2659.
- Haugo, R. D., B. S. Kellogg, C. A. Cansler, C. A. Kolden, K. B. Kemp, J. C. Robertson, K. L. Metlen, N. M. Vaillant, and C. M. Restaino. 2019. The missing fire: quantifying human exclusion of wildfire in Pacific Northwest forests, USA. *Ecosphere* 10:e02702.
- Hessburg, P. F., S. Charnley, A. N. Gray, T. A. Spies, D. W. Peterson, R. L. Flitcroft, K. L. Wendel, J. E. Halofsky, E. M. White, and J. Marshall. 2022. Climate and wildfire adaptation of inland Northwest US forests. *Frontiers in Ecology and the Environment* 20:40–48.
- Hessburg, P. F., S. J. Prichard, R. K. Hagmann, N. A. Povak, and F. K. Lake. 2021. Wildfire and climate change adaptation of western North American forests: a case for intentional management. *Ecological Applications* 31:e02432.

- Higuera, P. E., J. T. Abatzoglou, J. S. Littell, and P. Morgan. 2015. The Changing Strength and Nature of Fire-Climate Relationships in the Northern Rocky Mountains, U.S.A., 1902-2008. *PLOS ONE* 10:e0127563.
- Hoecker, T. J., S. A. Parks, M. Krosby, and S. Z. Dobrowski. 2023. Widespread exposure to altered fire regimes under 2 °C warming is projected to transform conifer forests of the Western United States. *Communications Earth & Environment* 4:295.
- Hoecker, T. J., and M. G. Turner. 2022. A short-interval reburn catalyzes departures from historical structure and composition in a mesic mixed-conifer forest. *Forest Ecology and Management* 504:119814.
- Holden, Z. A., A. Swanson, C. H. Luce, W. M. Jolly, M. Maneta, J. W. Oyler, D. A. Warren, R. Parsons, and D. Affleck. 2018. Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences* 115:E8349-E8357.
- Hood, S. M., B. J. Harvey, P. J. Fornwalt, C. E. Naficy, W. D. Hansen, K. T. Davis, M. A. Battaglia, C. S. Stevens-Rumann, and V. A. Saab. 2021. Fire Ecology of Rocky Mountain Forests. Pages 287–336 in C. H. Greenberg and B. Collins, editors. *Fire Ecology and Management: Past, Present, and Future of US Forested Ecosystems*. Springer International Publishing, Cham.
- Hudec, J. L., J. E. Halofsky, D. L. Peterson, and J. J. Ho. 2019. Climate change vulnerability and adaptation in southwest Washington. Page PNW-GTR-977. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Jain, P., X. Wang, M. D. Flannigan, P. Jain, X. Wang, and M. D. Flannigan. 2017. Trend analysis of fire season length and extreme fire weather in North America between 1979 and 2015. *International Journal of Wildland Fire* 26:1009–1020.
- Jolly, W. M., M. A. Cochrane, P. H. Freeborn, Z. A. Holden, T. J. Brown, G. J. Williamson, and D. M. J. S. Bowman. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications* 6:1–11.
- Keane, R. E., B. Bentz, L. M. Holsinger, V. A. Saab, and R. Loehman. 2022. Modeled interactions of mountain pine beetle and wildland fire under future climate and management scenarios for three western US landscapes. *Fire Ecology* 18:12.
- Keane, R. E., M. F. Mahalovich, B. L. Bollenbacher, M. E. Manning, R. A. Loehman, T. B. Jain, L. M. Holsinger, and A. J. Larson. 2018. Effects of Climate Change on Forest Vegetation in the Northern Rockies. Pages 59–95 in J. E. Halofsky and D. L. Peterson, editors. *Climate Change and Rocky Mountain Ecosystems*. Springer International Publishing, Cham.
- Kemp, K. B., P. E. Higuera, P. Morgan, and J. T. Abatzoglou. 2019. Climate will increasingly determine post-fire tree regeneration success in low-elevation forests, Northern Rockies, USA. *Ecosphere* 10:e02568.
- Kerns, B. K., D. C. Powell, S. Mellmann-Brown, G. Carnwath, and J. B. Kim. 2018. Effects of projected climate change on vegetation in the Blue Mountains ecoregion, USA. *Climate Services* 10:33–43.

- Kim, J. B., B. K. Kerns, R. J. Drapek, G. S. Pitts, and J. E. Halofsky. 2018. Simulating vegetation response to climate change in the Blue Mountains with MC2 dynamic global vegetation model. *Climate Services* 10:20–32.
- Klein, T., J. Torres-Ruiz, and J. Albers. 2023. Conifer desiccation in the 2021 NW heatwave confirms the role of hydraulic damage. *Copernicus Meetings*.
- Kleinman, J. S., J. D. Goode, A. C. Fries, and J. L. Hart. 2019. Ecological consequences of compound disturbances in forest ecosystems: a systematic review. *Ecosphere* 10:e02962.
- Knapp, E. E., A. A. Bernal, J. M. Kane, C. J. Fettig, and M. P. North. 2021. Variable thinning and prescribed fire influence tree mortality and growth during and after a severe drought. *Forest Ecology and Management* 479:118595.
- Kroiss, S. J., and J. HilleRisLambers. 2015. Recruitment limitation of long-lived conifers: implications for climate change responses. *Ecology* 96:1286–1297.
- Krosby, M., K. Davis, M. A. Rozance, A. Bagley, C. Dohrn, D. Lyons, K. Swensen, M. McClure, and C. Walls. 2020. Managing post-fire, climate-induced vegetation transitions in the Northwest: A synthesis of existing knowledge and research needs. *Deep Dive*, Northwest Climate Adaptation Science Center, University of Washington, Seattle, WA.
- Larson, A. J., S. M. A. Jeronimo, P. F. Hessburg, J. A. Lutz, N. A. Povak, C. A. Cansler, V. R. Kane, and D. J. Churchill. 2022. Tamm Review: Ecological principles to guide post-fire forest landscape management in the Inland Pacific and Northern Rocky Mountain regions. *Forest Ecology and Management* 504:119680.
- Laughlin, M. M., J. D. Bakker, D. J. Churchill, M. J. Gregory, T. DeMeo, E. C. Alvarado, and B. J. Harvey. 2023. Trends in forest structure restoration need over three decades with increasing wildfire activity in the interior Pacific Northwest US. *Forest Ecology and Management* 527:120607.
- Littell, J. S., D. McKenzie, H. Y. Wan, and S. A. Cushman. 2018. Climate Change and Future Wildfire in the Western United States: An Ecological Approach to Nonstationarity. *Earth's Future* 6:1097–1111.
- Littlefield, C. E. 2019. Topography and post-fire climatic conditions shape spatio-temporal patterns of conifer establishment and growth. *Fire Ecology* 15:34.
- Littlefield, C. E., S. Z. Dobrowski, J. T. Abatzoglou, S. A. Parks, and K. T. Davis. 2020. A climatic dipole drives short- and long-term patterns of postfire forest recovery in the western United States. *Proceedings of the National Academy of Sciences* 117:29730–29737.
- Loehman, R., B. Bentz, G. DeNitto, R. Keane, M. Manning, J. Duncan, J. Egan, M. Jackson, S. Kegley, I. Lockman, D. Pearson, J. Powell, S. Shelly, B. Steed, and P. Zambino. 2018. Effects of Climate Change on Ecological Disturbance in the Northern Rockies. Pages 115–141 *Advances in Global Change Research*.
- Long, J. W., A. Gray, and F. K. Lake. 2018. Recent Trends in Large Hardwoods in the Pacific Northwest, USA. *Forests* 9:651.
- Mathys, A. S., N. C. Coops, and R. H. Waring. 2017. An ecoregion assessment of projected tree species vulnerabilities in western North America through the 21st century. *Global Change Biology* 23:920–932.

- McDowell, N. G., C. D. Allen, K. Anderson-Teixeira, B. H. Aukema, B. Bond-Lamberty, L. Chini, J. S. Clark, M. Dietze, C. Grossiord, A. Hanbury-Brown, G. C. Hurtt, R. B. Jackson, D. J. Johnson, L. Kueppers, J. W. Lichstein, K. Ogle, B. Poulter, T. A. M. Pugh, R. Seidl, M. G. Turner, M. Uriarte, A. P. Walker, and C. Xu. 2020. Pervasive shifts in forest dynamics in a changing world. *Science* 368:eaaz9463.
- McIlroy, S. K., and D. J. Shinneman. 2020. Post-fire aspen (*Populus tremuloides*) regeneration varies in response to winter precipitation across a regional climate gradient. *Forest Ecology and Management* 455:117681.
- Meigs, G. W., J. L. Campbell, H. S. J. Zald, J. D. Bailey, D. C. Shaw, and R. E. Kennedy. 2015. Does wildfire likelihood increase following insect outbreaks in conifer forests? *Ecosphere* 6:1–24.
- Meigs, G. W., M. J. Case, D. J. Churchill, C. M. Hersey, S. M. A. Jeronimo, and L. A. C. Smith. 2023. Drought, wildfire and forest transformation: characterizing trailing edge forests in the eastern Cascade Range, Washington, USA. *Forestry: An International Journal of Forest Research* 96:340–354.
- Meigs, G. W., C. J. Dunn, S. A. Parks, and M. A. Krawchuk. 2020. Influence of topography and fuels on fire refugia probability under varying fire weather conditions in forests of the Pacific Northwest, USA. *Canadian Journal of Forest Research* 50:636–647.
- Mercer, C., V. M. Comeau, L. D. Daniels, and M. Carrer. 2022. Contrasting Impacts of Climate Warming on Coastal Old-Growth Tree Species Reveal an Early Warning of Forest Decline. *Frontiers in Forests and Global Change* 4.
- Mildrexler, D., Z. Yang, W. B. Cohen, and D. M. Bell. 2016. A forest vulnerability index based on drought and high temperatures. *Remote Sensing of Environment* 173:314–325.
- Morgan, H. A., A. Bagley, L. McGill, and C. L. Raymond. 2019. Managing western Washington wildfire risk in a changing climate. Workshop summary report prepared by the Northwest Climate Adaptation Science Center and the Climate Impacts Group, University of Washington, Seattle.
- Nigro, K. M., M. E. Rocca, M. A. Battaglia, J. D. Coop, and M. D. Redmond. 2022. Wildfire catalyzes upward range expansion of trembling aspen in southern Rocky Mountain beetle-killed forests. *Journal of Biogeography* 49:201–214.
- Paine, R. T., M. J. Tegner, and E. A. Johnson. 1998. Compounded perturbations yield ecological surprises. *Ecosystems* 1:535–545.
- Parks, S. A., and J. T. Abatzoglou. 2020. Warmer and Drier Fire Seasons Contribute to Increases in Area Burned at High Severity in Western US Forests From 1985 to 2017. *Geophysical Research Letters* 47:e2020GL089858.
- Parks, S. A., S. Z. Dobrowski, J. D. Shaw, and C. Miller. 2019. Living on the edge: trailing edge forests at risk of fire-facilitated conversion to non-forest. *Ecosphere* 10:e02651.
- Piao, S., Q. Liu, A. Chen, I. A. Janssens, Y. Fu, J. Dai, L. Liu, X. Lian, M. Shen, and X. Zhu. 2019. Plant phenology and global climate change: Current progresses and challenges. *Global Change Biology* 25:1922–1940.
- Prevéy, J. S., L. E. Parker, C. A. Harrington, C. T. Lamb, and M. F. Proctor. 2020. Climate change shifts in habitat suitability and phenology of huckleberry (*Vaccinium membranaceum*). *Agricultural and Forest Meteorology* 280:107803.

- Prichard, S. J., P. F. Hessburg, R. K. Hagmann, N. A. Povak, S. Z. Dobrowski, M. D. Hurteau, V. R. Kane, R. E. Keane, L. N. Kobziar, C. A. Kolden, M. North, S. A. Parks, H. D. Safford, J. T. Stevens, L. L. Yocom, D. J. Churchill, R. W. Gray, D. W. Huffman, F. K. Lake, and P. Khatri-Chhetri. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications* 31:e02433.
- Pureswaran, D. S., A. Roques, and A. Battisti. 2018. Forest Insects and Climate Change. *Current Forestry Reports* 4:35–50.
- Raymond, C. L., D. L. Peterson, and R. M. Rochefort. 2014. Climate change vulnerability and adaptation in the North Cascades region, Washington. Page PNW-GTR-892. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Reilly, M. J., J. E. Halofsky, M. A. Krawchuk, D. C. Donato, P. F. Hessburg, J. D. Johnston, A. G. Merschel, M. E. Swanson, J. S. Halofsky, and T. A. Spies. 2021. Fire Ecology and Management in Pacific Northwest Forests. Pages 393–435 *in* C. H. Greenberg and B. Collins, editors. *Fire Ecology and Management: Past, Present, and Future of US Forested Ecosystems*. Springer International Publishing, Cham.
- Reilly, M. J., A. Zuspan, J. S. Halofsky, C. Raymond, A. McEvoy, A. W. Dye, D. C. Donato, J. B. Kim, B. E. Potter, N. Walker, R. Davis, C. J. Dunn, D. M. Bell, M. J. Gregory, J. D. Johnston, B. J. Harvey, J. E. Halofsky, and B. K. Kerns. 2022. Cascadia Burning: the historic, but not historically unprecedented, 2020 wildfires in the Pacific Northwest, USA. *Ecosphere* 13:e4070.
- Ringo, C., K. Bennett, J. Noller, D. Jiang, and D. Moore. 2018. Modeling droughty soils at regional scales in Pacific Northwest Forests, USA. *Forest Ecology and Management* 424:121–135.
- Rosenblad, K. C., K. C. Baer, and D. D. Ackerly. 2023. Climate change, tree demography, and thermophilization in western US forests. *Proceedings of the National Academy of Sciences* 120:e2301754120.
- Schoennagel, T., J. K. Balch, H. Brenkert-Smith, P. E. Dennison, B. J. Harvey, M. A. Krawchuk, N. Mietkiewicz, P. Morgan, M. A. Moritz, R. Rasker, M. G. Turner, and C. Whitlock. 2017. Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences* 114:4582–4590.
- Seidl, R., D. Thom, M. Kautz, D. Martin-Benito, M. Peltoniemi, G. Vacchiano, J. Wild, D. Ascoli, M. Petr, J. Honkaniemi, M. J. Lexer, V. Trotsiuk, P. Mairota, M. Svoboda, M. Fabrika, T. A. Nagel, and C. P. O. Reyer. 2017. Forest disturbances under climate change. *Nature Climate Change* 7:395–402.
- Shaw, D. C., G. Ritóková, Y.-H. Lan, D. B. Mainwaring, A. Russo, R. Comeleo, S. Navarro, D. Norlander, and B. Smith. 2021. Persistence of the Swiss Needle Cast Outbreak in Oregon Coastal Douglas-Fir and New Insights from Research and Monitoring. *Journal of forestry* 119:407–421.
- Shriver, R. K., C. B. Yackulic, D. M. Bell, and J. B. Bradford. 2022. Dry forest decline is driven by both declining recruitment and increasing mortality in response to warm, dry conditions. *Global Ecology and Biogeography* 31:2259–2269.

- Simard, M., W. H. Romme, J. M. Griffin, and M. G. Turner. 2011. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? *Ecological Monographs* 81:3–24.
- Simler-Williamson, A. B., D. M. Rizzo, and R. C. Cobb. 2019. Interacting Effects of Global Change on Forest Pest and Pathogen Dynamics. *Annual Review of Ecology, Evolution, and Systematics* 50:381–403.
- Six, D. L., A. Trowbridge, M. Howe, D. Perkins, E. Berglund, P. Brown, J. A. Hicke, and G. Balasubramanian. 2021. Growth, Chemistry, and Genetic Profiles of Whitebark Pine Forests Affected by Climate-Driven Mountain Pine Beetle Outbreaks. *Frontiers in Forests and Global Change* 4.
- Six, D. L., C. Vergobbi, and M. Cutter. 2018. Are Survivors Different? Genetic-Based Selection of Trees by Mountain Pine Beetle During a Climate Change-Driven Outbreak in a High-Elevation Pine Forest. *Frontiers in Plant Science* 9.
- Stanke, H., A. O. Finley, G. M. Domke, A. S. Weed, and D. W. MacFarlane. 2021. Over half of western United States' most abundant tree species in decline. *Nature Communications* 12:451.
- Stevens-Rumann, C. S., K. B. Kemp, P. E. Higuera, B. J. Harvey, M. T. Rother, D. C. Donato, P. Morgan, and T. T. Veblen. 2018. Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters* 21:243–252.
- Still, C. J., A. Sibley, D. DePinte, P. E. Busby, C. A. Harrington, M. Schulze, D. R. Shaw, D. Woodruff, D. E. Rupp, C. Daly, W. M. Hammond, and G. F. M. Page. 2023. Causes of widespread foliar damage from the June 2021 Pacific Northwest Heat Dome: more heat than drought. *Tree Physiology* 43:203–209.
- Stralberg, D., C. Carroll, J. H. Pedlar, C. B. Wilsey, D. W. McKenney, and S. E. Nielsen. 2018. Macrorefugia for North American trees and songbirds: Climatic limiting factors and multi-scale topographic influences. *Global Ecology and Biogeography* 27:690–703.
- Talucci, A. C., L. M. Matosziuk, J. A. Hatten, and M. A. Krawchuk. 2020. An added boost in pyrogenic carbon when wildfire burns forest with high pre-fire mortality. *Fire Ecology* 16:21.
- Tepley, A. J., J. R. Thompson, H. E. Epstein, and K. J. Anderson-Teixeira. 2017. Vulnerability to forest loss through altered postfire recovery dynamics in a warming climate in the Klamath Mountains. *Global Change Biology* 23:4117–4132.
- Thompson, V., A. T. Kennedy-Asser, E. Vosper, Y. T. E. Lo, C. Huntingford, O. Andrews, M. Collins, G. C. Hegerl, and D. Mitchell. 2022. The 2021 western North America heat wave among the most extreme events ever recorded globally. *Science Advances* 8:eabm6860.
- Tortorelli, C. M., J. B. Kim, N. M. Vaillant, K. Riley, A. Dye, T. C. Nietupski, K. C. Vogler, R. Lemons, M. Day, M. A. Krawchuk, and B. K. Kerns. 2023. Feeding the fire: Annual grass invasion facilitates modeled fire spread across Inland Northwest forest-mosaic landscapes. *Ecosphere* 14:e4413.
- Turner, M. G., K. H. Braziunas, W. D. Hansen, and B. J. Harvey. 2019. Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests. *Proceedings of the National Academy of Sciences* 116:11319–11328.

- Turner, M. G., and R. Seidl. 2023. Novel Disturbance Regimes and Ecological Responses. *Annual Review of Ecology, Evolution, and Systematics* 54:63–83.
- Urza, A. K., and J. S. Sibold. 2017. Climate and seed availability initiate alternate post-fire trajectories in a lower subalpine forest. *Journal of Vegetation Science* 28:43–56.
- Van Mantgem, P. J., D. A. Falk, E. C. Williams, A. J. Das, and N. L. Stephenson. 2020. The influence of pre-fire growth patterns on post-fire tree mortality for common conifers in western US parks. *International Journal of Wildland Fire* 29:513.
- WADNR. 2022. Wildfire Season 2021 - Work of Wildfire Assessment. Washington State Department of Natural Resources, Olympia, WA.
- WADNR. 2023. Wildfire Season 2022 - Work of Wildfire Assessment. Washington State Department of Natural Resources, Olympia, WA.
- Westerling, A. L. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences* 371:1–10.
- Wolf, K. D., P. E. Higuera, K. T. Davis, and S. Z. Dobrowski. 2021. Wildfire impacts on forest microclimate vary with biophysical context. *Ecosphere* 12:e03467.
- Woolley, T., D. C. Shaw, L. T. Hollingsworth, M. C. Agne, S. Fitzgerald, A. Eglitis, and L. Kurth. 2019. Beyond red crowns: complex changes in surface and crown fuels and their interactions 32 years following mountain pine beetle epidemics in south-central Oregon, USA. *Fire Ecology* 15:4.
-

REFERENCES - BLUE MOUNTAINS

- Bradley, B. A., Curtis, C. A., Fusco, E. J., Abatzoglou, J. T., Balch, J. K., Dadashi, S., & Tuanmu, M.-N. (2018). Cheatgrass (*Bromus tectorum*) distribution in the intermountain Western United States and its relationship to fire frequency, seasonality, and ignitions. *Biological Invasions*, 20(6), 1493–1506. <https://doi.org/10.1007/s10530-017-1641-8>
- Fettig, C. J., Asaro, C., Nowak, J. T., Dodds, K. J., Gandhi, K. J. K., Moan, J. E., & Robert, J. (2022). Trends in Bark Beetle Impacts in North America During a Period (2000–2020) of Rapid Environmental Change. *Journal of Forestry*, 120(6), 693–713. <https://doi.org/10.1093/jofore/fvac021>
- Halofsky, J. E., Andrews-Key, S. A., Edwards, J. E., Johnston, M. H., Nelson, H. W., Peterson, D. L., Schmitt, K. M., Swanston, C. W., & Williamson, T. B. (2018). Adapting forest management to climate change: The state of science and applications in Canada and the United States. *Forest Ecology and Management*, 421, 84–97. <https://doi.org/10.1016/j.foreco.2018.02.037>
- Halofsky, J. E., & Peterson, D. L. (2017). *Climate change vulnerability and adaptation in the Blue Mountains region* (Gen. Tech. Rep. PNW-GTR-939 PNW-GTR-939; p. 331). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. https://www.fs.usda.gov/pnw/pubs/pnw_gtr939.pdf
- Kerns, B. K., Tortorelli, C., Day, M. A., Nietupski, T., Barros, A. M. G., Kim, J. B., & Krawchuk, M. A. (2020). Invasive grasses: A new perfect storm for forested ecosystems? *Forest Ecology and Management*, 463, 117985. <https://doi.org/10.1016/j.foreco.2020.117985>
- Six, D. L., Trowbridge, A., Howe, M., Perkins, D., Berglund, E., Brown, P., Hicke, J. A., & Balasubramanian, G. (2021). Growth, Chemistry, and Genetic Profiles of Whitebark Pine Forests Affected by Climate-Driven Mountain Pine Beetle Outbreaks. *Frontiers in Forests and Global Change*, 4, 671510. <https://doi.org/10.3389/ffgc.2021.671510>
- Six, D. L., Vergobbi, C., & Cutter, M. (2018). Are Survivors Different? Genetic-Based Selection of Trees by Mountain Pine Beetle During a Climate Change-Driven Outbreak in a High-Elevation Pine Forest. *Frontiers in Plant Science*, 9, 993. <https://doi.org/10.3389/fpls.2018.00993>
- Sohn, J. A., Saha, S., & Bauhus, J. (2016). Potential of forest thinning to mitigate drought stress: A meta-analysis. *Forest Ecology and Management*, 380, 261–273. <https://doi.org/10.1016/j.foreco.2016.07.046>
- Tortorelli, C. M., Kim, J. B., Vaillant, N. M., Riley, K., Dye, A., Nietupski, T. C., Vogler, K. C., Lemons, R., Day, M., Krawchuk, M. A., & Kerns, B. K. (2023). Feeding the fire: Annual grass invasion facilitates modeled fire spread across Inland Northwest forest-mosaic landscapes. *Ecosphere*, 14(2), e4413. <https://doi.org/10.1002/ecs2.4413>
- Ziska, L. H., Reeves III, J. B., & Blank, B. (2005). The impact of recent increases in atmospheric CO₂ on biomass production and vegetative retention of Cheatgrass (*Bromus tectorum*): Implications for fire disturbance. *Global Change Biology*, 11(8), 1325–1332. <https://doi.org/10.1111/j.1365-2486.2005.00992.x>

REFERENCES - CASCADES

- Agne, M. C., Beedlow, P. A., Shaw, D. C., Woodruff, D. R., Lee, E. H., Cline, S. P., & Comeleo, R. L. (2018). Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. *Forest Ecology and Management*, 409, 317–332. <https://doi.org/10.1016/j.foreco.2017.11.004>
- Agne, M. C., Fontaine, J. B., Enright, N. J., & Harvey, B. J. (2022). Fire interval and post-fire climate effects on serotinous forest resilience. *Fire Ecology*, 18, 1–20. <https://doi.org/10.1186/s42408-022-00145-4>
- Andrus, R. A., Peach, L. R., Cinquini, A. R., Mills, B., Yusi, J. T., Buhl, C., Fischer, M., Goodrich, B. A., Hulbert, J. M., Holz, A., Meddens, A. J. H., Moffett, K. B., Ramirez, A., & Adams, H. D. (2023). *Canary in the Forest? – Tree mortality and canopy dieback of western redcedar linked to drier and warmer summer conditions* (p. 2023.01.11.522134). bioRxiv. <https://doi.org/10.1101/2023.01.11.522134>
- Bell, D. M., Pabst, R. J., & Shaw, D. C. (2020). Tree growth declines and mortality were associated with a parasitic plant during warm and dry climatic conditions in a temperate coniferous forest ecosystem. *Global Change Biology*, 26(3), 1714–1724. <https://doi.org/10.1111/gcb.14834>
- Betzen, J. J., Ramsey, A., Omdal, D., Ettl, G. J., & Tobin, P. C. (2021). Bigleaf maple, *Acer macrophyllum* Pursh, decline in western Washington, USA. *Forest Ecology and Management*, 501, 119681. <https://doi.org/10.1016/j.foreco.2021.119681>
- Donato, D. C., Halofsky, J. S., & Reilly, M. J. (2020). Corraling a black swan: Natural range of variation in a forest landscape driven by rare, extreme events. *Ecological Applications*, 30(1), e02013. <https://doi.org/10.1002/eap.2013>
- Fettig, C. J., Asaro, C., Nowak, J. T., Dodds, K. J., Gandhi, K. J. K., Moan, J. E., & Robert, J. (2022). Trends in Bark Beetle Impacts in North America During a Period (2000–2020) of Rapid Environmental Change. *Journal of Forestry*, 120(6), 693–713. <https://doi.org/10.1093/jofore/fvac021>
- Halofsky, J. E., Peterson, D. L., & Harvey, B. J. (2020). Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, 16(1), 4. <https://doi.org/10.1186/s42408-019-0062-8>
- Halofsky, J. S., Conklin, D. R., Donato, D. C., Halofsky, J. E., & Kim, J. B. (2018). Climate change, wildfire, and vegetation shifts in a high-inertia forest landscape: Western Washington, U.S.A. *PLOS ONE*, 13(12), e0209490. <https://doi.org/10.1371/journal.pone.0209490>
- Hoecker, T. J., & Turner, M. G. (2022). A short-interval reburn catalyzes departures from historical structure and composition in a mesic mixed-conifer forest. *Forest Ecology and Management*, 504, 119814. <https://doi.org/10.1016/j.foreco.2021.119814>
- Hudec, J. L., Halofsky, J. E., Peterson, D. L., & Ho, J. J. (2019). *Climate change vulnerability and adaptation in southwest Washington* (p. 249) [Gen. Tech. Rep. PNW-GTR-977]. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. <https://doi.org/10.2737/PNW-GTR-977>
- Kleinman, J. S., Goode, J. D., Fries, A. C., & Hart, J. L. (2019). Ecological consequences of compound disturbances in forest ecosystems: A systematic review. *Ecosphere*,

CLIMATE EFFECTS: FOREST ECOSYSTEMS

10(11), e02962. <https://doi.org/10.1002/ecs2.2962>

Mercer, C., Comeau, V. M., Daniels, L. D., & Carrer, M. (2022). Contrasting Impacts of Climate Warming on Coastal Old-Growth Tree Species Reveal an Early Warning of Forest Decline. *Frontiers in Forests and Global Change*, 4, 775301.

<https://doi.org/10.3389/ffgc.2021.775301>

Reilly, M. J., Halofsky, J. E., Krawchuk, M. A., Donato, D. C., Hessburg, P. F., Johnston, J. D., Merschel, A. G., Swanson, M. E., Halofsky, J. S., & Spies, T. A. (2021). Fire Ecology and Management in Pacific Northwest Forests. In C. H. Greenberg & B. Collins (Eds.), *Fire Ecology and Management: Past, Present, and Future of US Forested Ecosystems* (pp. 393–435). Springer International Publishing.

https://doi.org/10.1007/978-3-030-73267-7_10

REFERENCES - COAST RANGE

- Agne, M. C., Beedlow, P. A., Shaw, D. C., Woodruff, D. R., Lee, E. H., Cline, S. P., & Comeleo, R. L. (2018). Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. *Forest Ecology and Management*, 409, 317–332. <https://doi.org/10.1016/j.foreco.2017.11.004>
- Andrus, R. A., Peach, L. R., Cinquini, A. R., Mills, B., Yusi, J. T., Buhl, C., Fischer, M., Goodrich, B. A., Hulbert, J. M., Holz, A., Meddens, A. J. H., Moffett, K. B., Ramirez, A., & Adams, H. D. (2024). Canary in the forest?—Tree mortality and canopy dieback of western redcedar linked to drier and warmer summers. *Journal of Biogeography*, 51(1), 103–119. <https://doi.org/10.1111/jbi.14732>
- Comeau, V. M., Daniels, L. D., Knochenmus, G., Chavardès, R. D., & Zeglen, S. (2019). Tree-Rings Reveal Accelerated Yellow-Cedar Decline with Changes to Winter Climate after 1980. *Forests*, 10(12), Article 12. <https://doi.org/10.3390/f10121085>
- Fettig, C. J., Egan, J. M., Delb, H., Hilszczański, J., Kautz, M., Munson, A. S., Nowak, J. T., & Negrón, J. F. (2022). Management tactics to reduce bark beetle impacts in North America and Europe under altered forest and climatic conditions. In K. J. K. Gandhi & R. W. Hofstetter (Eds.), *Bark Beetle Management, Ecology, and Climate Change* (pp. 345–394). Academic Press. <https://doi.org/10.1016/B978-0-12-822145-7.00006-4>
- Mercer, C., Comeau, V. M., Daniels, L. D., & Carrer, M. (2022). Contrasting Impacts of Climate Warming on Coastal Old-Growth Tree Species Reveal an Early Warning of Forest Decline. *Frontiers in Forests and Global Change*, 4, 775301. <https://doi.org/10.3389/ffgc.2021.775301>
- Shaw, D. C., Ritóková, G., Lan, Y.-H., Mainwaring, D. B., Russo, A., Comeleo, R., Navarro, S., Norlander, D., & Smith, B. (2021). Persistence of the Swiss Needle Cast Outbreak in Oregon Coastal Douglas-Fir and New Insights from Research and Monitoring. *Journal of Forestry*, 119(4), 407–421. <https://doi.org/10.1093/jofore/fvab011>
- Still, C. J., Sibley, A., DePinte, D., Busby, P. E., Harrington, C. A., Schulze, M., Shaw, D. R., Woodruff, D., Rupp, D. E., Daly, C., Hammond, W. M., & Page, G. F. M. (2023). Causes of widespread foliar damage from the June 2021 Pacific Northwest Heat Dome: More heat than drought. *Tree Physiology*, 43(2), 203–209. <https://doi.org/10.1093/treephys/tpac143>
- Thompson, V., Kennedy-Asser, A. T., Vosper, E., Lo, Y. T. E., Huntingford, C., Andrews, O., Collins, M., Hegerl, G. C., & Mitchell, D. (2022). The 2021 western North America heat wave among the most extreme events ever recorded globally. *Science Advances*, 8(18), eabm6860. <https://doi.org/10.1126/sciadv.abm6860>

REFERENCES - EASTERN CASCADE FOOTHILLS

- Coop, J. D., Parks, S. A., Stevens-Rumann, C. S., Crausbay, S. D., Higuera, P. E., Hurteau, M. D., Tepley, A., Whitman, E., Assal, T., Collins, B. M., Davis, K. T., Dobrowski, S., Falk, D. A., Fornwalt, P. J., Fulé, P. Z., Harvey, B. J., Kane, V. R., Littlefield, C. E., Margolis, E. Q., ... Rodman, K. C. (2020). Wildfire-Driven Forest Conversion in Western North American Landscapes. *BioScience*, 70(8), 659–673. <https://doi.org/10.1093/biosci/biaa061>
- Davis, K. T., Dobrowski, S. Z., Higuera, P. E., Holden, Z. A., Veblen, T. T., Rother, M. T., Parks, S. A., Sala, A., & Maneta, M. P. (2019). Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences*, 116(13), 6193–6198. <https://doi.org/10.1073/pnas.1815107116>
- Davis, K. T., Higuera, P. E., Dobrowski, S. Z., Parks, S. A., Abatzoglou, J. T., Rother, M. T., & Veblen, T. T. (2020). Fire-catalyzed vegetation shifts in ponderosa pine and Douglas-fir forests of the western United States. *Environmental Research Letters*, 15(10), 1040b8. <https://doi.org/10.1088/1748-9326/abb9df>
- Donato, D. C., Halofsky, J. S., Churchill, D. J., Haugo, R. D., Alina Cansler, C., Smith, A., & Harvey, B. J. (2023). Does large area burned mean a bad fire year? Comparing contemporary wildfire years to historical fire regimes informs the restoration task in fire-dependent forests. *Forest Ecology and Management*, 546, 121372. <https://doi.org/10.1016/j.foreco.2023.121372>
- Hagmann, R. K., Hessburg, P. F., Salter, R. B., Merschel, A. G., & Reilly, M. J. (2022). Contemporary wildfires further degrade resistance and resilience of fire-excluded forests. *Forest Ecology and Management*, 506, 119975. <https://doi.org/10.1016/j.foreco.2021.119975>
- Halofsky, J. E., Peterson, D. L., & Harvey, B. J. (2020). Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, 16(4), 1–26. <https://doi.org/10.1186/s42408-019-0062-8>
- Halofsky, J. E., Peterson, D. L., & Ho, J. J. (2019). *Climate change vulnerability and adaptation in south-central Oregon* (PNW-GTR-974; p. PNW-GTR-974). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. <https://doi.org/10.2737/PNW-GTR-974>
- Haugo, R. D., Kellogg, B. S., Cansler, C. A., Kolden, C. A., Kemp, K. B., Robertson, J. C., Metlen, K. L., Vaillant, N. M., & Restaino, C. M. (2019). The missing fire: Quantifying human exclusion of wildfire in Pacific Northwest forests, USA. *Ecosphere*, 10(4), e02702. <https://doi.org/10.1002/ecs2.2702>
- Hessburg, P. F., Charnley, S., Gray, A. N., Spies, T. A., Peterson, D. W., Flitcroft, R. L., Wendel, K. L., Halofsky, J. E., White, E. M., & Marshall, J. (2022). Climate and wildfire adaptation of inland Northwest US forests. *Frontiers in Ecology and the Environment*, 20(1), 40–48. <https://doi.org/10.1002/fee.2408>
- Laughlin, M. M., Bakker, J. D., Churchill, D. J., Gregory, M. J., DeMeo, T., Alvarado, E. C., & Harvey, B. J. (2023). Trends in forest structure restoration need over three decades with increasing wildfire activity in the interior Pacific Northwest US. *Forest Ecology*

- and Management*, 527, 120607. <https://doi.org/10.1016/j.foreco.2022.120607>
- Meigs, G. W., Case, M. J., Churchill, D. J., Hersey, C. M., Jeronimo, S. M. A., & Smith, L. A. C. (2023). Drought, wildfire and forest transformation: Characterizing trailing edge forests in the eastern Cascade Range, Washington, USA. *Forestry: An International Journal of Forest Research*, 96(3), 340–354. <https://doi.org/10.1093/forestry/cpac046>
- North, M. P., Stevens, J. T., Greene, D. F., Coppoletta, M., Knapp, E. E., Latimer, A. M., Restaino, C. M., Tompkins, R. E., Welch, K. R., York, R. A., Young, D. J. N., Axelson, J. N., Buckley, T. N., Estes, B. L., Hager, R. N., Long, J. W., Meyer, M. D., Ostojia, S. M., Safford, H. D., ... Wyrsh, P. (2019). Tamm Review: Reforestation for resilience in dry western U.S. forests. *Forest Ecology and Management*, 432, 209–224. <https://doi.org/10.1016/j.foreco.2018.09.007>

REFERENCES - IDAHO BATHOLITH

- Alizadeh, M. R., Abatzoglou, J. T., Luce, C. H., Adamowski, J. F., Farid, A., & Sadegh, M. (2021). Warming enabled upslope advance in western US forest fires. *Proceedings of the National Academy of Sciences*, 118(22), 1–6. <https://doi.org/10.1073/pnas.2009717118>
- Campbell, J. L., & Shinneman, D. J. (2017). Potential influence of wildfire in modulating climate-induced forest redistribution in a central Rocky Mountain landscape. *Ecological Processes*, 6(7), 1–17. <https://doi.org/10.1186/s13717-017-0073-9>
- Fettig, C. J., Egan, J. M., Delb, H., Hilszczański, J., Kautz, M., Munson, A. S., Nowak, J. T., & Negrón, J. F. (2022). Management tactics to reduce bark beetle impacts in North America and Europe under altered forest and climatic conditions. In K. J. K. Gandhi & R. W. Hofstetter (Eds.), *Bark Beetle Management, Ecology, and Climate Change* (pp. 345–394). Academic Press. <https://doi.org/10.1016/B978-0-12-822145-7.00006-4>
- Halofsky, J. E., Peterson, D. L., Dante-Wood, S. K., Hoang, L., Ho, J. J., & Joyce, L. A. (2018). *Climate change vulnerability and adaptation in the Northern Rocky Mountains. Part 1* (Gen. Tech. Rep. RMRS-GTR-374 RMRS-GTR-374; pp. 1–273). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Harvey, B. J., Hart, S. J., Tobin, P. C., Veblen, T. T., Donato, D. C., Buonanduci, M. S., Pane, A. M., Stanke, H. D., & Rodman, K. C. (2023). Emergent hotspots of biotic disturbances and their consequences for forest resilience. *Frontiers in Ecology and the Environment*, 21(8), 388–396. <https://doi.org/10.1002/fee.2659>
- Hoecker, T. J., & Turner, M. G. (2022). A short-interval reburn catalyzes departures from historical structure and composition in a mesic mixed-conifer forest. *Forest Ecology and Management*, 504, 119814. <https://doi.org/10.1016/j.foreco.2021.119814>
- Hood, S. M., Harvey, B. J., Fornwalt, P. J., Naficy, C. E., Hansen, W. D., Davis, K. T., Battaglia, M. A., Stevens-Rumann, C. S., & Saab, V. A. (2021). Fire Ecology of Rocky Mountain Forests. In C. H. Greenberg & B. Collins (Eds.), *Fire Ecology and Management: Past, Present, and Future of US Forested Ecosystems* (Vol. 39, pp. 287–336). Springer International Publishing. https://doi.org/10.1007/978-3-030-73267-7_8
- Keane, R. E., Mahalovich, M. F., Bollenbacher, B. L., Manning, M. E., Loehman, R. A., Jain, T. B., Holsinger, L. M., Larson, A. J., Halofsky, J. E., & Peterson, D. L. (2018). Effects of Climate Change on Forest Vegetation in the Northern Rockies. In J. E. Halofsky & D. L. Peterson (Eds.), *Climate Change and Rocky Mountain Ecosystems* (Vol. 63, pp. 59–95). Springer International Publishing. https://doi.org/10.1007/978-3-319-56928-4_5
- Loehman, R., Bentz, B., DeNitto, G., Keane, R., Manning, M., Duncan, J., Egan, J., Jackson, M., Kegley, S., Lockman, I., Pearson, D., Powell, J., Shelly, S., Steed, B., & Zambino, P. (2018). Effects of Climate Change on Ecological Disturbance in the Northern Rockies. In J. E. Halofsky & D. L. Peterson (Eds.), *Climate Change and Rocky Mountain Ecosystems* (Vol. 63, pp. 115–141). Springer International Publishing. https://doi.org/10.1007/978-3-319-56928-4_7
- Nigro, K. M., Rocca, M. E., Battaglia, M. A., Coop, J. D., & Redmond, M. D. (2022). Wildfire catalyzes upward range expansion of trembling aspen in southern Rocky Mountain beetle-killed forests. *Journal of Biogeography*, 49(1), 201–214. <https://doi.org/10.1111/jbi.14302>

CLIMATE EFFECTS: FOREST ECOSYSTEMS

- Six, D. L., Trowbridge, A., Howe, M., Perkins, D., Berglund, E., Brown, P., Hicke, J. A., & Balasubramanian, G. (2021). Growth, Chemistry, and Genetic Profiles of Whitebark Pine Forests Affected by Climate-Driven Mountain Pine Beetle Outbreaks. *Frontiers in Forests and Global Change*, 4, 671510. <https://doi.org/10.3389/ffgc.2021.671510>
- Six, D. L., Vergobbi, C., & Cutter, M. (2018). Are Survivors Different? Genetic-Based Selection of Trees by Mountain Pine Beetle During a Climate Change-Driven Outbreak in a High-Elevation Pine Forest. *Frontiers in Plant Science*, 9, 993. <https://doi.org/10.3389/fpls.2018.00993>
- Tomback, D. F., Keane, R. E., Schoettle, A. W., Snieszko, R. A., Jenkins, M. B., Nelson, C. R., Bower, A. D., DeMastus, C. R., Guiberson, E., Krakowski, J., Murray, M. P., Pansing, E. R., & Shamhart, J. (2022). Tamm review: Current and recommended management practices for the restoration of whitebark pine (*Pinus albicaulis* Engelm.), an imperiled high-elevation Western North American forest tree. *Forest Ecology and Management*, 522, 119929. <https://doi.org/10.1016/j.foreco.2021.119929>

REFERENCES - KLAMATH MOUNTAINS

- Agne, M. C., Fontaine, J. B., Enright, N. J., & Harvey, B. J. (2022). Fire interval and post-fire climate effects on serotinous forest resilience. *Fire Ecology*, 18, 1–20.
<https://doi.org/10.1186/s42408-022-00145-4>
- Bennett, M., Shaw, D. C., & Lowrey, L. (2023). Recent Douglas-fir Mortality in the Klamath Mountains Ecoregion of Oregon: Evidence for a Decline Spiral. *Journal of Forestry*, 121(3), 246–261. <https://doi.org/10.1093/jofore/fvad007>
- Filipe, J. A. N., Cobb, R. C., Meentemeyer, R. K., Lee, C. A., Valachovic, Y. S., Cook, A. R., Rizzo, D. M., & Gilligan, C. A. (2012). Landscape Epidemiology and Control of Pathogens with Cryptic and Long-Distance Dispersal: Sudden Oak Death in Northern Californian Forests. *PLOS Computational Biology*, 8(1), e1002328.
<https://doi.org/10.1371/journal.pcbi.1002328>
- Standiford, R. B., & Purcell, K. L. (2015). *Proceedings of the seventh California oak symposium: Managing oak woodlands in a dynamic world* (PSW-GTR-251; p. PSW-GTR-251). U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.
<https://doi.org/10.2737/PSW-GTR-251>
- Swiecki, T. J., & Bernhardt, E. A. (2016). Sudden Oak Death in California. In Paine & F. Lieutier (Eds.), *Insects and Diseases of Mediterranean Forest Systems* (pp. 329–378). Springer International Publishing. https://doi.org/10.1007/978-3-319-24744-1_12
- Tepley, A. J., Thompson, J. R., Epstein, H. E., & Anderson-Teixeira, K. J. (2017). Vulnerability to forest loss through altered postfire recovery dynamics in a warming climate in the Klamath Mountains. *Global Change Biology*, 23(10), 4117–4132.
<https://doi.org/10.1111/gcb.13704>

REFERENCES - NORTH CASCADES

- Case, M. J., & Lawler, J. J. (2016). Relative vulnerability to climate change of trees in western North America. *Climatic Change*, 136(2), 367–379.
<https://doi.org/10.1007/s10584-016-1608-2>
- Donato, D. C., Halofsky, J. S., Churchill, D. J., Haugo, R. D., Alina Cansler, C., Smith, A., & Harvey, B. J. (2023). Does large area burned mean a bad fire year? Comparing contemporary wildfire years to historical fire regimes informs the restoration task in fire-dependent forests. *Forest Ecology and Management*, 546, 121372.
<https://doi.org/10.1016/j.foreco.2023.121372>
- Fettig, C. J., Asaro, C., Nowak, J. T., Dodds, K. J., Gandhi, K. J. K., Moan, J. E., & Robert, J. (2022). Trends in Bark Beetle Impacts in North America During a Period (2000–2020) of Rapid Environmental Change. *Journal of Forestry*, 120(6), 693–713.
<https://doi.org/10.1093/jofore/fvac021>
- Hagmann, R. K., Hessburg, P. F., Salter, R. B., Merschel, A. G., & Reilly, M. J. (2022). Contemporary wildfires further degrade resistance and resilience of fire-excluded forests. *Forest Ecology and Management*, 506, 119975.
<https://doi.org/10.1016/j.foreco.2021.119975>
- Halofsky, J. E., Peterson, D. L., & Harvey, B. J. (2020). Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, 16(4), 1–26. <https://doi.org/10.1186/s42408-019-0062-8>
- Haugo, R. D., Kellogg, B. S., Cansler, C. A., Kolden, C. A., Kemp, K. B., Robertson, J. C., Metlen, K. L., Vaillant, N. M., & Restaino, C. M. (2019). The missing fire: Quantifying human exclusion of wildfire in Pacific Northwest forests, USA. *Ecosphere*, 10(4), e02702.
<https://doi.org/10.1002/ecs2.2702>
- Hessburg, P. F., Charnley, S., Gray, A. N., Spies, T. A., Peterson, D. W., Flitcroft, R. L., Wendel, K. L., Halofsky, J. E., White, E. M., & Marshall, J. (2022). Climate and wildfire adaptation of inland Northwest US forests. *Frontiers in Ecology and the Environment*, 20(1), 40–48. <https://doi.org/10.1002/fee.2408>
- Laughlin, M. M., Bakker, J. D., Churchill, D. J., Gregory, M. J., DeMeo, T., Alvarado, E. C., & Harvey, B. J. (2023). Trends in forest structure restoration need over three decades with increasing wildfire activity in the interior Pacific Northwest US. *Forest Ecology and Management*, 527, 120607. <https://doi.org/10.1016/j.foreco.2022.120607>
- Littlefield, C. E. (2019). Topography and post-fire climatic conditions shape spatio-temporal patterns of conifer establishment and growth. *Fire Ecology*, 15(1), 34.
<https://doi.org/10.1186/s42408-019-0047-7>
- Rocheftort, R. M., Howlin, S., Jeroue, L., Boetsch, J. R., & Grace, L. P. (2018). Whitebark Pine in the Northern Cascades: Tracking the Effects of Blister Rust on Population Health in North Cascades National Park Service Complex and Mount Rainier National Park. *Forests*, 9(5), Article 5. <https://doi.org/10.3390/f9050244>
- Rogers, B. M., Neilson, R. P., Drapek, R., Lenihan, J. M., Wells, J. R., Bachelet, D., & Law, B. E. (2011). Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest. *Journal of Geophysical Research: Biogeosciences*, 116(G3).
<https://doi.org/10.1029/2011JG001695>

CLIMATE EFFECTS: FOREST ECOSYSTEMS

- Six, D. L., Trowbridge, A., Howe, M., Perkins, D., Berglund, E., Brown, P., Hicke, J. A., & Balasubramanian, G. (2021). Growth, Chemistry, and Genetic Profiles of Whitebark Pine Forests Affected by Climate-Driven Mountain Pine Beetle Outbreaks. *Frontiers in Forests and Global Change*, 4, 671510. <https://doi.org/10.3389/ffgc.2021.671510>
- Six, D. L., Vergobbi, C., & Cutter, M. (2018). Are Survivors Different? Genetic-Based Selection of Trees by Mountain Pine Beetle During a Climate Change-Driven Outbreak in a High-Elevation Pine Forest. *Frontiers in Plant Science*, 9, 993. <https://doi.org/10.3389/fpls.2018.00993>

REFERENCES - ROCKY MOUNTAINS

- Davis, K. T., Dobrowski, S. Z., Holden, Z. A., Higuera, P. E., & Abatzoglou, J. T. (2019). Microclimatic buffering in forests of the future: The role of local water balance. *Ecography*, 42(1), 1–11. <https://doi.org/10.1111/ecog.03836>
- Davis, K. T., Higuera, P. E., Dobrowski, S. Z., Parks, S. A., Abatzoglou, J. T., Rother, M. T., & Veblen, T. T. (2020). Fire-catalyzed vegetation shifts in ponderosa pine and Douglas-fir forests of the western United States. *Environmental Research Letters*, 15(10), 1040b8. <https://doi.org/10.1088/1748-9326/abb9df>
- Hankin, L. E., Higuera, P. E., Davis, K. T., & Dobrowski, S. Z. (2019). Impacts of growing-season climate on tree growth and post-fire regeneration in ponderosa pine and Douglas-fir forests. *Ecosphere*, 10(4), e02679. <https://doi.org/10.1002/ecs2.2679>
- Hessburg, P. F., Prichard, S. J., Hagmann, R. K., Povak, N. A., & Lake, F. K. (2021). Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*, 31(8), e02432. <https://doi.org/10.1002/eap.2432>
- Higuera, P. E., Abatzoglou, J. T., Littell, J. S., & Morgan, P. (2015). The Changing Strength and Nature of Fire-Climate Relationships in the Northern Rocky Mountains, U.S.A., 1902-2008. *PLOS ONE*, 10(6), e0127563. <https://doi.org/10.1371/journal.pone.0127563>
- Hoecker, T. J., Parks, S. A., Krosby, M., & Dobrowski, S. Z. (2023). Widespread exposure to altered fire regimes under 2 °C warming is projected to transform conifer forests of the Western United States. *Communications Earth & Environment*, 4(295), 1–12. <https://doi.org/10.1038/s43247-023-00954-8>
- Keane, R. E., Mahalovich, M. F., Bollenbacher, B. L., Manning, M. E., Loehman, R. A., Jain, T. B., Holsinger, L. M., Larson, A. J., Halofsky, J. E., & Peterson, D. L. (2018). Effects of Climate Change on Forest Vegetation in the Northern Rockies. In J. E. Halofsky & D. L. Peterson (Eds.), *Climate Change and Rocky Mountain Ecosystems* (Vol. 63, pp. 59–95). Springer International Publishing. https://doi.org/10.1007/978-3-319-56928-4_5
- Kemp, K. B., Higuera, P. E., Morgan, P., & Abatzoglou, J. T. (2019). Climate will increasingly determine post-fire tree regeneration success in low-elevation forests, Northern Rockies, USA. *Ecosphere*, 10(1), e02568. <https://doi.org/10.1002/ecs2.2568>
- Parks, S. A., Dobrowski, S. Z., Shaw, J. D., & Miller, C. (2019). Living on the edge: Trailing edge forests at risk of fire-facilitated conversion to non-forest. *Ecosphere*, 10(3), e02651. <https://doi.org/10.1002/ecs2.2651>

REFERENCES - PUGET LOWLANDS

- Andrus, R. A., Peach, L. R., Cinquini, A. R., Mills, B., Yusi, J. T., Buhl, C., Fischer, M., Goodrich, B. A., Hulbert, J. M., Holz, A., Meddens, A. J. H., Moffett, K. B., Ramirez, A., & Adams, H. D. (2023). *Canary in the Forest? – Tree mortality and canopy dieback of western redcedar linked to drier and warmer summer conditions* (p. 2023.01.11.522134). bioRxiv. <https://doi.org/10.1101/2023.01.11.522134>
- Betzen, J. J., Ramsey, A., Omdal, D., Ettl, G. J., & Tobin, P. C. (2021). Bigleaf maple, *Acer macrophyllum* Pursh, decline in western Washington, USA. *Forest Ecology and Management*, 501, 119681. <https://doi.org/10.1016/j.foreco.2021.119681>
- Case, M. J., & Lawler, J. J. (2016). Relative vulnerability to climate change of trees in western North America. *Climatic Change*, 136(2), 367–379. <https://doi.org/10.1007/s10584-016-1608-2>
- Long, J. W., Gray, A., & Lake, F. K. (2018). Recent Trends in Large Hardwoods in the Pacific Northwest, USA. *Forests*, 9(651), Article 10. <https://doi.org/10.3390/f9100651>
- Prichard, S. J., Hessburg, P. F., Hagmann, R. K., Povak, N. A., Dobrowski, S. Z., Hurteau, M. D., Kane, V. R., Keane, R. E., Kobziar, L. N., Kolden, C. A., North, M., Parks, S. A., Safford, H. D., Stevens, J. T., Yocom, L. L., Churchill, D. J., Gray, R. W., Huffman, D. W., Lake, F. K., & Khatri-Chhetri, P. (2021). Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications*, 31(8), e02433. <https://doi.org/10.1002/eap.2433>

REFERENCES - WILLAMETTE VALLEY

- Beckmann, J. J., Sherriff, R. L., Kerhoulas, L. P., & Kane, J. M. (2021). Douglas-fir encroachment reduces drought resistance in Oregon white oak of northern California. *Forest Ecology and Management*, 498, 119543. <https://doi.org/10.1016/j.foreco.2021.119543>
- Copes-Gerbitz, K., Arabas, K., Larson, E., & Gildehaus, S. (2017). A Multi-Proxy Environmental Narrative of Oregon White Oak (*Quercus garryana*) Habitat in the Willamette Valley, Oregon. *Northwest Science*, 91(2), 160–185. <https://doi.org/10.3955/046.091.0207>
- Filipe, J. A. N., Cobb, R. C., Meentemeyer, R. K., Lee, C. A., Valachovic, Y. S., Cook, A. R., Rizzo, D. M., & Gilligan, C. A. (2012). Landscape Epidemiology and Control of Pathogens with Cryptic and Long-Distance Dispersal: Sudden Oak Death in Northern Californian Forests. *PLOS Computational Biology*, 8(1), e1002328. <https://doi.org/10.1371/journal.pcbi.1002328>
- Halofsky, J. E., Peterson, D. L., & Gravenmier, R. A. (2022). *Climate change vulnerability and adaptation in southwest Oregon* (PNW-GTR-995; p. PNW-GTR-995). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.
- Long, J. W., Gray, A., & Lake, F. K. (2018). Recent Trends in Large Hardwoods in the Pacific Northwest, USA. *Forests*, 9(651), Article 10. <https://doi.org/10.3390/f9100651>
- Standiford, R. B., & Purcell, K. L. (2015). *Proceedings of the seventh California oak symposium: Managing oak woodlands in a dynamic world* (p. 579) [Gen. Tech. Rep. PSW-GTR-251]. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. https://www.fs.usda.gov/psw/publications/documents/psw_gtr251/psw_gtr251.pdf
- Swiecki, T. J., & Bernhardt, E. A. (2016). Sudden Oak Death in California. In Paine & F. Lieutier (Eds.), *Insects and Diseases of Mediterranean Forest Systems* (pp. 329–378). Springer International Publishing. https://doi.org/10.1007/978-3-319-24744-1_12

REFERENCES - ADAPTATION

- D'Amato, A. W., B. J. Palik, P. Raymond, K. J. Puettmann, and M. M. Girona. 2023. Building a Framework for Adaptive Silviculture Under Global Change. Pages 359–381 *in* M. M. Girona, H. Morin, S. Gauthier, and Y. Bergeron, editors. *Boreal Forests in the Face of Climate Change: Sustainable Management*. Springer International Publishing, Cham.
- Donato, D. C., J. S. Halofsky, and M. J. Reilly. 2020. Corraling a black swan: natural range of variation in a forest landscape driven by rare, extreme events. *Ecological Applications* 30:e02013.
- Hagmann, R. K., P. F. Hessburg, R. B. Salter, A. G. Merschel, and M. J. Reilly. 2022. Contemporary wildfires further degrade resistance and resilience of fire-excluded forests. *Forest Ecology and Management* 506:119975.
- Halofsky, J. E., and D. L. Peterson. 2017. Climate change vulnerability and adaptation in the Blue Mountains region. Page 331. Gen. Tech. Rep. PNW-GTR-939, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Halofsky, J. E., D. L. Peterson, S. K. Dante-Wood, L. Hoang, J. J. Ho, and L. A. Joyce. 2018a. Climate change vulnerability and adaptation in the Northern Rocky Mountains. Part 1. Pages 1–273. Gen. Tech. Rep. RMRS-GTR-374, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Halofsky, J. E., D. L. Peterson, and J. J. Ho. 2019. Climate change vulnerability and adaptation in south-central Oregon. Page PNW-GTR-974. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Halofsky, J. S., D. C. Donato, J. F. Franklin, J. E. Halofsky, D. L. Peterson, and B. J. Harvey. 2018b. The nature of the beast: examining climate adaptation options in forests with stand-replacing fire regimes. *Ecosphere* 9:e02140.
- Larson, A. J., S. M. A. Jeronimo, P. F. Hessburg, J. A. Lutz, N. A. Povak, C. A. Cansler, V. R. Kane, and D. J. Churchill. 2022. Tamm Review: Ecological principles to guide post-fire forest landscape management in the Inland Pacific and Northern Rocky Mountain regions. *Forest Ecology and Management* 504:119680.
- Palik, B. J., P. W. Clark, A. W. D'Amato, C. Swanston, and L. Nagel. 2022. Operationalizing forest-assisted migration in the context of climate change adaptation: Examples from the eastern USA. *Ecosphere* 13:e4260.
- Prichard, S. J., P. F. Hessburg, R. K. Hagmann, N. A. Povak, S. Z. Dobrowski, M. D. Hurteau, V. R. Kane, R. E. Keane, L. N. Kobziar, C. A. Kolden, M. North, S. A. Parks, H. D. Safford, J. T. Stevens, L. L. Yocom, D. J. Churchill, R. W. Gray, D. W. Huffman, F. K. Lake, and P. Khatri-Chhetri. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications* 31:e02433.
- Schuurman, G. W., D. N. Cole, A. E. Cravens, S. Covington, S. D. Crausbay, C. H. Hoffman, D. J. Lawrence, D. R. Magness, J. M. Morton, E. A. Nelson, and R. O'Malley. 2022. Navigating Ecological Transformation: Resist–Accept–Direct as a Path to a New Resource Management Paradigm. *BioScience* 72:16–29.
- Sohn, J. A., S. Saha, and J. Bauhus. 2016. Potential of forest thinning to mitigate drought stress: A meta-analysis. *Forest Ecology and Management* 380:261–273.

Tomback, D. F., R. E. Keane, A. W. Schoettle, R. A. Sniezko, M. B. Jenkins, C. R. Nelson, A. D. Bower, C. R. DeMastus, E. Guiberson, J. Krakowski, M. P. Murray, E. R. Pansing, and J. Shamhart. 2022. Tamm review: Current and recommended management practices for the restoration of whitebark pine (*Pinus albicaulis* Engelm.), an imperiled high-elevation Western North American forest tree. *Forest Ecology and Management* 522:119929.

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SHRUB AND GRASSLAND ECOSYSTEMS



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Photo: Shrub grass ecosystem in western Washington. Credit: Emily Fusco

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SHRUBLAND AND GRASSLAND ECOSYSTEM DESCRIPTION

Shrubland and grassland ecosystems cover a broad area of the Northwest (NW). The environmental conditions and vegetation communities of these ecosystems are diverse and consist largely of dry-climate systems limited by water availability. The terminology associated with dryland ecosystems is also diverse and includes shrublands and grasslands, steppe, shrub, scrub, scrubland, chaparral, shrubsteppe, sagebrush steppe, cold upland deserts, cold desert shrublands, hot desert shrublands, salt desert shrubland, and cold semi-arid deserts. Each ecosystem has nuanced differences largely a product of topography, geography, and prevailing local climatic conditions.

Shrublands exist along a climatic continuum, encompassing arid to semi-arid climates with heterogeneous patches of shrubby vegetation and exposed substrates (Figure 1) (Brown et al. 2022). Shrubland plant communities are typically well-adapted to arid climates and can be characterized by a stable or mature vegetation type, or they can be a transitional community. Shrublands are typically defined as lands with shrub plant cover – woody/shrubby perennial vegetation – but other plants in these ecosystems include grasses, herbaceous vegetation, subshrubs, and forbs. Many species of sagebrush (*Artemisia* spp.) are native to semi-arid or arid shrublands. Mountain big sagebrush (*A. t. ssp. vaseyana*) is typically found at high-elevations where annual precipitation and snowfall are higher. Basin big sagebrush (*A. t. ssp. tridentata*) occurs at the low elevations in warmer areas. Wyoming big sagebrush (*A. t. ssp. wyomingensis*) occurs at intermediate elevations and overlaps with mountain and Wyoming big sagebrush. Grasslands refer to open areas dominated by homogenous grasses with few shrubs or trees (Figure 2) (Brown et al. 2022).

Shrubland and grassland systems develop under drier prevailing environmental conditions and have comparatively lower biomass than forested systems (Cartwright et al. 2020). Precipitation variability and seasonal temperature greatly affect these ecosystems where

CLIMATE EFFECTS: SHRUB AND GRASSLAND ECOSYSTEMS OVERVIEW

productivity is limited by water availability (Palmquist et al. 2016, 2021, Bradford et al. 2020). Environmental conditions affect ecosystem resilience, resistance, and vegetation type changes, with implications for native and invasive non-native species occurrence and competition (Chambers et al. 2017, Roundy et al. 2018, Bishop et al. 2020).

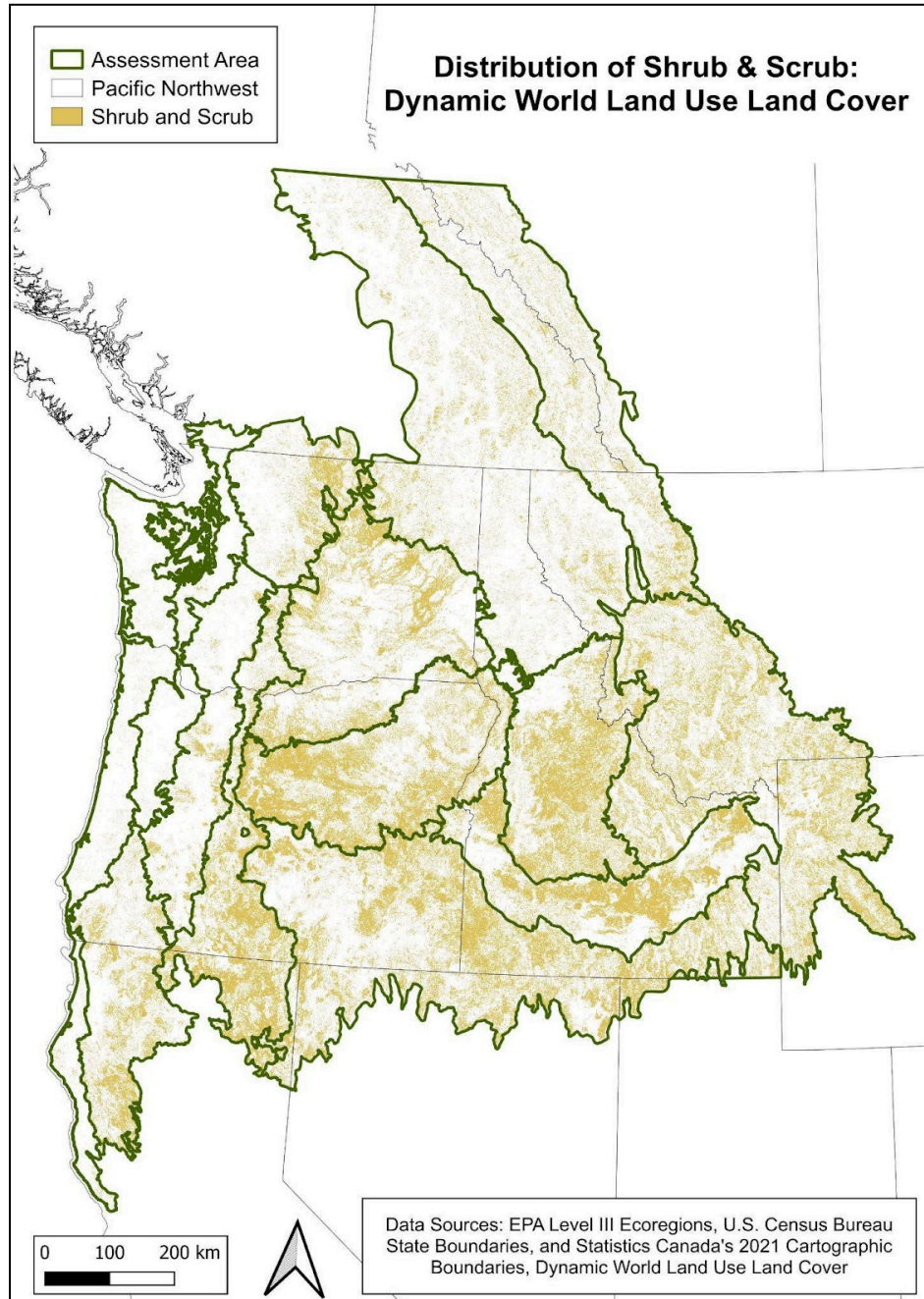


Figure 1. Shrubland distribution across ecoregions of the Northwest.

INTERACTION OF CLIMATE CHANGE AND ECOSYSTEM STRESSORS

Shrubland and grassland ecosystems have high conservation value for biodiversity and provide critical ecosystem services, such as soil erosion mitigation, carbon sequestration, pasture for livestock, and cultural services and values (Friggens et al. 2012, Maestre et al. 2016). For example, climate-induced ecosystem stressors are expected to threaten sagebrush ecological integrity (Doherty et al. 2022). Interactions between climate stressors and disturbances, such as wildfire and invasive grasses, are expected to further threaten native species in shrublands and grasslands.

DIRECT EFFECTS OF CLIMATE CHANGE

Changes in the climate, including rising temperatures, changing precipitation patterns, and elevated atmospheric carbon dioxide (CO₂) (Huang et al. 2016), will affect dryland ecosystems. Temperatures are projected to increase across dryland ecosystems in the NW. Precipitation form, seasonal timing, and seasonal amount are also expected to change; although projections of precipitation are less certain than projections of temperature (see Climate Overview).

Figure 2. Grass vegetation type is distributed across Northwest ecoregions.



Shrubland and grassland ecosystems demonstrate variable and species-specific sensitivity to the direct effects of higher temperatures and changes in precipitation, with consequences for plant diversity and the distribution and abundance of species.

- Higher annual and growing season temperatures are expected to directly affect big sagebrush. Growing season temperatures above 22° C have been documented to negatively affect growth rates (Kleinhesselink and Adler 2018). The number of hot days and days with maximum temperatures greater than 34°C have been documented to negatively affect germination and seedling success, particularly at the edge of the range (Schlaepfer et al. 2015).
- Higher temperatures are expected to decrease big sagebrush cover, growth, and recruitment in the warmest areas and southern edge of the range, while increasing them in cooler north and high-elevation areas of the range (Renwick et al. 2018, Schlaepfer et al. 2015, Kleinhesselink and Adler 2018).

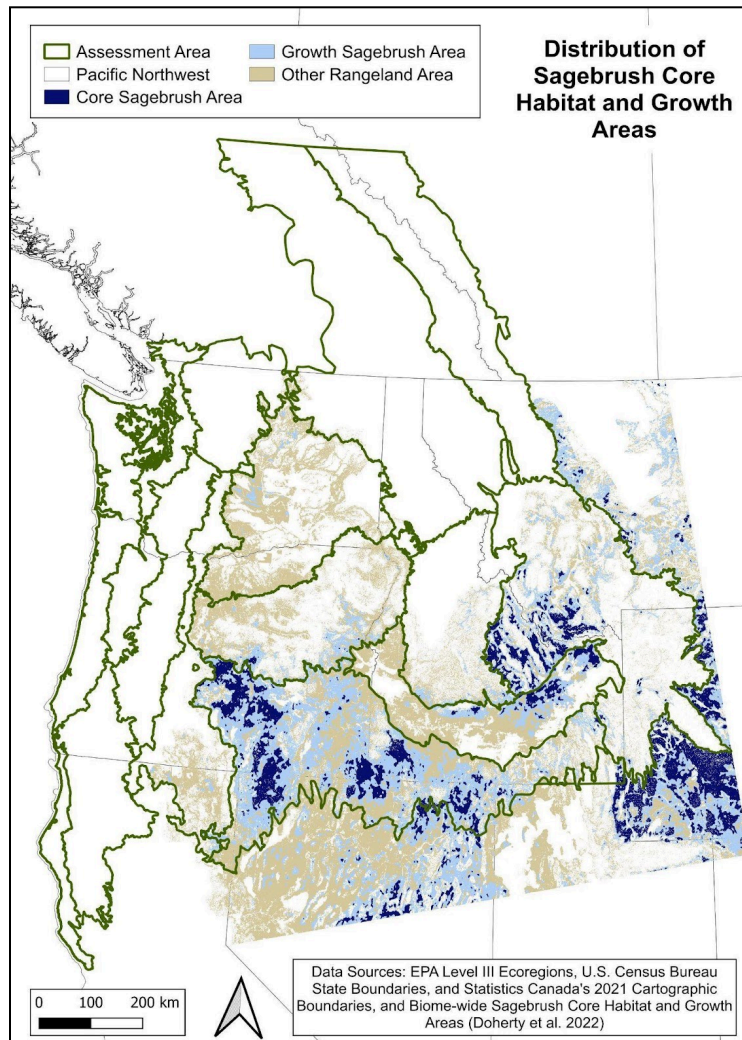


Figure 3. The distribution of sagebrush core and growth habitat areas across the Northwest ecoregions

- Sagebrush distribution and abundance may be more strongly affected by changes in temperature than by changes in precipitation (Kleinhesselink and Adler 2018, Renwick et al. 2018), although this is still uncertain (Still and Richardson et al. 2015).
- Subspecies of big sagebrush are defined by different climatic niches (Still and Richardson 2015), so they are expected to respond differently to climate change (Kleinhesselink and Adler 2018). For example, big sagebrush subspecies vary in their responses to freezing temperatures and freezing resistance mechanisms (Lazarus et al. 2019). Mountain big sagebrush is more susceptible to freezing temperatures than Wyoming big sagebrush, contrary to expectation (Brabec et al. 2017, Kleinhesselink and Adler 2018). Wyoming big sagebrush has greater freezing resistance and is comparatively better adapted to cold temperatures and drought relative to other sagebrush subspecies (Brabec et al. 2017, Kleinhesselink and Adler 2018).

Higher temperatures and elevated atmospheric CO₂ concentrations are expected to affect C₃ and C₄ photosynthetic pathways in different ways, likely favoring C₄ plants.

- C₃ (Calvin cycle) and C₄ (Hatch-Slack cycle) photosynthesis are two pathways used by plants to fix atmospheric CO₂ and produce glucose. These pathways influence a plant's ability to withstand high temperatures, low water and nitrogen availability, and high atmospheric CO₂ concentrations. Because of these differences, C₃ and C₄ grasses are expected to respond to climate change differently (Havrilla et al. 2023). Most plants in temperate ecosystems are C₃ plants. Only grasslands comprise C₃ (cool-season) and C₄ (warm-season) plants.
- In the short term, C₃ grasses are expected to benefit from greater precipitation variability, particularly in cool seasons. In the long term, rising temperatures and precipitation variability are expected to favor C₄ grasses because of their higher tolerance of water stress, high temperature extremes, and low nitrogen availability.
- Climate suitability for warm season grasses is expected to increase, shifting from suitability for C₃ toward C₄ species and increasing the likelihood that C₄ grasses will replace C₃ grasses where C₃ species abundance declines (Palmquist et al. 2021, Havrilla et al. 2023).
- Model projections of perennial grass abundance with climate change indicate that C₃ abundance will decrease across NW grasslands, and C₄ abundance will increase, particularly at higher-latitudes (Havrilla et al. 2023).
- Projected shifts in C₃ and C₄ plant distribution would cause reorganization of vegetation communities with subsequent impacts on wildlife and grazing systems that are widespread in the area (Havrilla et al. 2023).
- The larger and more certain projected changes in temperature are expected to affect both C₃ and C₄ grasses more than the smaller and less certain projected changes in precipitation (see Climate Overview).

Changes in vegetation phenology can influence the carbon balance of dryland ecosystems and synchrony with interacting species.

- Climate change is expected to alter grass phenology, with shifts towards earlier spring emergence and later autumn senescence (Hufkens et al. 2016).
- Higher spring temperatures and earlier snowmelt are causing first-flowering to occur earlier in montane sagebrush communities, including earlier blooming of early-spring flowers, mid-summer flowers, berry-producing shrubs, and nonnative species (Bloom et al. 2022).
- Peak yield dates for herbaceous vegetation in sagebrush systems are strongly affected by annual climatic variability, and changes in spring precipitation and reference evapotranspiration may have the greatest effect (Bates et al. 2023).

Higher temperatures and associated declines in snowpack depth and duration in high- and mid-elevation shrublands will have implications for ecosystem services and species functions.

- Long, cold, and wet winters, with abundant winter snowpack, have been documented to be important for maintaining annual carbon uptake and carbon balance in some semiarid ecosystems (Yao et al. 2022), although how consistent this finding is across sagebrush ecosystems in the region is unknown.
- Winter snowpack is a key driver of water availability in dryland ecosystems and because of this, changes in snowpack are expected to greatly influence how carbon cycling in dryland ecosystems responds to climate change (Yao et al. 2022).
- Shallower snowpack depth and less snow cover are expected to affect soil respiration in sagebrush systems in the winter and early spring growing seasons. Total soil respiration is expected to decrease with declining snowpack due to higher temperatures, but it remains unknown how higher temperatures may directly affect soil respiration (Tucker et al. 2016).
- Decreasing snowpack depth and duration are expected to favor populations of cheatgrass at mid-elevational sites (Smull et al. 2019).

Sensitivity to drought varies greatly among dryland ecosystems in the NW (Cartwright et al. 2020) with variation in current climate and water availability, elevation, topography, and soil characteristics. Assessing drought impacts in these ecosystems continues to be challenged by defining and measuring ecologically relevant drought metrics, as well as uncertain projections for changes in precipitation (See Climate Overview).

- At regional scales, shrubland and grassland ecosystems in the NW are more sensitive to drought than are forested ecosystems and show less evidence of drought refugia in valleys and riparian areas, likely due to the prevalence of intermittent streams (Cartwright et al. 2020).
- Shrubland and grassland drought sensitivity is influenced by climate, as well as topographic features and soil characteristics that affect water availability (Bradford et al. 2020, Cartwright et al. 2020).

CLIMATE EFFECTS: SHRUB AND GRASSLAND ECOSYSTEMS OVERVIEW

- Generally drier ecosystems are more sensitive to productivity losses due to drought (Smith et al. 2024). However, this varies greatly within ecosystems. In the NW, cold, upland shrub-steppe communities appear to be more sensitive to drought despite higher water availability (Cartwright et al. 2020).
- Drought stress associated with combined high temperatures and low soil moisture is expected to increase in many areas of dryland ecosystems in the NW, despite variation in precipitation projections for this region (Bradford et al. 2020), which may affect plant mortality and productivity as has been documented for plants in other vegetation types (Breshears et al., 2018).
- Climate change effects on the ecohydrology of sagebrush systems will include longer, drier summer soil conditions because of increased evaporative demand and changes in the dynamics of soil water recharge. Along with warming, these factors may affect sagebrush regeneration and cause range shifts, especially if winter precipitation cannot offset drier summer conditions (Bradford et al. 2014, Schlaepfer et al. 2012, Schlaepfer et al. 2015, Palmquist et al. 2021).

The time and spatial scales over which drought occurs will shift with climate change. Shorter duration droughts over smaller areas are likely to become more important for understanding and managing drought responses at the species, community, and ecosystem level.

- Climate models project changes that are relevant for seasonal and annual drought; fine-scale variation in daily environmental conditions will become increasingly important (Cartwright et al. 2020, Applestein et al. 2021), with ecological drought being relevant in terms of days, not just months to years (O'Connor et al. 2020).
- Small-scale and short-duration changes in temperature and water availability are expected to contribute to vegetation shifts (O'Connor et al. 2020), such as from native perennial shrublands to invasive annual grasses (Bishop et al. 2020). These changes are evident across the sagebrush-dominated Great Basin where daily soil water availability in early spring is vital for native plant germination, emergence and establishment (James et al. 2019, O'Connor et al. 2020).

CLIMATE CHANGE EFFECTS ON FIRE REGIMES IN GRASSLANDS AND SHRUBLANDS

Higher temperatures and changes in precipitation patterns will interact to alter fire regimes, the distribution of invasive non-native species, and their interactions in shrubland and grassland ecosystems. Biomass and fuel availability are low in these ecosystems relative to forest ecosystems (Cartwright et al. 2020), but fire frequency and size have increased in recent decades, especially in areas heavily invaded by non-native grasses (Balch et al. 2013).

Climate change is expected to increase the frequency of climatic conditions that are conducive to fire and invasive grass species, while reducing the climatic conditions that are favorable for post-fire recovery of native species.

CLIMATE EFFECTS: SHRUB AND GRASSLAND ECOSYSTEMS OVERVIEW

- Fire activity varies greatly across grassland and shrubland ecosystems in the NW associated with local variability in climate. The probability of fire is greater in areas with a low proportion of annual precipitation in summer, intermediate precipitation amounts, and higher temperatures (Holdrege et al. 2024).
- Higher temperatures and changes in precipitation amount and variability are expected to increase the frequency of climatic conditions that support fire ignition and spread, while lengthening the fire season (Abatzoglou and Kolden 2011).
- Projected climate-driven changes in fire activity in shrubland and grassland ecosystems suggest that fire return intervals will increase (i.e. fire frequency will decrease), but changes in fire severity are variable and less certain (Parks et al. 2018). However, interactions with changes in vegetation and fuel abundance are critical for understanding how changes in the climate will affect future fire regimes in these ecosystems where fire is limited by fuel availability.
- As water-limited ecosystems, shrublands and grasslands are especially vulnerable to drought (Breshears et al. 2016, Smith et al. 2024) and its effect on post-fire recovery of native species.

More frequent and severe fire reduces the extent of sagebrush and associated habitat and biodiversity, although the effects of changing fire regimes on individual sagebrush subspecies is still unknown.

- Sagebrush is sensitive to fire. For example, in low-elevation sites, a single fire can alter vegetation composition and accelerate conversion from a shrub-dominated system to a system of invasive annual grasses (Mahood and Balch 2019).
- Repeat burns in sagebrush communities can have long-lasting effects, including reduced species richness and diversity (Mahood and Balch 2019).
- In low-elevation Wyoming big sagebrush systems, individual and repeated fires reduce species richness and diversity (Mahood and Balch 2019). Higher temperatures impede Wyoming big sagebrush post-fire recovery, whereas cooler, wetter conditions favor sagebrush resilience (Mahood and Balch 2019).
- More frequent and severe fire can inhibit post-fire recovery of sagebrush and favor establishment of invasive non-native species through decreased plant competition (Innes and Zouhar 2018).
- Shifts in the seasonality of fire have species-specific effects, as the phenology at the time of the fire is relevant to recovery (Ruckman et al. 2012). The stages from seed ripening to germination are particularly sensitive (Stavi 2019). Warm-season grasses benefit more from spring burning relative to cool-season grasses, and forbs benefit more from fall burning (Roundy et al. 2018).

CLIMATE CHANGE EFFECTS ON INVASIVE GRASSES AND FUELS

Higher temperatures are expected to increase the climate suitability for invasive annual grasses. Wetter winters and springs have direct effects on the distribution and abundance of invasive grasses. However, projected changes in precipitation magnitude and seasonality remain less certain than changes in temperature (See Climate Overview).

- Cooler soil temperatures and wetter soils promote sagebrush ecosystem resilience and resistance, whereas warmer, drier soil conditions favor cheatgrass occurrence and dominance (Roundy et al. 2018).
- Habitat suitability for invasive annual grasses is most likely to increase at higher elevations and at the northern edge of its current invaded range (Bradley et al. 2016, Smith et al. 2022, Terry 2023, Harris et al. 2024).
- Invasive annual grass expansion is expected to be faster on hot, dry south-facing aspects, but also increasingly on cooler north-facing aspects (Smith et al. 2022).
- Higher temperatures will reduce snowpack (See Hydrology Overview and Ecoregion Summaries), which is expected to favor cheatgrass survival, establishment, and growth at mid-elevations in non-drought conditions (Compagnoni and Adler 2014b, 2014a, Bradley et al. 2016, Smull et al. 2019).
- Interannual variability and timing of precipitation are associated with cheatgrass presence and abundance (Boyte et al. 2016, Williamson et al. 2020), with preceding wet years favoring cheatgrass growth and abundance (Pilliod et al. 2017).
- Cheatgrass is favored by high precipitation during the late winter and early spring growing season and is negatively affected by drought during the fall germination season (Bradley et al. 2016). In contrast, precipitation later in fall is more likely to favor native plant competition with cheatgrass and areas with high summer precipitation are less likely to experience cheatgrass invasion (Bradley et al. 2009, Williamson et al. 2020).

Invasive grasses will likely contribute to altered fire regimes due to increased continuity and biomass of fine fuels, especially after wetter years, which together facilitate fire spread.

- Invasive annual grasses are associated with changes in fire regimes, including greater fire probability, shorter fire return intervals, increased risk of larger fires, and earlier fire seasonality Balch et al. 2013, (Bradley et al. 2018, Davies et al. 2021).
- Abundant spring precipitation promotes the growth of fine fuels in the form of invasive annual grasses (e.g., cheatgrass). Live fuel from one growing season becomes dead fuel at the end of the season and can persist into the next year unless removed by fire or grazing (Li et al. 2020).
- More fine fuel increases the probability of fire, particularly when a wet period is followed by abnormally dry seasons or years (Pilliod et al. 2017). This lag effect means that successive wet years followed by a dry year increase fuels and the potential for fire.

- More continuous fine fuel increases the size and severity of fires in shrubland and grassland ecosystems (Li et al. 2020).
- Increased biomass of fine fuels characterized by shallow root systems may also increase soil temperature relative to sagebrush habitats and decrease soil moisture (Balch et al. 2013).
- Precipitation and drought are critical drivers of vegetation recruitment and restoration success following fire, particularly in determining whether an area will re-established with native perennial species, or whether invasive non-native annual grasses will dominate post-fire, further contributing to the grass-fire cycle (James et al. 2019, O'Connor et al. 2020).

VEGETATION TYPE CONVERSION AND HABITAT FRAGMENTATION

Climate stressors will likely drive the contraction and expansion of vegetation types, habitat fragmentation, and vegetation type conversion in grassland and shrubland ecosystems.

- Current climate conditions are favorable for the expansion of both invasive annual grasses and native conifers, such as juniper (*Juniperus* spp.) and pinyon (*Pinus* spp.), into shrubland communities, and expected changes in the climate have the potential to accelerate expansion rates (Young et al. 2023).
- Due to native tree expansion, absolute tree cover in rangelands across the U.S. increased by about 50% between 1990 and 2019 (Morford et al. 2022). More precipitation during the wet season and longer growing seasons are expected to accelerate the expansion of native tree and woody plant species into shrublands and grasslands (Morford et al. 2022).
- Higher temperatures and more precipitation during the wet season are expected to cause a contraction of sagebrush distribution, as warm-desert vegetation expands northward and woody plant communities expand down in elevation (Schlaepfer et al. 2012, Palmquist et al. 2021). If precipitation decreases, warm-desert vegetation may still encroach from the south, but woody plant species may instead move up in elevation (Neilson et al. 2005).
- Woody plant and tree encroachment alter the structure and function of shrubland and grassland systems by increasing habitat fragmentation, reducing habitat quality, and altering herbaceous forage production (Morford et al. 2022).

INTERACTIONS BETWEEN CLIMATE-RELATED STRESSORS AND OTHER HUMAN-CAUSED STRESSORS

Climate change stressors will interact with existing human-induced stressors to contribute to shrubland and grassland fragmentation and reduced connectivity, with consequences for biodiversity and ecosystem services (Chambers et al. 2017).

- Human-induced stressors other than climate change, include livestock grazing (Roundy et al. 2018), conversion to agriculture (Knight et al. 2016), urban and

exurban development (Radeloff et al. 2023), energy development, and resource extraction (Chambers et al. 2017).

- Human-induced stressors will have interactive and synergistic effects with climate-induced stressors (Williamson et al. 2020, Requena-Mullor et al. 2023). For example, human-caused fire ignitions are strongly associated with cheatgrass spread and abundance, which further threatens native dryland species (Bradley et al. 2018).
- Invasive grass establishment and spread are accelerated by fire, but fire mechanisms do not exclusively drive these processes. Other factors facilitate grass invasion, such as improperly managed grazing and increasing recreational use of public lands associated with human population growth (Smith et al. 2023).

AREAS FOR FUTURE RESEARCH

- Key native species, primarily sagebrush and the greater sage-grouse, are often the focus of research on climate change in shrublands (Rottler et al. 2015). The effects of climate change on other sagebrush-obligate species, and shrubland and grassland flora and fauna broadly, are still less well studied (Rottler et al. 2015).
- More research is needed on how changes in plant phenology will indirectly affect potential migration rates of species that depend on the timing of plant green-up. For example, changes in plant phenology due to drought may alter temporal availability of forage and habitat, affecting the timing of migration for ungulates (Aikens et al. 2020) and nesting for sage grouse (Stoner et al. 2020).
- More research is needed to explore the influence of CO₂ on enhancing water use efficiency and mitigating drought stress in plants. Modeling of changes in species abundance often does not explicitly include the effects of higher atmospheric CO₂ concentrations on C₃ and C₄. Experiments from other regions suggest that elevated atmospheric CO₂ will favor C₃ species by reducing transpiration rates, improving water use efficiency, and increasing carbon fixation rate (Morgan et al. 2004).
- Understanding how shrubland and grasslands will respond to changes in the climate is complicated by the effects of interacting disturbances, such as erosion (Shi et al. 2018, Boyte et al. 2020). Soil erosion by water is expected to increase landscape vulnerability across shrublands and grasslands, yet the mechanisms and interactions of how climate change will affect wind erosion across these systems are less well understood (Bradford et al. 2014, Edwards et al. 2019).
- Changes in disturbances may have opposite or reinforcing effects on dryland systems compared to changes in the climate alone. For example, climate models project no change in cheatgrass and declines in sagebrush in the southern NW (Zimmer et al. 2021), but more frequent fire is expected to favor cheatgrass and reduce sagebrush. Consideration of changes in the climate, disturbances, and their interactions are necessary to understand future conditions (Schlaepfer et al. 2021).

CLIMATE EFFECTS: SHRUB AND GRASSLAND ECOSYSTEMS OVERVIEW

- More research is needed on how climate change will affect invasive species dynamics and phenology. For example, accurately modeling cheatgrass cover across large areas remains challenging due to difficulties in differentiating cheatgrass from other annual grasses using remote imagery techniques (Bradley et al. 2018).
- In sagebrush ecosystems, research on invasive annual grasses has focused heavily on cheatgrass. Further research is needed to understand the effects of climate change on less ubiquitous invasive grasses that may become greater threats in the future (McMahon et al. 2021).

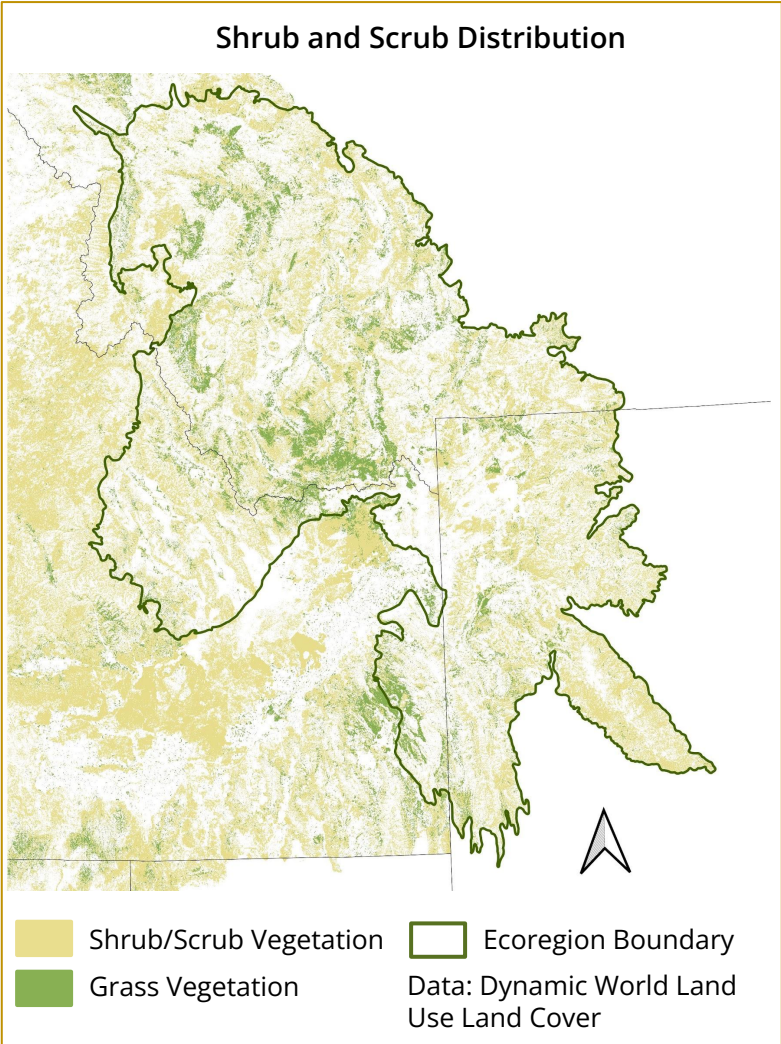
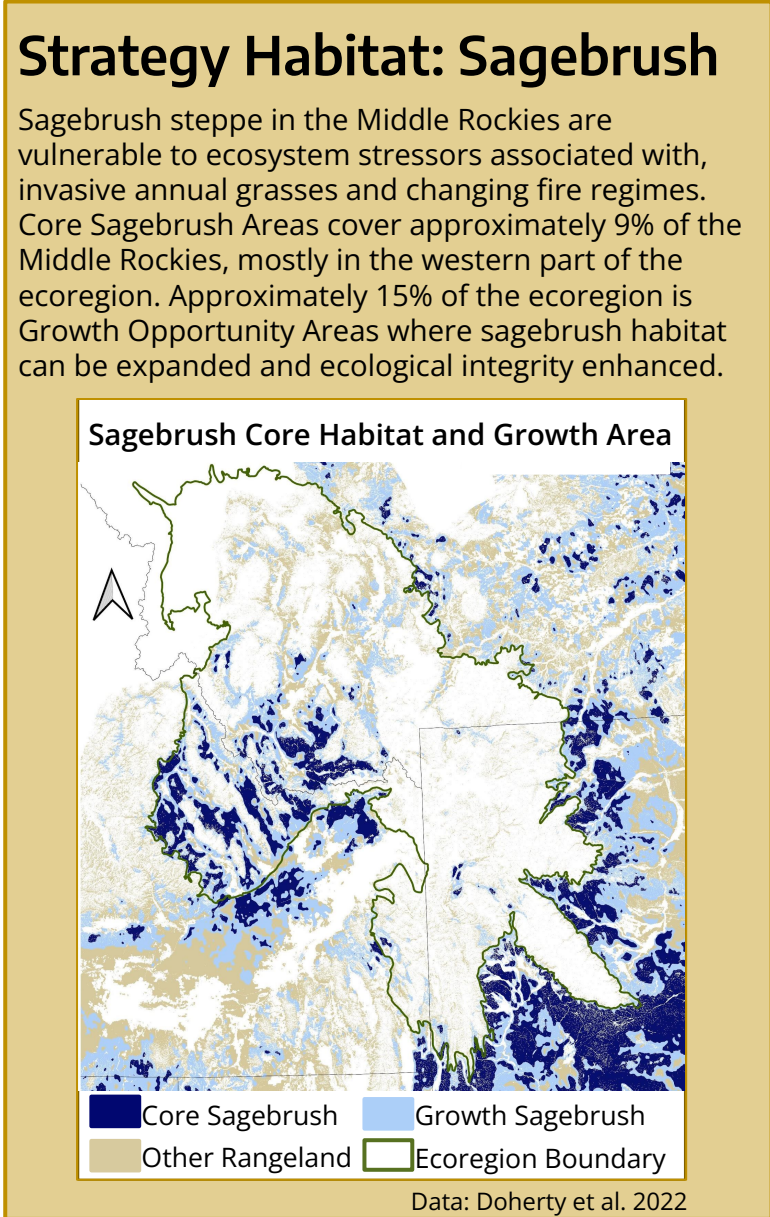
Middle Rockies

Shrub and Grassland Ecosystems



Regional Description

In the Middle Rockies ecoregion, shrublands and grasslands are in the intermontane valleys and foothills. The broad intermountain basins of the Middle Rockies are dominated by arid grasses, shrub and scrub. Sagebrush species (*Artemisia* spp.) are the dominant vegetation, along with rabbitbrush (*Chrysothamnus viscidiflorus*), and serviceberry (*Amelanchier arborea*). Common grass species include wheatgrass (*Eremopyrum* spp.), needlegrass (*Nassella* spp.), and grama grass (*Bouteloua* spp.).



Shrub and scrub cover approximately 29% of the Middle Rockies; grass covers approximately 10%. In the Northwest, the Middle Rockies ecoregion has the highest percentage of grass cover, similar only to southeast Idaho.

Management Considerations

- Timber harvest, recreation, and agriculture are three of the most common land uses in the Middle Rockies ecoregion.
- In the intermontane valleys, agricultural production includes managed pasture lands, hay fields, and irrigated alfalfa.
- Cattle and sheep grazing occur year-round both in the valleys and open sites at higher elevations during summer seasons.

Middle Rockies Shrub and Grassland Ecosystems



Managing Ecosystem Stressors



Changing Fire Regimes

Description

Fire activity in sagebrush systems is linked to abundant winter and spring precipitation that increases grass biomass and fire potential in the following season when grasses cure and become available as fine fuels. Fire return intervals that were decades to centuries historically have become more frequent in areas with invasive grasses, yet sagebrush resilience to fire is low. Fire frequency is also expected to increase with continued climate change as more winter and spring precipitation increases grass production and hotter, drier summers increase fire potential (Abatzoglou and Kolden 2011).

Management Actions

- Strategically using fuel breaks in fire-prone sagebrush steppe can aid fire management. However, mitigation efforts may be necessary to reduce the detrimental effects that fuel breaks can have by fragmenting habitat and facilitating the spread of invasive grasses to new areas (Shinneman et al. 2019).
- Increase monitoring of the effectiveness of fuel treatments in sagebrush steppe to continue to refine the best approaches for these ecosystems.
- Increase community engagement and public outreach efforts focused on reducing human-caused ignitions.



Invasive Annual Grasses

Description

The invasive annual grass-fire cycle is expected to intensify with climate change, substantially affecting native shrubland and grassland ecosystems. The resilience of sagebrush ecosystems to changes in the climate is reduced by the detrimental effects of invasive annual grasses, such as cheatgrass and ventenata. These introduced grasses outcompete native vegetation and increase fuel continuity, perpetuating the invasive grass-fire cycle (Fusco et al. 2022) and accelerating conversion from sagebrush to invasive grass-dominated systems.

Management Actions

- Targeted management of invasive species to reduce fine fuels, such as mowing, herbicide application, and grazing can slow the invasive annual grass-fire cycle.
- Prioritize the protection and enhancement of native vegetation in remaining intact sagebrush core habitat areas (Doherty et al. 2022).
- Identify new areas of invasive species establishment through Early Detection and Rapid Response (EDRR). Tracking shifts in the range of invasive grasses can help prioritize areas for prevention and control (McMahon et al. 2021).



Sagebrush at the Yankee Jim Interpretive Trail at the Custer Gallatin National Forest. Credit: USDA Forest Service photo taken in 2023 by Jeremy Zimmer.

Northern Basin and Range Shrub and Grassland Ecosystems



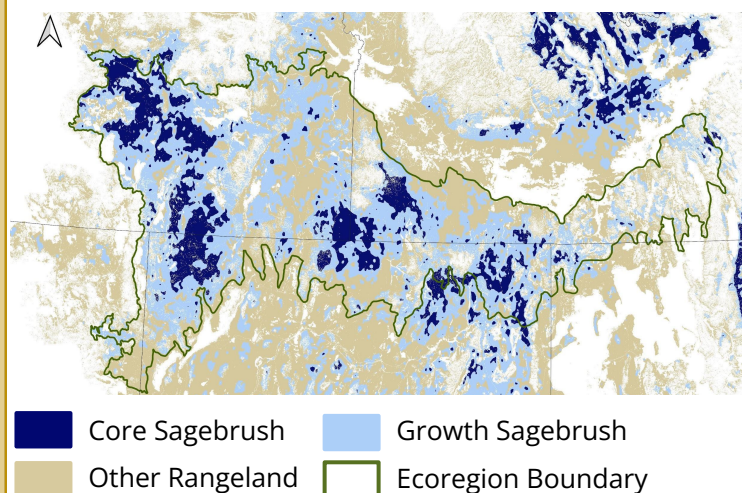
Regional Description

Forming part of the northern Great Basin, the Northern Basin and Range ecoregion is characterized by isolated mountain ranges and flat basins and valleys with varied elevation, soil characteristics, and precipitation patterns. Examples of common, dominant vegetation include mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*), Wyoming big sagebrush (*A. t.* ssp. *wyomingensis*), bluebunch wheatgrass (*Pseudoroegneria spicata*), rabbitbrush (*Ericameria nauseosa*), and Idaho fescue (*Festuca idahoensis*).

Strategy Habitat: Sagebrush

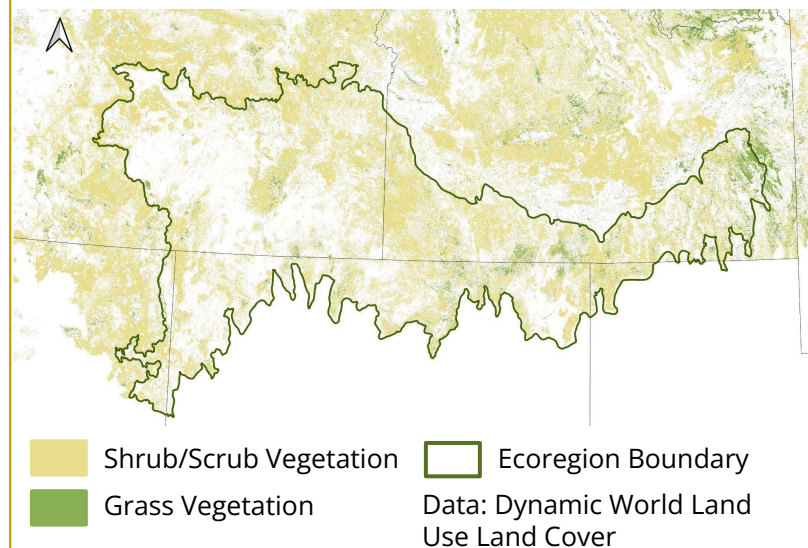
Sagebrush steppe is an important habitat in the Northern Basin and Range that is vulnerable to ecosystem stressors associated with climate change, including higher temperatures, invasive species, and land management practices. Core Sagebrush Areas cover approximately 75% of the Northern Basin and Range and are especially concentrated in the western portion of the ecoregion. Within the NW, sagebrush habitat ecological integrity is highest in this ecoregion. The Northern Basin and Range also has extensive, dispersed Growth Opportunity Areas with moderate to high ecological integrity due to higher coverage of annual grasses and conifers.

Sagebrush Core Habitat and Growth Area



Data: Doherty et al. 2022

Shrub and Scrub Distribution



Shrub and scrub cover approximately 33% of the Northern Basin and Range, while grass only covers approximately 3%.

Management Considerations

- The predominant land use in the Northern Basin and range ecoregion is livestock grazing. Overgrazing modifies fire regimes, reduces native plant community cover, and contributes to greater coverage of invasive grasses.

Future Research Areas

- Direct effects of climate change on different subspecies of sagebrush, such as differences in how changes in precipitation amount and timing will affect the distribution and abundance of subspecies
- Effectiveness of fuel breaks in fire-prone sagebrush ecosystems and potential tradeoffs with invasive species spread and habitat fragmentation
- Effectiveness of sagebrush restoration approaches and impacts on native biodiversity and sagebrush dependent species, such as the conditions under which sagebrush seeding is successful given cheatgrass prevalence, fire activity, and agricultural conversion (Schlaepfer et al. 2021)

Northern Basin and Range Shrub and Grassland Ecosystems



Managing Ecosystem Stressors



Changing Fire Regimes

Description

Fire activity in sagebrush systems is linked to abundant winter and spring precipitation that increases grass biomass and fire potential in the following season when this biomass cures and becomes available as fine fuels. Fire frequency is expected to increase with climate change as more winter and spring precipitation increases grass production and hotter, drier summers further increase fire potential (Abatzoglou and Kolden 2011). Fire regimes are changing. Historical fire return intervals of multiple decades to centuries between fires are shifting to much more frequent fires, yet sagebrush resilience to frequent fire is low.

Management Actions

- Increase monitoring of fuel treatment effectiveness and the effects on sagebrush restoration, biodiversity and sagebrush-obligate species to better understand potential tradeoffs.
- Livestock grazing at moderate to high intensities during appropriate seasons can be a beneficial wildfire management tool to reduce fuels in native-dominated shrub systems (Orr et al. 2022). The effects of grazing are site and context specific and depend on environmental conditions and management objectives. Grazing can increase cheatgrass (Williamson et al. 2020), so grazing as a wildfire management tool requires mitigating the potential to facilitate invasive grasses.



Invasive Annual Grasses

Description

The effects of climate change on the persistence and resilience of sagebrush are driven by the detrimental effects of invasive annual grasses, such as cheatgrass, that benefit from climate change. Introduced cheatgrass outcompetes native vegetation and increases fuel continuity, which perpetuates the invasive grass-fire cycle (Fusco et al. 2022) and accelerates conversion from sagebrush steppe to invasive grass-dominated landscapes. Cheatgrass is pervasive in the region (Hak and Comer 2022).

Management Actions

- Management actions to reduce invasive grasses depend on current ecosystem condition and whether they are core areas, growth areas, or other rangeland (USDA, 2020).
- Defend core areas of high ecological integrity with management aimed at protecting remaining sagebrush and previous restoration investments (Doherty et al. 2022).
- Control, slow, and reduce invasive grass spread with management including mowing, herbicide application, and grazing. Prioritize areas proximal to development (Bradley et al. 2018).



Juniper Encroachment

Description

In colder, wetter areas of the sagebrush range, juniper encroachment threatens sagebrush prevalence and extent with associated reductions in habitat quality for species that depend on the less dense vegetation provided by shrub and grassland habitats. In these areas, fire was more frequent prior to fire exclusion and abundant livestock grazing that reduced fine grass fuels. Warmer winter temperatures and more winter precipitation have also favored juniper growth and contributed to juniper encroachment into these sagebrush ecosystems.

Management Actions

- Reduce juniper expansion through targeted removal with mechanical treatments (cutting and chipping) in core and growth sagebrush areas, especially before juniper woodlands become established.
- Prescribed fire can be used to control young juniper. However, prescribed fire may not be an appropriate treatment in areas with sagebrush species that are highly sensitive to fire and expected to have longer recovery times, such as low sagebrush communities,

Snake River Plain

Shrub and Grassland Ecosystems



Regional Description

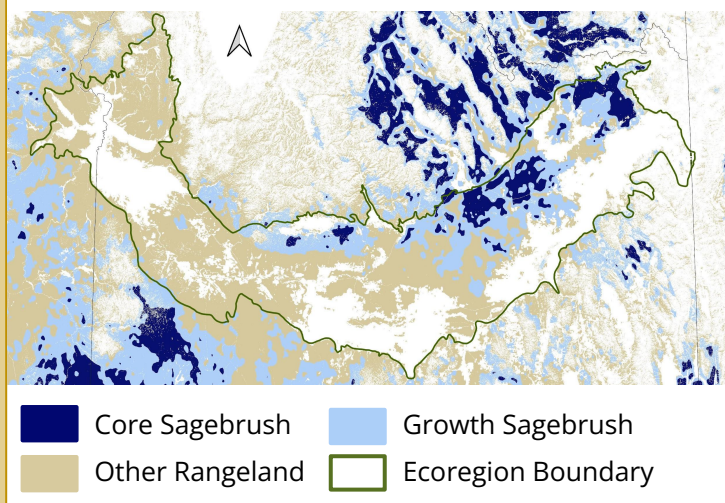
The Snake River Plain is a broad low-lying plain characterized by alluvial valleys and gently sloping hills. Fed by the expansive Snake River Aquifer, this area hosts diverse landscapes and unique ecosystems and has an arid to semi-arid climate with dry, hot summers. Shrublands and grasslands dominated two-thirds of the Snake River Plain in 2000, primarily across the plains and low hills which comprise the xeric NW. Heterogeneous patches of sagebrush (*Artemisia tridentata*) intersperse native and invasive non-native perennial grasses, such as bluebunch wheatgrass (*Pseudoroegneria spicata*). Diversity and abundance of wildlife species depend on the vegetation type and condition.

Strategy Habitat: Sagebrush

Sagebrush steppe ecosystems, an important habitat in the upper Snake River Plain, are especially vulnerable to ecosystem stressors associated with climate change, including warmer temperatures, invasive species, and land management practices.

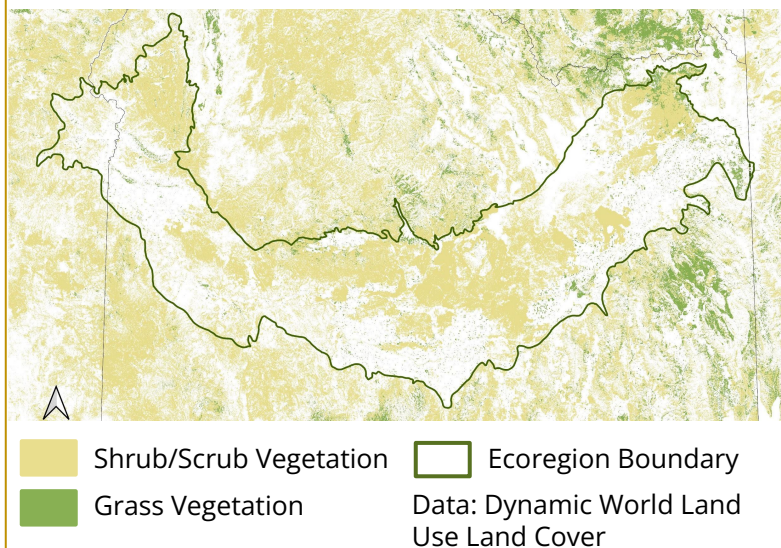
Core Sagebrush Areas cover only approximately 14% of the Snake River Plain and approximately 35% of the ecoregion is considered to be Growth Opportunity Areas to expand the sagebrush biome and improve sagebrush ecological integrity.

Sagebrush Core Habitat and Growth Area



Data: Doherty et al. 2022

Shrub and Scrub Distribution



Shrub and scrub cover approximately 35% of the Snake River Plain, while grass only covers approximately 3%.

Management Considerations

- Human activities substantially affect remaining native shrubland and grassland ecosystems through conversion to agriculture and cropland, livestock grazing, urban development, recreation, cultural practices, and human-ignited wildfires.
- A key region for NW agriculture, the Snake River Plain is highly valued for food production and water management.

Future Research Areas

- Direct effects of climate change on different subspecies of sagebrush, such as differences in how changes in precipitation amount and timing will affect the distribution and abundance of subspecies
- Effectiveness of fuel breaks in fire-prone sagebrush ecosystems and potential tradeoffs with invasive species spread and habitat fragmentation
- Effectiveness of sagebrush restoration approaches and impacts on native biodiversity and sagebrush dependent species, such as the conditions under which sagebrush seeding is successful given cheatgrass prevalence, fire activity, and agricultural conversion (Schlaepfer et al. 2021)

Snake River Plain Shrub and Grassland Ecosystems



Managing Ecosystem Stressors



Changing Fire Regimes

Description

Fire activity in sagebrush ecosystems is linked to abundant winter and spring precipitation that increases grass biomass and fire potential in the following season when this biomass cures and becomes available as fine fuels. Fire frequency is expected to increase with climate change as more winter and spring precipitation increases grass production and hotter, drier summers and further increase fire potential (Abatzoglou and Kolden 2011). Fire regimes are changing. Historical fire return intervals of multiple decades to centuries between fires are shifting to much more frequent fires, yet sagebrush resilience to frequent fire is low.

Management Actions

- Strategically using fuel breaks in fire-prone sagebrush steppe can aid fire management. However, mitigation efforts may be necessary to reduce the detrimental ecosystem effects that fuel breaks can have by fragmenting habitat and facilitating the spread of invasive grasses to new areas (Shinneman et al. 2019).
- Conduct research and monitoring of a variety of sagebrush restoration treatments and their effects on biodiversity and species that live in sagebrush ecosystems.
- Increase community engagement and public outreach efforts focused on reducing human-caused ignitions.



Invasive Annual Grasses

Description

The effects of climate change on the persistence and resilience of sagebrush are driven by the detrimental effects of invasive annual grasses, such as cheatgrass, that are introduced by people and benefit from climate change. Cheatgrass outcompetes native vegetation and increases fuel continuity, which perpetuates the invasive grass-fire cycle (Fusco et al. 2022) and accelerates conversion from sagebrush steppe to invasive grass-dominated landscapes. Cheatgrass is pervasive across the southwest Snake River Plain (Hak and Comer 2022).

Management Actions

- Appropriate treatments to reduce invasive grasses depend on current ecosystem condition and whether areas are core areas, growth areas, or other rangeland (USDA, 2020).
- Defend core areas of high ecological integrity with management aimed at protecting remaining sagebrush and previous restoration investments (Doherty et al. 2022).
- Control, slow, and reduce the spread of nonnative grasses with mowing, herbicide application, or grazing. Prioritize areas proximal to development (Bradley et al. 2018).



Conifer Encroachment

Description

In colder, wetter areas of the sagebrush range, especially for Mountain Big Sagebrush, conifer encroachment threatens sagebrush prevalence and extent with associated reductions in habitat quality for species that inhabit sagebrush ecosystems. In these areas, fire frequency has declined due to fire exclusion and abundant livestock grazing that have reduced fine grass fuels. Warmer winters with more precipitation in recent decades have also favored conifer growth and contributed to conifer encroachment into these sagebrush ecosystems.

Management Actions

- Mechanical removal of conifers with hand-cutting, mastication, and lop and scatter techniques can be effective for removal of smaller lower density trees in early stages of encroachment.
- Prescribed fire can reduce the density of fire-intolerant conifer species. Reintroducing fire is likely to be a more effective long-term conservation solution to limit conifer encroachment than mechanical removal.

CLIMATE ADAPTATION: Shrub and Grassland Ecosystems



Overview

Climate change impacts vary across shrublands and grassland ecosystems with variation in topography, climate, and species composition, making consistent approaches to climate change adaptation challenging. Climate change interacts with non-climatic ecosystem stressors that are typically the focus of restoration in these ecosystems. Managing invasive grasses, agricultural and urban development, changing fire regimes, and overgrazing are critical for successfully adapting to a changing climate. Appropriate adaptation strategies consistent with the Resist, Accept, Direct (RAD) Framework (Schoorman et al. 2020) depend on the current condition and integrity of local ecosystems.

Adaptation Options

Improving Carbon Storage and Sequestration

WHAT IT MEANS: Shrublands, particularly cold desert systems, store vast amounts of carbon, an ecosystem function that is affected by climate change, land-use change, wildfire, and invasive annual grasses. Conserving intact shrublands can increase carbon storage, which mitigates greenhouse gases and also can be synergistic with adaptation.

WHY IT WORKS: Cold desert shrubs have deep rooting systems, contributing to net carbon sinks when ecosystems are intact and full-functioning. Invasive annual grasses transform these systems into net carbon sources. Minimizing invasive grasses and restoring degraded shrublands contributes to restoring these systems as net carbon sinks. Avoiding conversion to cropland also reduces greenhouse gas emissions.

FINDING THE SCIENCE:

Provencher et al. 2023. Range. Eco. & Man.

- Carbon sequestration in sagebrush shrublands is comparable to more productive systems.
- Reseeding perennial grasses and shrubs can be combined with other actions to increase seeding success.

Nagy et al. 2021 J. App. Ecology

- Sagebrush-steppe conversion due to cheatgrass invasion causes carbon losses.
- Removing cheatgrass or restoring native vegetation can aid carbon sequestration.

A NATIVE RESEEDING

DESCRIPTION: The National Park Service is collecting, producing, and storing native seed for application across national parks in intermountain sagebrush systems. Efforts target native species that are highly competitive, can stabilize sites quickly, and are early seral. Sourcing native seeds is a limiting factor in restoration nationally. Native seed sources are critical for successful restoration, as genetically appropriate native seed sources have higher success rates, which can increase resilience in the face of climate change, invasive species, and more frequent wildfire. This project is one among a suite of nature-based solutions - using the Resist-Accept-Direct (RAD) framework and the Sagebrush Conservation Design - in response to ecological transformations occurring in national parks across the sagebrush biome.

AT A GLANCE:

- Goals: Contribute to the National Seed Strategy and help meet National Park Service planned and emergent restoration goals with use of native seed.
- Location: Parks across the western US with Intermountain sagebrush ecosystems (Colorado Plateau and Rocky Mountains ecoregions of Arizona, Colorado, New Mexico, Utah, and Wyoming)
- Timeline: Ongoing since 2021
- Strategies: Mapping native seed zones, restoration with native seed
- Project Link: [Seed for Intermountain Sagebrush](#)



A Wyoming big sagebrush seedling with a long taproot, which is necessary for resilience to drought conditions. Photo Credit: Tom Koerner/USFWS. CC BY-SA 2.0.

CLIMATE ADAPTATION: Shrub and Grassland Ecosystems



WHAT IT MEANS: In shrublands, climate change is expected to favor non-native invasive grasses and forbs, such as cheatgrass (*Bromus tectorum* L.), medusahead (*Taeniatherum caput-medusae*), and ventenata (*Ventenata dubia*) (McMahon et al. 2021). Protecting high-integrity sagebrush habitat (areas with abundant sagebrush, native understories, and minimal impacts from invasive species and human modification) enhances overall ecosystem resilience by protecting remaining intact sagebrush steppe. This strategy *accepts* that heavily ‘invaded’ landscapes are likely to remain dominated by invasive annuals, and *resists* invasion in high priority core areas. Proactive management strategies, such as native reseeding and prescribed burning, can be tailored for each priority habitat area designated for protection.

WHY IT WORKS: Defend the core, grow the core’ maintains areas of higher quality habitat that host native perennials and shrubs for fauna that use sagebrush ecosystems. Efforts focused on more intact, less ‘invaded’ shrublands have the potential to increase habitat connectivity, improve climate change refugia, accommodate species dispersal and range shifts, and are more likely to be effective and cost efficient.

FINDING THE SCIENCE:

Maestre et al. 2022. Annu Rev Ecol Evol Syst. Defending rangeland core habitat from annual grass conversion includes:

- Reducing exposure to annual grass seed sources
- Improving resilience and resistance by promoting perennial plants
- Building capacity to adapt to changing conditions

Doherty et al. 2022 Conservation Design

- Identifying core sagebrush areas helps prioritize resources and focus restoration efforts where they can increase resilience.
- Targeted restoration contributes to stabilizing the remaining sagebrush core from further fragmentation and degradation and improves habitat quality, connectivity, and climate change refugia.

SAGE GROUSE INITIATIVE

DESCRIPTION: Climate change, along with land use practices and agricultural development, contributes to habitat loss of the greater sage-grouse. The Sage Grouse Initiative, part of Working Lands for Wildlife, is a voluntary conservation program designed to benefit agricultural producers and wildlife species that depend on sagebrush for habitat. It is a partnership between the USDA, NRCS and agricultural producers that leverages the Farm Bill to incentivize conservation efforts that simultaneously improve agricultural productivity and wildlife habitat. The program directs resources to where they can be most effective and relies on science-based strategies to improve habitat resilience.

AT A GLANCE:

- Goals: Conserve at-risk wildlife, increase intact and resilient grasslands and sagebrush steppe, reduce conflict among land uses, incentivize voluntary conservation, support agricultural producers
- Location: This large land conservation effort covers 11 western states, including Washington, Oregon, Idaho, and Montana.
- Timeline: Ongoing since 2010
- Strategies: Increase resilience of sagebrush habitat and wildlife species that depend on sagebrush, improve habitat quality, increase habitat connectivity, support agricultural productivity.
- Project Link: [Sage Grouse Initiative](#)



Greater Sage Grouse, is threatened by invasive species and climate change, including changes related to droughts, wildfires. Photo Credit: Peter Olsoy

CLIMATE ADAPTATION: Shrub and Grassland Ecosystems



WHAT IT MEANS: Changing vegetation composition, including from the introduction and spread of invasive species, has altered the abundance and arrangement of fuels in sagebrush ecosystems. These changes, along with a warmer drier climate, are increasing the frequency, size, and severity of wildfires. Methods to manage fuels in sagebrush ecosystems include mechanical, chemical, biological and fire treatments. These fuel treatments are intended to reduce the behavior, spread, and severity of fire. Treatment selection depends on ecosystem conditions and management objectives. Multiple treatments can be used in combination to achieve desired levels of fuel reduction.

WHY IT WORKS: Most species of sagebrush are not fire-adapted and the development of mature sagebrush ecosystems can take decades after fire. Prior to the invasion of nonnative grasses, fire exclusion, and human-caused climate change, the amount of fuel varied spatially in these ecosystems creating patches that limited fire spread and severity (Bukowski and Baker 2013). Fuel treatments reduce fuel loading and breakup fuel continuity so that wildfires will have heterogeneous effects. This increases the sagebrush ecosystem resilience and resistance to changing fire regimes and decreases potential for vegetation type conversion following fire.

FINDING THE SCIENCE:

Shinneman et al. 2023, Ecol. App.

A review of fuel treatments effects and intended benefits in sagebrush ecosystems that considers the Resist-Accept-Direct (RAD).

- 'Resist' strategies include reducing expansion of woodland species or implementing fuel breaks that protect intact sagebrush habitat.
- 'Accept' strategies include de-prioritizing cheatgrass-dominated areas and prioritizing high-integrity core habitat.
- 'Direct' strategies focus on creating diverse plant communities of native fire-adapted grasses and shrubs that are better suited to a changing climate with the goal of reducing the likelihood of conversion to systems dominated by invasive species.

SAGEBRUSH STEPPE TREATMENT EVALUATION PROJECT (SageSTEP)

DESCRIPTION: The SageSTEP project investigates the long-term ecological impacts of fuel treatments in sagebrush steppe and juniper woodlands across the intermountain west. Fuel treatments were implemented across a network of sites from 2005-2010, including prescribed burns, mowing and herbicide application, and mechanical treatments (chainsaw and mastication treatments). Short-term effects on ecosystems were evaluated, specifically effects on cheatgrass invasion and woodland encroachment. Long-term monitoring began in 2011 with the goal of measuring ecosystem effects for up to 25 years post-treatment to understand climate change influences on vegetation, wildlife, and treatment effectiveness.

AT A GLANCE:

- Goals: Evaluate fuel treatments in sagebrush steppe that are intended to minimize cheatgrass invasion and woodland expansion.
- Location: The Great Basin region in six states, California, Idaho, Nevada, Oregon, Utah and Washington
- Timeline: Fuel treatments were implemented over 5 years. Long-term monitoring of the project began in 2010 and is expected to last 25 years.
- Strategies: Managing fuels, increasing shrubland resilience, minimizing invasive species, reducing woody plant encroachment
- Project Links: [SageSTEP Project Page](#)



A sagebrush plot included in SageSTEP before a mowing treatment is applied. Photo Credit: SageSTEP CC BY-SA 2.0

CLIMATE ADAPTATION: Shrub and Grassland Ecosystems



WHAT IT MEANS: Maps of seed zones can help managers determine where species may be planted with low risk of being poorly adapted to the local climate conditions. Seed transfer guidelines assist with selecting plants that are adapted to a specific restoration site. Mapping seed zones based on climate-driven plant adaptations improves seed sourcing. However, most seed zone maps do not consider climate change. Future maps and guidelines that consider species-specific adaptive capacity and incorporate local knowledge of microclimates can increase restoration success. Seed zones can be used to indicate how plants will respond to future changes in the climate and guide assisted migration. Iterative mapping of seed zones allows for recognizing shifts in species ranges.

WHY IT WORKS: Native shrub and grassland species are adapted to different ecological niches and exhibit phenotypic plasticity and intraspecific variation in survival, seed production, and plant size (Chaney et al. 2016) such as climate-driven genetic differences among sagebrush populations. Such variations allow for adaptation to future climates. Using seed zones to select and plant seeds increases restoration success because these seeds may be better adapted for future climates, increase genetic diversity, adaptive capacity, and the ability of a species to persist despite climate change stressors.

FINDING THE SCIENCE:

Baughman et al. 2022. Rangeland

- A review of the history and current trends of using native plants in seed-based restoration of sagebrush steppe ecosystems.
- Suggestions to improve the success of native plant restoration.

Bower et al. 2014. Ecological App.

- Seed zones for native plants across the US based on minimum winter temperatures and aridity.
- Seed zones can be used as guidelines for seed transfer distances.

Summary for Managers: [Seeding Big Sagebrush Successfully on Intermountain Rangelands](#)

MORE ADAPTATION RESOURCES:

● TRAINING FOR GRASSLANDS CONSERVATION PRACTITIONERS

This training series for grasslands conservation practitioners was developed by the South Central CASC, in partnership with the USFWS, and the Northwest, North Central, and Midwest CASCs. It includes video presentations and activity sheets that discuss climate impacts and adaptation in western US grassland ecosystems.

Resource Link: [Training for Grasslands Conservation Practitioners – South Central CASC](#)

● TRAINING FOR SAGEBRUSH CONSERVATION PRACTITIONERS

This training series for sagebrush conservation practitioners was developed by the South Central CASC, in partnership with the USFWS, and the Northwest, North Central, and Midwest CASCs. It includes video presentations and activity sheets that discuss climate impacts and adaptation in western US sagebrush ecosystems.

Resource Link: [Training for Sagebrush Conservation Practitioners – South Central CASC](#)

● CLIMATE CHANGE VULNERABILITIES AND ADAPTATION STRATEGIES FOR LAND MANAGERS ON NORTHWEST US RANGELANDS

This publication from Maher et al. 2024 synthesizes key climate change vulnerabilities and adaptation options for Northwest rangelands.

Resource Link: [Climate Change Vulnerabilities and Adaptation Strategies for Land Managers on Northwest US Rangelands - ScienceDirect](#)

● GREATER SAGE-GROUSE HABITAT AND CONNECTIVITY IN A CHANGING LANDSCAPE AND CLIMATE

This includes models of habitat suitability and connectivity for greater sage-grouse in the Columbia Basin. Models predict the best remaining habitat given the current landscape condition and climate.

Resource Link: [Greater Sage-Grouse Habitat and Connectivity in a Changing Landscape and Climate Climate Impacts Group](#)

REFERENCES - OVERVIEW

- Aikens, E. O., K. L. Monteith, J. A. Merkle, S. P. H. Dwinell, G. L. Fralick, and M. J. Kauffman. 2020. Drought reshuffles plant phenology and reduces the foraging benefit of green-wave surfing for a migratory ungulate. *Global Change Biology* 26:4215–4225.
- Applestein, C., T. T. Caughlin, and M. J. Germino. 2021. Weather affects post-fire recovery of sagebrush-steppe communities and model transferability among sites. *Ecosphere* 12:e03446.
- Balch, J. K., B. A. Bradley, C. M. D'Antonio, and J. Gómez-Dans. 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980-2009). *Global Change Biology* 19:173–183.
- Bates, J., D. Johnson, K. W. Davies, T. Svejcar, and S. Hardegree. 2023. Effects of Annual Weather Variation on Peak Herbaceous Yield Date in Sagebrush Steppe. *Western North American Naturalist* 83:220–231.
- Bishop, T. B. B., B. C. Nusink, R. Lee Molinari, J. B. Taylor, and S. B. St. Clair. 2020. Earlier fall precipitation and low severity fire impacts on cheatgrass and sagebrush establishment. *Ecosphere* 11:e03019.
- Bloom, T. D. S., D. S. O'Leary, and C. Riginos. 2022. Flowering time advances since the 1970s in a sagebrush steppe community: Implications for management and restoration. *Ecological Applications: A Publication of the Ecological Society of America* 32:e2583.
- Boyte, S. P., B. K. Wylie, Y. Gu, and D. J. Major. 2020. Estimating Abiotic Thresholds for Sagebrush Condition Class in the Western United States. *Rangeland Ecology & Management* 73:297–308.
- Brabec, M. M., M. J. Germino, and B. A. Richardson. 2017. Climate adaptation and post-fire restoration of a foundational perennial in cold desert: insights from intraspecific variation in response to weather. *Journal of Applied Ecology* 54:293–302.
- Bradford, J. B., D. R. Schlaepfer, and W. K. Lauenroth. 2014. Ecohydrology of Adjacent Sagebrush and Lodgepole Pine Ecosystems: The Consequences of Climate Change and Disturbance. *Ecosystems* 17:590–605.
- Bradford, J. B., D. R. Schlaepfer, W. K. Lauenroth, and K. A. Palmquist. 2020. Robust ecological drought projections for drylands in the 21st century. *Global Change Biology* 26:3906–3919.
- Bradley, B. A., C. A. Curtis, and J. C. Chambers. 2016. *Bromus* Response to Climate and Projected Changes with Climate Change. Pages 257–274 in M. J. Germino, J. C. Chambers, and C. S. Brown, editors. *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US*. Springer International Publishing, Cham.
- Bradley, B. A., C. A. Curtis, E. J. Fusco, J. T. Abatzoglou, J. K. Balch, S. Dadashi, and M.-N. Tuanmu. 2018. Cheatgrass (*Bromus tectorum*) distribution in the intermountain Western United States and its relationship to fire frequency, seasonality, and ignitions. *Biological Invasions* 20:1493–1506.
- Breshears, D. D., A. K. Knapp, D. J. Law, M. D. Smith, D. Twidwell, and C. L. Wonkka. 2016. Rangeland Responses to Predicted Increases in Drought Extremity. *Rangelands* 38:191–196.

- Brown, C. F., S. P. Brumby, B. Guzder-Williams, T. Birch, S. B. Hyde, J. Mazzariello, W. Czerwinski, V. J. Pasquarella, R. Haertel, S. Ilyushchenko, K. Schwehr, M. Weisse, F. Stolle, C. Hanson, O. Guinan, R. Moore, and A. M. Tait. 2022. Dynamic World, Near real-time global 10 m land use land cover mapping. *Scientific Data* 9:251.
- Cartwright, J. M., C. E. Littlefield, J. L. Michalak, J. J. Lawler, and S. Z. Dobrowski. 2020. Topographic, soil, and climate drivers of drought sensitivity in forests and shrublands of the Pacific Northwest, USA. *Scientific Reports* 10.
- Chambers, J. C., J. D. Maestas, D. A. Pyke, C. S. Boyd, M. Pellant, and A. Wuenschel. 2017. Using Resilience and Resistance Concepts to Manage Persistent Threats to Sagebrush Ecosystems and Greater Sage-grouse. *Rangeland Ecology & Management* 70:149–164.
- Compagnoni, A., and P. Adler. 2014a. Warming, Competition, and *Bromus tectorum* Population Growth Across an Elevation Gradient. *Ecosphere* 5:1–34.
- Compagnoni, A., and P. B. Adler. 2014b. Warming, soil moisture, and loss of snow increase *Bromus tectorum*'s population growth rate. *Elementa: Science of the Anthropocene* 2:000020.
- Davies, K. W., E. A. Leger, C. S. Boyd, and L. M. Hallett. 2021. Living with exotic annual grasses in the sagebrush ecosystem. *Journal of Environmental Management* 288:112417.
- Edwards, B. L., N. P. Webb, D. P. Brown, E. Elias, D. E. Peck, F. B. Pierson, C. J. Williams, and J. E. Herrick. 2019. Climate change impacts on wind and water erosion on US rangelands. *Journal of Soil and Water Conservation* 74:405–418.
- Friggens, M. M., J. R. Pinto, R. K. Dumroese, and N. L. Shaw. 2012. Decision Support: Vulnerability, Conservation, and Restoration.
- Harris, T., D. D. Johnson, and R. C. O'Connor. 2024. A brief history of sagebrush management in the Great Basin: From removal to reduction and beyond. *Rangelands*.
- Havrilla, C. A., J. B. Bradford, C. B. Yackulic, and S. M. Munson. 2023. Divergent climate impacts on C3 versus C4 grasses imply widespread 21st century shifts in grassland functional composition. *Diversity and Distributions* 29:379–394.
- Holdrege, M. C., D. R. Schlaepfer, K. A. Palmquist, M. Crist, K. E. Doherty, W. K. Lauenroth, T. E. Remington, K. Riley, K. C. Short, J. C. Tull, L. A. Wiechman, and J. B. Bradford. 2024. Wildfire probability estimated from recent climate and fine fuels across the big sagebrush region. *Fire Ecology* 20:22.
- Huang, J., H. Yu, X. Guan, G. Wang, and R. Guo. 2016. Accelerated dryland expansion under climate change. *Nature Climate Change* 6:166–171.
- Hufkens, K., T. F. Keenan, L. B. Flanagan, R. L. Scott, C. J. Bernacchi, E. Joo, N. A. Brunsell, J. Verfaillie, and A. D. Richardson. 2016. Productivity of North American grasslands is increased under future climate scenarios despite rising aridity. *Nature Climate Change* 6:710–714.
- Innes, R. J., and K. Zouhar. 2018. Fire regimes of mountain big sagebrush communities. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory.

- James, J. J., R. L. Sheley, E. A. Leger, P. B. Adler, S. P. Hardegree, E. S. Gornish, and M. J. Rinella. 2019. Increased soil temperature and decreased precipitation during early life stages constrain grass seedling recruitment in cold desert restoration. *Journal of Applied Ecology* 56:2609–2619.
- Kleinhesselink, A. R., and P. B. Adler. 2018. The response of big sagebrush (*Artemisia tridentata*) to interannual climate variation changes across its range. *Ecology* 99:1139–1149.
- Knight, E., N. Mahony, and D. Green. 2016. Effects of agricultural fragmentation on the bird community in sagebrush shrubsteppe. *Agriculture, Ecosystems & Environment* 223:278–288.
- Lazarus, B. E., M. J. Germino, and B. A. Richardson. 2019. Freezing resistance, safety margins, and survival vary among big sagebrush populations across the western United States. *American Journal of Botany* 106:922–934.
- Li, Z., H. Shi, J. E. Vogelmann, T. J. Hawbaker, and B. Peterson. 2020. Assessment of Fire Fuel Load Dynamics in Shrubland Ecosystems in the Western United States Using MODIS Products. *Remote Sensing* 12:1911.
- Maestre, F. T., D. J. Eldridge, S. Soliveres, S. Kéfi, M. Delgado-Baquerizo, M. A. Bowker, P. García-Palacios, J. Gaitán, A. Gallardo, R. Lázaro, and M. Berdugo. 2016. Structure and Functioning of Dryland Ecosystems in a Changing World. *Annual Review of Ecology, Evolution, and Systematics* 47:215–237.
- Mahood, A. L., and J. K. Balch. 2019. Repeated fires reduce plant diversity in low-elevation Wyoming big sagebrush ecosystems (1984–2014). *Ecosphere* 10:e02591.
- McMahon, D. E., A. K. Urza, J. L. Brown, C. Phelan, and J. C. Chambers. 2021. Modelling species distributions and environmental suitability highlights risk of plant invasions in western United States. *Diversity and Distributions* 27:710–728.
- Morford, S. L., B. W. Allred, D. Twidwell, M. O. Jones, J. D. Maestas, C. P. Roberts, and D. E. Naugle. 2022. Herbaceous production lost to tree encroachment in United States rangelands. *Journal of Applied Ecology* 59:2971–2982.
- Morgan, J. A., A. R. Mosier, D. G. Milchunas, D. R. LeCain, J. A. Nelson, and W. J. Parton. 2004. CO₂ Enhances Productivity, Alters Species Composition, and Reduces Digestibility of Shortgrass Steppe Vegetation. *Ecological Applications* 14:208–219.
- Neilson, R., J. Lenihan, D. Bachelet, and R. Drapek. 2005. Climate change implications for sagebrush ecosystems. *Transactions of the 70th North American Wildlife and Natural Resources Conference* 70:145–159.
- O'Connor, R. C., M. J. Germino, D. M. Barnard, C. M. Andrews, J. B. Bradford, D. S. Pilliod, R. S. Arkle, and R. K. Shriver. 2020. Small-scale water deficits after wildfires create long-lasting ecological impacts. *Environmental Research Letters* 15:044001.
- Palmquist, K. A., D. R. Schlaepfer, J. B. Bradford, and W. K. Lauenroth. 2016. Mid-latitude shrub steppe plant communities: climate change consequences for soil water resources. *Ecology* 97:2342–2354.
- Palmquist, K. A., D. R. Schlaepfer, R. R. Renne, S. C. Torbit, K. E. Doherty, T. E. Remington, G. Watson, J. B. Bradford, and W. K. Lauenroth. 2021. Divergent climate change effects on widespread dryland plant communities driven by climatic and ecohydrological

- gradients. *Global Change Biology* 27:5169–5185.
- Parks, S. A., L. M. Holsinger, C. Miller, and M.-A. Parisien. 2018. Analog-based fire regime and vegetation shifts in mountainous regions of the western US. *Ecography* 41:910–921.
- Parks, S. A., C. Miller, J. T. Abatzoglou, L. M. Holsinger, M.-A. Parisien, and S. Z. Dobrowski. 2016. How will climate change affect wildland fire severity in the western US? *Environmental Research Letters* 11:035002.
- Pilliod, D. S., J. L. Welty, and R. S. Arkle. 2017. Refining the cheatgrass–fire cycle in the Great Basin: Precipitation timing and fine fuel composition predict wildfire trends. *Ecology and Evolution* 7:8126–8151.
- Radeloff, V. C., M. H. Mockrin, D. Helmers, A. Carlson, T. J. Hawbaker, S. Martinuzzi, F. Schug, P. M. Alexandre, H. A. Kramer, and A. M. Pidgeon. 2023. Rising wildfire risk to houses in the United States, especially in grasslands and shrublands. *Science* 382:702–707.
- Requena-Mullor, J., J. Brandt, M. Williamson, and T. Caughlin. 2023. Human population growth and accessibility from cities shape rangeland condition in the American West. *Landscape and Urban Planning* 232.
- Rottler, C. M., C. E. Noseworthy, B. Fowers, and J. L. Beck. 2015. Effects of Conversion From Sagebrush to Non-Native Grasslands on Sagebrush-Associated Species. *Rangelands* 37:1–6.
- Roundy, B. A., J. C. Chambers, D. A. Pyke, R. F. Miller, R. J. Tausch, E. W. Schupp, B. Rau, and T. Gruell. 2018. Resilience and resistance in sagebrush ecosystems are associated with seasonal soil temperature and water availability. *Ecosphere* 9:e02417.
- Ruckman, E. M., S. Schwinning, and K. G. Lyons. 2012. Effects of Phenology at Burn Time on Post-Fire Recovery in an Invasive C_4 Grass. *Restoration Ecology* 20:756–763.
- Schlaepfer, D. R., J. B. Bradford, W. K. Lauenroth, and R. K. Shriver. 2021. Understanding the future of big sagebrush regeneration: challenges of projecting complex ecological processes. *Ecosphere* 12:e03695.
- Schlaepfer, D. R., W. K. Lauenroth, and J. B. Bradford. 2012. Ecohydrological niche of sagebrush ecosystems. *Ecohydrology* 5:453–466.
- Schlaepfer, D. R., K. A. Taylor, V. E. Pennington, K. N. Nelson, T. E. Martin, C. M. Rottler, W. K. Lauenroth, and J. B. Bradford. 2015. Simulated big sagebrush regeneration supports predicted changes at the trailing and leading edges of distribution shifts.
- Shi, H., M. Rigge, C. G. Homer, G. Xian, D. K. Meyer, and B. Bunde. 2018. Historical Cover Trends in a Sagebrush Steppe Ecosystem from 1985 to 2013: Links with Climate, Disturbance, and Management. *Ecosystems* 21:913–929.
- Smith, J. T., B. W. Allred, C. S. Boyd, K. W. Davies, M. O. Jones, A. R. Kleinhesselink, J. D. Maestas, S. L. Morford, and D. E. Naugle. 2022. The elevational ascent and spread of exotic annual grass dominance in the Great Basin, USA. *Diversity and Distributions* 28:83–96.
- Smith, M. D., et al. . 2024. Extreme drought impacts have been underestimated in grasslands and shrublands globally. *Proceedings of the National Academy of Sciences* 121:e2309881120.
- Smull, D. M., N. Pendleton, A. R. Kleinhesselink, and P. B. Adler. 2019. Climate change, snow

- mold and the *Bromus tectorum* invasion: mixed evidence for release from cold weather pathogens. *AoB PLANTS* 11:plz043.
- Still, S. M., and B. A. Richardson. 2015. Projections of contemporary and future climate niche for Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis*): A guide for restoration. *Natural Areas Journal*. 35(1): 30-43. 35:30-43.
- Stoner, D. C., T. A. Messmer, R. T. Larsen, S. N. Frey, M. T. Kohl, E. T. Thacker, and D. K. Dahlgren. 2020. Using satellite-derived estimates of plant phenological rhythms to predict sage-grouse nesting chronology. *Ecology and Evolution* 10:11169-11182.
- Terry, T. 2023. Precipitation and Soil Properties Determine Long-Term Consequences of Disturbance and Invasion in Drylands. All Graduate Theses and Dissertations, Spring 1920 to Summer 2023.
- Tucker, C. L., S. Tamang, E. Pendall, and K. Ogle. 2016. Shallow snowpack inhibits soil respiration in sagebrush steppe through multiple biotic and abiotic mechanisms. *Ecosphere* 7:e01297.
- Williamson, M. A., E. Fleishman, R. C. Mac Nally, J. C. Chambers, B. A. Bradley, D. S. Dobkin, D. I. Board, F. A. Fogarty, N. Horning, M. Leu, and M. Wohlfeil Zillig. 2020. Fire, livestock grazing, topography, and precipitation affect occurrence and prevalence of cheatgrass (*Bromus tectorum*) in the central Great Basin, USA. *Biological Invasions* 22:663-680.
- Yao, J., W. Yuan, Z. Gao, H. Liu, X. Chen, Y. Ma, E. Arntzen, and D. Mcfarland. 2022. Impact of Shifts in Vegetation Phenology on the Carbon Balance of a Semiarid Sagebrush Ecosystem. *Remote Sensing* 14:5924.
- Young, A. C., T. E. Katzner, D. J. Shinneman, and T. N. Johnson. 2023. Implications of tree expansion in shrubland ecosystems for two generalist avian predators. *PLOS ONE* 18:e0286478.
- Zimmer, S. N., G. J. Groszklos, P. Belmont, and P. B. Adler. 2021. Agreement and Uncertainty Among Climate Change Impact Models: A Synthesis of Sagebrush Steppe Vegetation Projections. *Rangeland Ecology & Management* 75:119-129.

REFERENCES - MIDDLE ROOKIES

- Abatzoglou, J. T., and C. A. Kolden. 2011. Climate Change in Western US Deserts: Potential for Increased Wildfire and Invasive Annual Grasses. *Rangeland Ecology & Management* 64:471–478.
- Doherty, K., D. M. Theobald, J. B. Bradford, L. A. Wiechman, G. Bedrosian, C. S. Boyd, M. Cahill, P. S. Coates, M. K. Creutzburg, M. R. Crist, S. P. Finn, A. V. Kumar, C. E. Littlefield, J. D. Maestas, K. L. Prentice, B. G. Prochazka, T. E. Remington, W. D. Sparklin, J. C. Tull, Z. Wurtzebach, and K. A. Zeller. 2022. A sagebrush conservation design to proactively restore America's sagebrush biome. Page Open-File Report. U.S. Geological Survey.
- Fusco, E. J., J. K. Balch, A. L. Mahood, R. C. Nagy, A. D. Syphard, and B. A. Bradley. 2022. The human-grass-fire cycle: how people and invasives co-occur to drive fire regimes. *Frontiers in Ecology and the Environment* 20:117–126.
- McMahon, D. E., A. K. Urza, J. L. Brown, C. Phelan, and J. C. Chambers. 2021. Modelling species distributions and environmental suitability highlights risk of plant invasions in western United States. *Diversity and Distributions* 27:710–728.
- Shinneman, D. J., M. J. Germino, D. S. Pilliod, C. L. Aldridge, N. M. Vaillant, and P. S. Coates. 2019. The ecological uncertainty of wildfire fuel breaks: examples from the sagebrush steppe. *Frontiers in Ecology and the Environment* 17:279–288.

REFERENCES - NORTHERN BASIN AND RANGE

- Abatzoglou, J. T., and C. A. Kolden. 2011. Climate Change in Western US Deserts: Potential for Increased Wildfire and Invasive Annual Grasses. *Rangeland Ecology & Management* 64:471–478.
- Bradley, B. A., C. A. Curtis, E. J. Fusco, J. T. Abatzoglou, J. K. Balch, S. Dadashi, and M.-N. Tuanmu. 2018. Cheatgrass (*Bromus tectorum*) distribution in the intermountain Western United States and its relationship to fire frequency, seasonality, and ignitions. *Biological Invasions* 20:1493–1506.
- Doherty, K., D. M. Theobald, J. B. Bradford, L. A. Wiechman, G. Bedrosian, C. S. Boyd, M. Cahill, P. S. Coates, M. K. Creutzburg, M. R. Crist, S. P. Finn, A. V. Kumar, C. E. Littlefield, J. D. Maestas, K. L. Prentice, B. G. Prochazka, T. E. Remington, W. D. Sparklin, J. C. Tull, Z. Wurtzebach, and K. A. Zeller. 2022. A sagebrush conservation design to proactively restore America's sagebrush biome. Page Open-File Report. U.S. Geological Survey.
- Fusco, E. J., J. K. Balch, A. L. Mahood, R. C. Nagy, A. D. Syphard, and B. A. Bradley. 2022. The human-grass-fire cycle: how people and invasives co-occur to drive fire regimes. *Frontiers in Ecology and the Environment* 20:117–126.
- Hak, J. C., and P. J. Comer. 2020. Modeling Invasive Annual Grass Abundance in the Cold Desert Ecoregions of the Interior Western United States. *Rangeland Ecology & Management* 73:171–180.
- Orr, D. A., J. D. Bates, and K. W. Davies. 2022. Grazing Intensity Effects on Fire Ignition Risk and Spread in Sagebrush Steppe. *Rangeland Ecology & Management*.
- Schlaepfer, D. R., J. B. Bradford, W. K. Lauenroth, and R. K. Shriver. 2021. Understanding the future of big sagebrush regeneration: challenges of projecting complex ecological processes. *Ecosphere* 12:e03695.
- Williamson, M. A., E. Fleishman, R. C. Mac Nally, J. C. Chambers, B. A. Bradley, D. S. Dobkin, D. I. Board, F. A. Fogarty, N. Horning, M. Leu, and M. Wohlfeil Zillig. 2020. Fire, livestock grazing, topography, and precipitation affect occurrence and prevalence of cheatgrass (*Bromus tectorum*) in the central Great Basin, USA. *Biological Invasions* 22:663–680.

REFERENCES - SNAKE RIVER PLAIN

- Abatzoglou, J. T., and C. A. Kolden. 2011. Climate Change in Western US Deserts: Potential for Increased Wildfire and Invasive Annual Grasses. *Rangeland Ecology & Management* 64:471–478.
- Bradley, B. A., C. A. Curtis, E. J. Fusco, J. T. Abatzoglou, J. K. Balch, S. Dadashi, and M.-N. Tuanmu. 2018. Cheatgrass (*Bromus tectorum*) distribution in the intermountain Western United States and its relationship to fire frequency, seasonality, and ignitions. *Biological Invasions* 20:1493–1506.
- Doherty, K., D. M. Theobald, J. B. Bradford, L. A. Wiechman, G. Bedrosian, C. S. Boyd, M. Cahill, P. S. Coates, M. K. Creutzburg, M. R. Crist, S. P. Finn, A. V. Kumar, C. E. Littlefield, J. D. Maestas, K. L. Prentice, B. G. Prochazka, T. E. Remington, W. D. Sparklin, J. C. Tull, Z. Wurtzebach, and K. A. Zeller. 2022. A sagebrush conservation design to proactively restore America's sagebrush biome. Page Open-File Report. U.S. Geological Survey.
- Fusco, E. J., J. K. Balch, A. L. Mahood, R. C. Nagy, A. D. Syphard, and B. A. Bradley. 2022. The human–grass–fire cycle: how people and invasives co-occur to drive fire regimes. *Frontiers in Ecology and the Environment* 20:117–126.
- Hak, J. C., and P. J. Comer. 2020. Modeling Invasive Annual Grass Abundance in the Cold Desert Ecoregions of the Interior Western United States. *Rangeland Ecology & Management* 73:171–180.
- Schlaepfer, D. R., J. B. Bradford, W. K. Lauenroth, and R. K. Shriver. 2021. Understanding the future of big sagebrush regeneration: challenges of projecting complex ecological processes. *Ecosphere* 12:e03695.
- Shinneman, D. J., M. J. Germino, D. S. Pilliod, C. L. Aldridge, N. M. Vaillant, and P. S. Coates. 2019. The ecological uncertainty of wildfire fuel breaks: examples from the sagebrush steppe. *Frontiers in Ecology and the Environment* 17:279–288.

REFERENCES - ADAPTATION

- Baughman, O. W., S. M. Kulpa, and R. L. Sheley. 2022. Four paths toward realizing the full potential of using native plants during ecosystem restoration in the Intermountain West. *Rangelands* 44:218–226.
- Bower, A. D., J. B. St. Clair, and V. Erickson. 2014. Generalized provisional seed zones for native plants. *Ecological Applications* 24:913–919.
- Bukowski, B. E., and W. L. Baker. 2013. Historical fire regimes, reconstructed from land-survey data, led to complexity and fluctuation in sagebrush landscapes. *Ecological Applications* 23:546–564.
- Chaney, L., B. A. Richardson, and M. J. Germino. 2017. Climate drives adaptive genetic responses associated with survival in big sagebrush (*Artemisia tridentata*). *Evolutionary Applications* 10:313–322.
- Doherty, K., D. M. Theobald, J. B. Bradford, L. A. Wiechman, G. Bedrosian, C. S. Boyd, M. Cahill, P. S. Coates, M. K. Creutzburg, M. R. Crist, S. P. Finn, A. V. Kumar, C. E. Littlefield, J. D. Maestas, K. L. Prentice, B. G. Prochazka, T. E. Remington, W. D. Sparklin, J. C. Tull, Z. Wurtzebach, and K. A. Zeller. 2022. A sagebrush conservation design to proactively restore America's sagebrush biome. Page Open-File Report. U.S. Geological Survey.
- Maestre, F. T., D. J. Eldridge, S. Soliveres, S. Kéfi, M. Delgado-Baquerizo, M. A. Bowker, P. García-Palacios, J. Gaitán, A. Gallardo, R. Lázaro, and M. Berdugo. 2016. Structure and Functioning of Dryland Ecosystems in a Changing World. *Annual Review of Ecology, Evolution, and Systematics* 47:215–237.
- Maher, A. T., H. R. Prendeville, J. E. Halofsky, M. M. Rowland, K. W. Davies, and C. S. Boyd. 2024. Climate Change Vulnerabilities and Adaptation Strategies for Land Managers on Northwest US Rangelands. *Rangeland Ecology & Management*.
- McMahon, D. E., A. K. Urza, J. L. Brown, C. Phelan, and J. C. Chambers. 2021. Modelling species distributions and environmental suitability highlights risk of plant invasions in western United States. *Diversity and Distributions* 27:710–728.
- Nagy, R. C., E. J. Fusco, J. K. Balch, J. T. Finn, A. Mahood, J. M. Allen, and B. A. Bradley. 2021. A synthesis of the effects of cheatgrass invasion on US Great Basin carbon storage. *Journal of Applied Ecology* 58:327–337.
- Provencher, L., S. Byer, L. Frid, S. Senthivasan, K. J. Badik, and K. Szabo. 2023. Carbon Sequestration in Degraded Intermountain West Rangelands, United States. *Rangeland Ecology & Management* 90:22–34.
- Schuurman, G. W., D. N. Cole, A. E. Cravens, S. Covington, S. D. Crausbay, C. H. Hoffman, D. J. Lawrence, D. R. Magness, J. M. Morton, E. A. Nelson, and R. O'Malley. 2022. Navigating Ecological Transformation: Resist–Accept–Direct as a Path to a New Resource Management Paradigm. *BioScience* 72:16–29.
- Shinneman, D. J., E. K. Strand, M. Pellant, J. T. Abatzoglou, M. W. Brunson, N. F. Glenn, J. A. Heinrichs, M. Sadegh, and N. M. Vaillant. 2023. Future Direction of Fuels Management in Sagebrush Rangelands. *Rangeland Ecology and Management* 86:50–63.