Fifth Oregon Climate Assessment

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We are grateful to the many authors, other contributors, reviewers, and advisors to this Assessment, especially during a year that was extraordinarily difficult for so many. We welcome readers to contact us with ideas for ensuring that the sustained assessment process is relevant to their priorities.

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Executive Summary

Established and emerging understanding of observed and projected climate change in Oregon, and knowledge of the opportunities and risks that climate change poses to natural and human systems, may serve as a resource for actions including but not limited to planning for mitigation of climate-related natural hazards and implementation of Oregon's 2021 Climate Change Adaptation Framework.

State of Climate Science

Temperature. Oregon's annual average temperature increased by about 2.2°F per century since 1895. If greenhouse gas emissions continue at current levels, temperature in Oregon is projected to increase on average by 5°F by the 2050s and 8.2°F by the 2080s, with the greatest seasonal increases in summer.

Precipitation. Precipitation is projected to increase during winter and decrease during summer. The number and intensity of heavy precipitation events, particularly in winter, is projected to increase throughout the twenty-first century. Furthermore, as temperatures warm, the proportion of precipitation falling as rain rather than snow in Oregon is projected to increase, especially at lower to intermediate elevations in the Cascade Range.

Snowpack and runoff. Snowpack throughout Oregon, especially on the west slope of the Cascade Range, is accumulating more slowly, reaching lower peak values, and melting earlier. These trends are likely to continue, and may accelerate, as temperature increases. Concomitantly, runoff is expected to begin and peak earlier in the year, decline in summer, and increase in winter, but will vary geographically.

Science advances. In addition to simulations of future climate from the newest generation of global climate models, advances in climate science have improved the accuracy of climate forecasts one week to one month into the future. Also, it is becoming more feasible to estimate the extent to which human-caused climate change affects the likelihood of some types of extreme weather events.

Climate-Related Natural Hazards

Extreme heat. The frequency and magnitude of days that are warmer than 90°F is increasing across Oregon. During summer, relative increases in nighttime minimum temperatures have been greater than those in daytime maximum temperatures. The frequency, duration, and intensity of extreme heat events is expected to increase throughout the state during the twenty-first century.

Drought. Over the past 20 years, the incidence, extent, and severity of drought in the Northwest increased. These changes partially are attributable to human-caused climate change. As summers in Oregon continue to become warmer and drier, and mountain snowpack decreases, the frequency of droughts, particularly snow droughts such as those in 2014 and 2015, is likely to increase.

Wildfire. Wildfire dynamics are affected by climate change, past and contemporary land management and human activity, and expansion of non-native invasive grasses. From 1984 through 2018, annual area burned in Oregon increased considerably. Over the next 50 to 100 years, area burned and fire frequency are projected to increase substantially, initially east of the crest of the Cascade Range and then in the western Cascade Range. Over the long term, depending on how vegetation and fire weather shift with climatic changes and fuel and fire management, fire severity also may increase.

Floods. Flood magnitudes in Oregon are likely to increase. Heavy precipitation events are expected to become more intense because a warmer atmosphere can carry more moisture. Also, in a warmer climate, the relatively contribution to floods of rainfall will be greater than that of snowmelt. The consequence is larger flood peaks because, for a given amount of precipitation, the peaks of rainfall-driven floods tend to be larger than those of snowmelt-driven floods. Projected increases in wet-season precipitation also are likely to increase winter flood magnitude. Increases in regulated flows from the main stem of the Columbia River during winter appear likely to increase flood risk throughout the Columbia River reservoir system.

Coastal hazards. Sea-level rise, storminess, sediment supply, and human adaptation measures influence whether a given stretch of Oregon's coastline has eroded or built up in recent decades. Therefore, predicting future shoreline change is challenging. As sea level rises, coastal storms and high tides are likely to increase the frequency and severity of flooding along Oregon's coastline. By the year 2050, relative sea level at Newport is very likely to rise between 0.6 and 1.8 feet, and at least one flood is likely to exceed four feet above mean high tide. Accounting for plausible, yet uncertain, estimates of Antarctic ice sheet melt suggests that sea level could rise 2.9 feet by the year 2050, with regular nuisance flooding occurring earlier.

Marine and coastal change. Off the Northwest coast, the open-ocean surface temperature increased by more than 1.2 ± 0.5°F since the year 1900, and is projected to increase by about another 5.0 ± 1.1°F by the year 2080. These changes in temperature have the potential to affect many other drivers of ocean change, such as by accelerating the rate of reduction in dissolved oxygen in the water and increasing the toxicity of harmful algal blooms. Ocean acidity also is projected to change by roughly 100–150%, resulting in a drop in open-ocean pH from 8.1 to 7.8. The change in pH is likely to affect shell formation in diverse species of commercial, recreational, and cultural value.

Adaptation Sectors

Natural systems. Climate change is affecting the timing of seasonal events in the life cycle of some plants and animals, and the viability of some species. Projected decreases in freshwater flows and connectivity are likely to decrease survival and growth of salmon. Projected increases in temperature and changes in precipitation also may have negative effects on some protected species. The ability of Oregon's species to adapt behaviorally, physically, or genetically to climate change in part depends on the speed of climate change, the level of other environmental stressors, and genetic diversity.

Built environment. Climate change is likely to stress Oregon's infrastructure. Projected increases in sea level and precipitation intensities are expected to strain levees, tide gates, and sewer and stormwater infrastructure. Droughts may diminish hydropower production and the effectiveness of water-supply infrastructure. Wildfires may threaten communities directly and indirectly via, for example, landslides and degraded water quality. Urban heat island effects are expected to increase summer electricity demand and risks of heat stress. Opportunities for mitigation and adaptation include wind and solar power, grid integration of electric transportation, and green infrastructure for resilience to flooding. Data-driven, science-based capital planning that engages stakeholders can help to realize these adaptations.

Public health. Racial and economic injustices have created disparities in health outcomes among populations in Oregon. Black, Indigenous, and People of Color; underinvested rural, Tribal, and low-income communities; the young and the old; and those with pre-existing conditions or disabilities are more likely to experience negative health effects of climate extremes. One in two households in Oregon spends 30% or more of their income on rent or a mortgage. These households are less likely to rebuild in the event of home loss or severe damage from an extreme weather event. Displacement and income loss associated with climate impacts will increase the risk of homelessness, food insecurity, and mental health effects.

Tribal cultural resources. Tribes may experience distinct impacts of climate change that relate to their cultures, identities, histories, relations with other governments, and land-holding status. Tribes throughout Oregon are using Traditional Knowledges to prepare for and increase their resilience to climate change. Priority topics include access to first foods, community health, changes in the distributions or status of native species, and wetland alterations. Tribal climate adaptation strategies also help to reassert treaty rights, advocate for equitable investment in civil infrastructure, and reestablish Tribal sovereignty.

Social systems. Social, political, and economic systems mediate the effects of climate change. The costs of adaptations to climate change in the agricultural sector likely will be passed on to consumers, exacerbating the existing challenges some communities face in obtaining affordable produce. Agricultural laborers' incidence of heat-related illnesses and exposure to wildfire smoke are expected to increase as climate changes. In Oregon, 28% of agricultural workers are undocumented immigrants who may be unable or reluctant to seek health care.

The full Fifth Oregon Climate Assessment is available at blogs.oregonstate.edu/occri/oregon-climate-assessments/.

Introduction

Consistent with its charge under Oregon House Bill 3543, the Oregon Climate Change Research Institute (OCCRI) conducts a biennial assessment of the state of climate change science, including biological, physical, and social science, as it relates to Oregon and the likely effects of climate change on Oregon. This fifth Oregon Climate Assessment builds on previous assessments (Dello and Mote 2010; Dalton et al. 2013, 2017; Mote et al. 2019) by continuing to evaluate past and projected future changes in Oregon's climate and hydrology. This Assessment is structured with the goal of serving as a resource for the state's mitigation planning for natural hazards and implementation of the 2021 Oregon Climate Change Adaptation Framework.

The first section of this Assessment, *State of Climate Science*, reflects OCCRI's sustained appraisal of observed trends and future projections of temperature, precipitation, snowpack, and streamflow. New research and insights are consistent with previous key messages about projected changes in Oregon's climate, such as warmer temperatures, drier summers, wetter winters, heavier rains, less snowpack, and associated shifts in the timing and discharge of streamflow. *State of Climate Science* also summarizes the latest research related to simulations of future climate, including preliminary insights on the newest generation of global climate models, subseasonal to seasonal climate prediction, and attribution of extreme events.

The dependence of human communities on their surrounding natural, economic, and social environment is magnified by climate extremes and associated hazards (Guidotti et al. 2016, Martinez-Diaz et al. 2020). The second section of this Oregon Climate Assessment explores how climate change is expected to affect climate-related natural hazards, including extreme heat, drought, wildfire, floods, and coastal hazards, in support of Oregon's 2020 Natural Hazards Mitigation Plan. Furthermore, this Oregon Climate Assessment examines recent observed and projected changes in the physical and biological environment of marine and coastal systems in Oregon and the Northwest. Implicit in the Assessment's treatment of hazards is the fact that disasters may result either from single, major events or from recurrent events that individually are not extreme, but degrade a community's social and economic infrastructure (Field et al. 2012).

The third section of this Assessment addresses six sectors within which Oregon's 2021 Climate Change Adaptation Framework aggregates vulnerabilities and strategic responses: economy, natural world, built environment and infrastructure, public health, cultural heritage, and social systems. The Framework aims to guide state decisions about investment of resources as climate changes and to facilitate collaboration among state agencies. This Assessment dedicates a chapter each to five of the sectors. These chapters describe the latest research in climate science and climate adaptation that is relevant to the sector in Oregon. Economic aspects of climate change are integrated throughout chapters on other sectors rather than treated independently. The economic risks of gradual changes in climate and extreme climate-related events vary among regions. Additionally, given the distinct impacts of climate change on Tribal cultures, identities, histories, relations with other governments, and land-holding status, this Assessment emphasizes Tribal cultural heritage.

Both the Climate Change Adaptation Framework and this Assessment recognize that the myriad interactions and feedbacks among natural and human systems are complex and can be difficult to differentiate. Evidence from Oregon's natural hazards mitigation planning process, the climate science literature, and a sustained assessment process can help indicate the extent to which natural hazards may affect adaptation sectors, and inform selection of actions to maximize resilience.

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State of Climate Science

Meghan Dalton, Heejun Chang, Benjamin Hatchett, Paul Loikith, Philip Mote, Laura Queen, and David Rupp

This chapter synthesizes observed trends and projections of future climate and hydrology from previous Oregon Climate Assessments, provides updates, and reports on new knowledge. In addition, this chapter reports on major advances in the field of climate science that are relevant to Oregon, including simulations of future climate under a new generation of global climate models, prediction of weather conditions three to four weeks into the future, and attribution of extreme weather events.

Observed and Projected Trends in Greenhouse Gases

In 2019, carbon dioxide concentrations measured at the long-term monitoring site on Mauna Loa, Hawaii, averaged 411 parts per million (ppm) by volume (NOAA 2020). Monthly concentrations from January through October 2020 were above 411 ppm. Global carbon dioxide emissions decreased during 2020 due to the COVID-19 pandemic. In April 2020, at the maximum confinement in many countries, carbon emissions dropped by 17% compared to 2019, reducing emissions to 2006 levels. However, by June 2020, carbon dioxide emissions had nearly rebounded to 2019 levels. Estimated 2020 carbon dioxide emissions are four to seven percent lower than those in 2019, similar to the yearly declines of emissions sustained over decades that are necessary to limit global warming to 2.7°F (1.5°C) (Luterbracher et al. 2020). Nevertheless, despite the temporarily lowered emissions, global concentrations of greenhouse gases in the atmosphere continued to increase, albeit at a slower rate.

Projections and analysis of future climate in this and other chapters primarily are based on the suite of global climate models from the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012). The future climate scenarios associated with CMIP5, called representative concentration pathways (RCPs), encompass plausible trajectories of greenhouse gas emissions and concentrations that would lead to different amounts of warming by the end of the twenty-first century (van Vuuren et al. 2011). This assessment references the two most commonly cited future scenarios, RCP 4.5 and RCP 8.5. RCP 4.5, a lower scenario, represents moderate reductions in global greenhouse gas emissions, with a peak near mid-century. RCP 8.5, a higher scenario, represents a continuation of current levels of emissions throughout the twenty-first century. The newest generation of global climate models, which are part of phase six of the Coupled Model Intercomparison Project (CMIP6), simulate future climate under scenarios called shared socioeconomic pathways (SSPs). CMIP6 and SSPs are described in more detail in *Recent Advances in Climate Science*, below.

Observed and Projected Trends in Climate

Temperature

Oregon's average temperature increased at a rate of 2.2°F (1.2°C) per century from 1895–2019 (NCEI 2020). All of the past 20 years (2000–2019) except 2011 were warmer than the twentieth century (1900–1999) average, and all except the two strongest La Niña years in the twenty-first century, 2008 and 2011, were warmer than the 1970–1999 average (NCEI 2020). The year 2015 was Oregon's warmest on record from 1895 through 2019 (NCEI 2020) (Fig. 1a).

	2050s		2080s	
	RCP 4.5	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**
Annual	3.6 (1.8, 5.4)	5.0 (2.9, 6.9)	4.6 (2.1, 6.7)	8.2 (4.8, 10.7)
Winter	3.3 (1.6, 5.1)	4.5 (2.4, 6.5)	4.2 (1.8, 6.5)	7.4 (4.2, 9.8)
Spring	3.1 (1.4, 5.0)	4.1 (2.0, 5.9)	3.8 (1.7, 6.0)	6.7 (3.8, 9.2)
Summer	4.5 (2.2, 6.8)	6.3 (3.6, 8.9)	5.5 (2.7, 8.3)	10.2 (6.5, 13.9)
Autumn	3.7 (1.5, 5.4)	5.2 (2.6, 7.0)	4.7 (2.0, 6.9)	8.6 (4.6, 11.4)

Table 1. Projected future changes in mean annual and seasonal temperature (°F) in Oregon from the historical baseline (1970–1999) for the 2050s (2040–2069) and 2080s (2070–2099) under RCP 4.5 and RCP 8.5. Values in boldface are the average changes from 35 global climate models and the 5th to 95th percentile range across those models. Table reproduced from Dalton et al. 2017, with data for Oregon from Rupp et al. 2017. Winter includes December, January, and February; spring includes March, April, and May; summer includes June, July, and August; autumn includes September, October, and November.

Oregon's temperatures are projected to increase in all seasons, particularly summer. Dalton et al. (2017) reported projected average changes in Oregon's annual and seasonal temperatures for the periods 2040–2069 and 2070–2099 relative to 1970–1999 under RCP 4.5 and RCP 8.5 (Table 1). These projections, which were based on 35 global climate models from CMIP5, are still the most current projections for Oregon. Preliminary results from comparisons of CMIP6 with CMIP5 for Oregon, reported in *Recent Advances in Climate Science* (below), suggested slightly greater warming under CMIP6 than CMIP5. Under the CMIP5 models and RCP 8.5, Oregon's annual average temperature is projected to increase by 5°F (~2.8°C) by the 2050s and 8.2°F (~4.6°C) by the 2080s (Dalton et al. 2017) (Fig. 1a, Table 1). Summer temperatures are projected to increase by 6.3°F (~3.7°C) by the 2050s and 10.2°F (~5.7°C) by the 2080s under RCP 8.5 (Table 1). Changes in extreme temperatures and heat events are described in *Extreme Heat* (this volume).

Precipitation

Oregon's annual precipitation varies considerably among years, and has not changed significantly over the observational record (+0.58 inches [1.5 cm] per century from 1895–2019) (NCEI 2020). Some statistically significant increases in heavy precipitation have been documented in Oregon (e.g., Dalton et al. 2017 and reviews therein). However, the relatively small sample sizes and large variability in intense precipitation makes it difficult to detect long-term observed trends, and results often depend on location, time frame, and definition of heavy precipitation (Mote et al. 2013). The maximum consecutive five-day precipitation in October and March in Portland, Oregon, increased from 1977 through 2016 ($p < 0.1$), but not in the intervening months (Cooley and Chang 2020).

	2050s		2080s	
	RCP 4.5	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**
Annual	1.9 (-4.9, 9.0)	2.7 (-6.0, 11.4)	3.4 (-5.6, 15.3)	6.3 (-5.2, 19.9)
Winter	4.9 (-6.4, 16.5)	7.9 (-4.7, 24.3)	7.3 (-6.3, 19.9)	14.5 (-2.8, 37.1)
Spring	1.9 (-8.9,12.1)	2.7 (-7.2, 17.4)	3.4 (-7.7, 14.9)	3.6 (-9.4, 15.6)
Summer	-6.3 (-28.5, 16.1)	-8.7 (-33.1, 22.5)	-4.6 (-24.2, 22.3)	-7.7 (-38.7, 33.5)
Autumn	0.5 (-17.0, 14.4)	-0.8 (-17.1, 14.9)	1.5 (-15.0, 18.1)	1.9 (-17.2, 24.2)

Table 2. Projected future relative changes in total annual and seasonal precipitation (%) in Oregon from the historical baseline (1970–1999) for the 2050s (2040–2069) and 2080s (2070–2099) under RCP 4.5 and RCP 8.5. Values in boldface are the average changes from 35 global climate models and the 5th to 95th percentile range across those models. Table reproduced from Dalton et al. 2017, with data for Oregon from Rupp et al. 2017. Winter includes December, January, and February; spring includes March, April, and May; summer includes June, July, and August; autumn includes September, October, and November.

Annual variability is expected to continue to dominate annual precipitation, with a slight increasing trend (Fig. 1b, Table 2). Precipitation is expected to increase during the wet season and decrease in summer in the Columbia River Basin (Rupp et al. 2017) and, on average, for Oregon as a whole (Table 2). In general, the intensity of heavy precipitation events during the twenty-first century in Oregon is projected to increase, although not uniformly across the state (e.g., Dalton et al. 2017 and reviews therein, Cooley and Chang 2020).

Atmospheric rivers. Atmospheric rivers are long, narrow corridors that transport high amounts of atmospheric water vapor and are important mechanisms for precipitation across the Pacific Northwest (Ralph et al. 2020). Atmospheric rivers are common features of autumn and winter storms in Oregon (Payne and Magnusdottir 2014), and are associated with around 25–30% of precipitation in those seasons over most of the state. The majority of autumn and winter extreme precipitation events, defined on the basis of three-day total precipitation, also are associated with atmospheric rivers, especially in western Oregon (Fig. 2) (Slinskey et al. 2020).

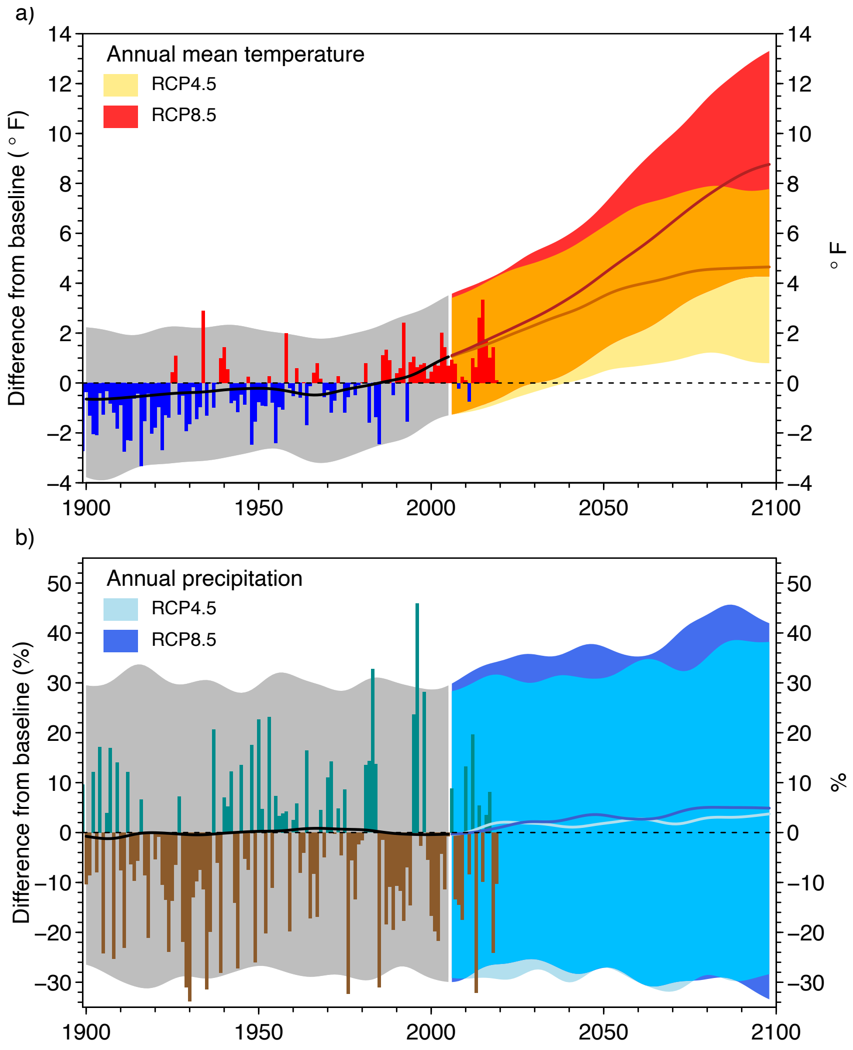

Figure 1. Observed, simulated, and projected changes in Oregon's mean annual (a) temperature and (b) precipitation relative to 1970–1999 (baseline) under RCP 4.5 and RCP 8.5 future scenarios. Colored bars are observed values (1900–2019) from the National Centers for Environmental Information. The thicker solid lines are the mean values of simulations from 35 climate models for the 1900–2005 period, which were based on observed climate forcings (black line), and the 2006–2099 period for the two future scenarios (orange [RCP 4.5] and red [RCP 8.5] lines in the top panel, light blue [RCP 4.5] and darker blue [RCP 8.5] lines in the bottom panel). Shading indicates the range in annual temperatures or precipitation from all models. The mean and range were smoothed to emphasize long-term variability.

Because a warmer atmosphere can hold more water vapor, the intensity of atmospheric rivers, as defined by the amount of water vapor transported, is projected to increase (Gao et al. 2015, Warner and Mass 2017, Espinoza et al. 2018, Ralph et al. 2020), and possibly to penetrate further inland (Mahoney et al. 2018). How this translates into changes to atmospheric river-related precipitation across Oregon and other parts of the west coast is an active area of research (Payne et al. 2020). The number of days with an atmospheric rivers present across Oregon is projected to increase by roughly 5–10% over western Oregon by the end of the twenty-first century under RCP 8.5, although this does not mean that the number of atmospheric rivers, or of the storms with which they are associated, will change (Espinoza et al. 2018, Massoud et al. 2019). The increase in water

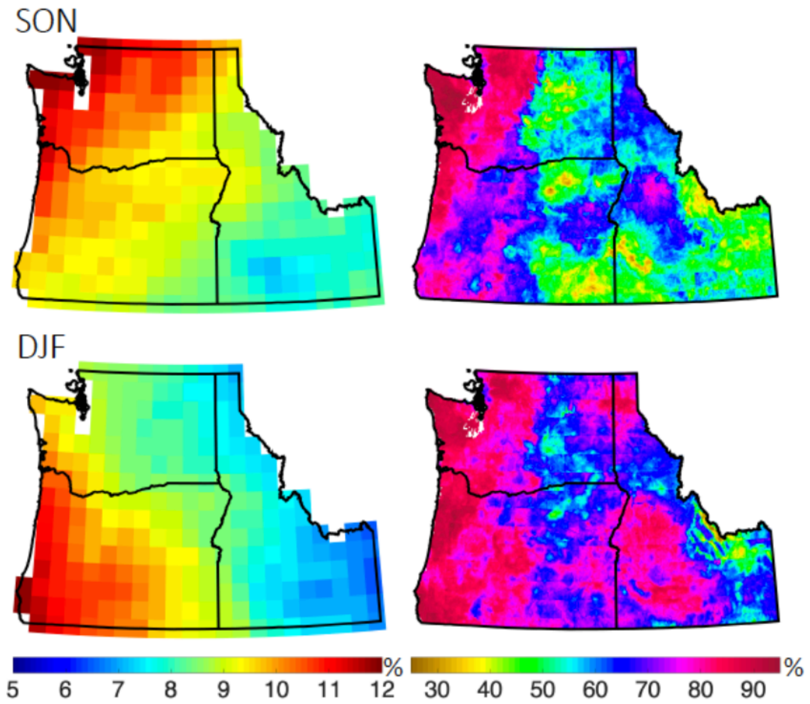

Figure 2. Percentage of days with (left) atmospheric rivers and (right) extreme precipitation that also have an atmospheric rivers, based on data from 1981–2016. Results are for (top row) September, October, and November and (bottom row) December, January, and February. Source: Slinskey et al. 2020 © American Meteorological Society. Used with permission.

vapor-holding capacity of the atmosphere as it warms also is projected to increase the intensity of atmospheric rivers. As reported in Dalton et al. (2017), the latter inference is supported by a projected 250% or greater increase in the number of days with extreme atmospheric river conditions (highest 1% of intensity) by the end of the twenty-first century under RCP 8.5 (Warner et al. 2015). Climate models also project an increase in the contribution of atmospheric river-produced precipitation to total annual precipitation across the region (Gershunov et al. 2019).

Observed and Projected Trends in Hydrology

Snowpack

Snow is a major source of water for natural ecosystems and for human consumption and recreation in Oregon. Snow is most common in Oregon's mountain ranges (Fig. 3), but also occurs at lower elevations, particularly east of the Cascade Range. Many ecosystem processes and human consumptive uses depend on the presence of a seasonal snowpack that accumulates during the cool season and melts during spring and summer, providing streamflow during the warm season and refilling reservoirs. Snowpack, often analyzed in terms of snow water equivalent (SWE)—the amount of water contained in the snowpack—can be classified as seasonal, ephemeral, or non-snowy (Fig. 4) on the basis of a snow seasonality metric (Petersky and Harpold 2018). The snow seasonality metric is based on the duration of seasonal (persisting 60 or more consecutive days) and ephemeral (persisting for fewer than 60 consecutive days) snowpacks compared to the total number of days with snow. Oregon's highest mountain ranges, including the Cascade Range and Wallowa, Blue, Steens, Siskiyou, Trout Creek, and Santa Rosa Mountains, have seasonal snowpacks. Ephemeral snowpacks occur at lower elevations east of the Cascades Range, in the northern Coast Ranges, along the west slope of the Cascade Range, and in the Klamath and Siskiyou Mountains.

Median peak SWE increases as elevation increases. The greatest SWE values, which often exceed 39.4 inches (1000 mm), are in the Cascade Range (Fig. 5a). Along the west side of the Cascade Range, peak SWE increases as the snowpack transitions from low-elevation non-snowy to mid-elevation ephemeral to high-elevation seasonal. On the east side of the northern Cascade Range, peak SWE decreases sharply as elevation decreases. This elevational gradient in SWE is less apparent in the southern Cascade Range. Peak SWE values are lower (less than 7.9 inches [200 mm]) in the Coast Ranges and the Klamath and Siskiyou Mountains. The lower-elevation ranges of eastern Oregon generally have relatively low peak SWE values, whereas the higher-elevation Wallowa Mountains, Steens Mountains, and Strawberry and Elkhorn Mountains within the Blue Mountains have relatively high SWE values. Peak SWE values in the Blue Mountains of east-central Oregon and the Warner, Santa Rosa, and Trout Creek Mountains of southeastern Oregon are relatively low, less than 15.7 inches (400 mm), but colder temperatures facilitate seasonal snowpacks.

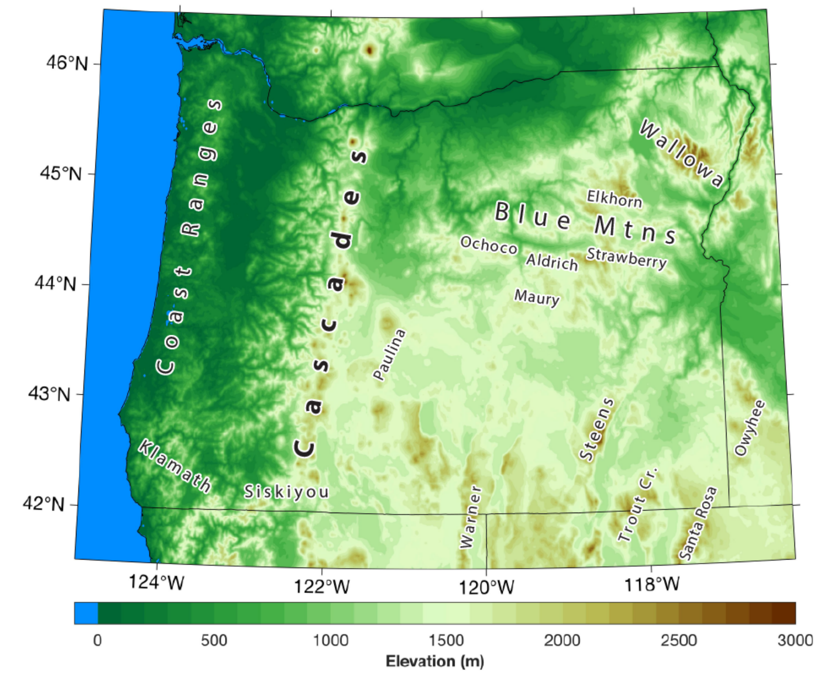

Figure 3. Elevations and major mountain ranges in Oregon.

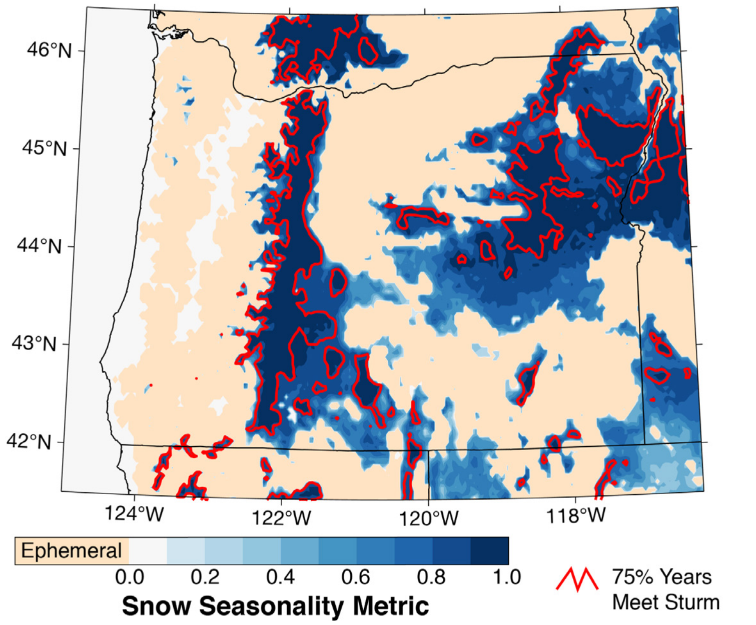

Figure 4. Snow seasonality classified by the median snow seasonality metric (Petersky and Harpold 2018). The metric varies continuously from -1 (ephemeral) to 1 (seasonal). Values greater than zero indicate seasonal snowpack and values less than zero indicate ephemeral snowpack. White indicates non-snowy areas (no days with SWE greater than zero). Red contour denotes the area in which 75% of years meet the Sturm et al. (1995) definition of seasonal snowpack, generally snow seasonality metric values greater than about 0.9.

The median timing of peak SWE in Oregon occurs from February (low elevation, ephemeral snowpacks) through May (high elevation, seasonal snowpacks; Fig. 5b). In the interior mountain ranges, elevated valleys, and plateaus, SWE values are relatively low. Nevertheless, colder winter temperatures, which are typical of inland regions where mountains inhibit the moderating effect of warmer oceanic airmasses, generally correspond to later dates of peak SWE. The latest peak SWE occurs near the crest of the Cascade Range and in the Steens and Wallowa Mountains.

Observed trends. From 1955 through 2016, spring snowpack, in terms of 1 April SWE, decreased at nearly every snow-observing station in Oregon (Mote et al. 2018, 2019). Because computing the area

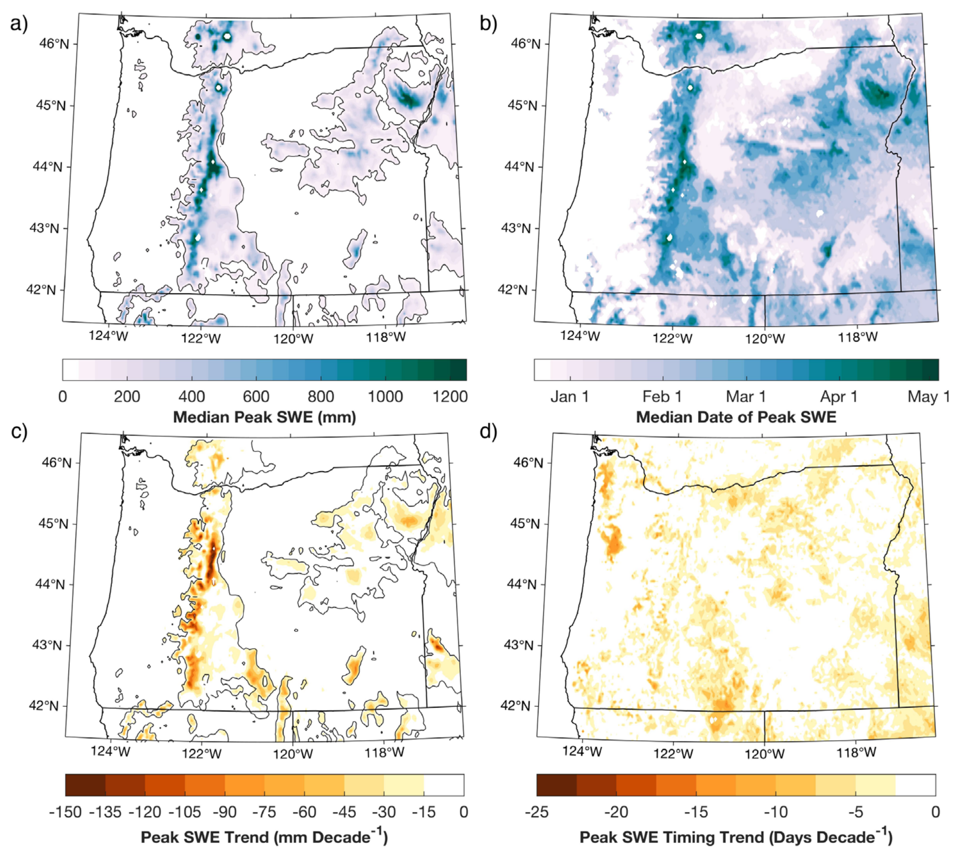

Figure 5. Oregon snowpack characteristics and trends analyzed over the period 1982–2017. (a) Median peak snow water equivalent (SWE; mm) and (b) timing of peak SWE (days past 1 October). (c–d) As in (a–b) but illustrating decadal trends (none statistically significant at p<0.001). Trends were assessed with nonparametric Mann-Kendall tests with lag-1 autocorrelation removed (Hamed and Rao 1998). Black contour lines in (a) and (c) enclose areas exceeding 2 inches (50 mm) median peak SWE.

averages from point observations alone is challenging, Mote et al. (2018) also analyzed gridded outputs from a variable infiltration capacity hydrologic model, and found that 1 April SWE averaged over the western United States decreased by roughly 15–30% since the middle of the twentieth century. The effects of anthropogenic forcing on spring snowpack trends since 1980 may have been mitigated by natural variability forced by large-scale changes in atmospheric circulation. Those changes in circulation, in turn, were driven by Pacific sea surface temperatures, suggesting that once the cycle of natural variability shifts from its current mode, snowpack declines may accelerate (Siler et al. 2019).

This section presents a new examination of trends and characteristics of Oregon's snowpack that was based on a new, gridded data product that interpolates point-based observations and normalizes by prior-year snowfall accumulations to estimate daily SWE and snow depth on a continuous 4 km horizontal grid over water years 1982–2017 (Broxton et al. 2016, Zeng et al. 2018). This gridded product also was used to calculate the snow seasonality metric (Fig. 4). The new exploration described here addressed the amount and timing of peak SWE (Fig. 5), number of days with snow cover, and timing of snowmelt and snow sufficient for recreation (Fig. 6). Results indicated that from 1982–2017, the snowpack throughout all of Oregon's mountains, especially the west slope of the Cascade Range, accumulated more slowly, had lower peak SWE values, and melted earlier.

Peak SWE declined in the southern and central Cascade Range, Warner Mountains, Steens Mountains, Trout Creek Mountains, and Wallowa Mountains (Fig. 5c). The largest declines (on the order of more than 5.3 inches [135 mm] per decade, or a >70% decline over the 36-year period) were observed on the east side of the central Cascade Range near Mt. Jefferson. Declines were greater than 3.5 inches (90 mm) per decade (a 50–80% decline over the 36-year period) along the west side of the Cascade Range. Trends in other mountain ranges and the easternmost side of the southern Cascades ranged from 0.6–3.5 inches (15–90 mm) per decade (a 20–50% decline over the 36-year period). However, these trends in peak SWE were not statistically significant at the conservative p<0.001 level. Trends in the timing of peak SWE varied (Fig. 5d). The largest negative (earlier) trends, on the order of 5–10 days per decade, were along the southeastern side of the Cascade Range. Negative trends of lower magnitude (2.5–7.5 days per decade) were observed along the west side of the Cascade Range and scattered throughout other mountain ranges in Oregon.

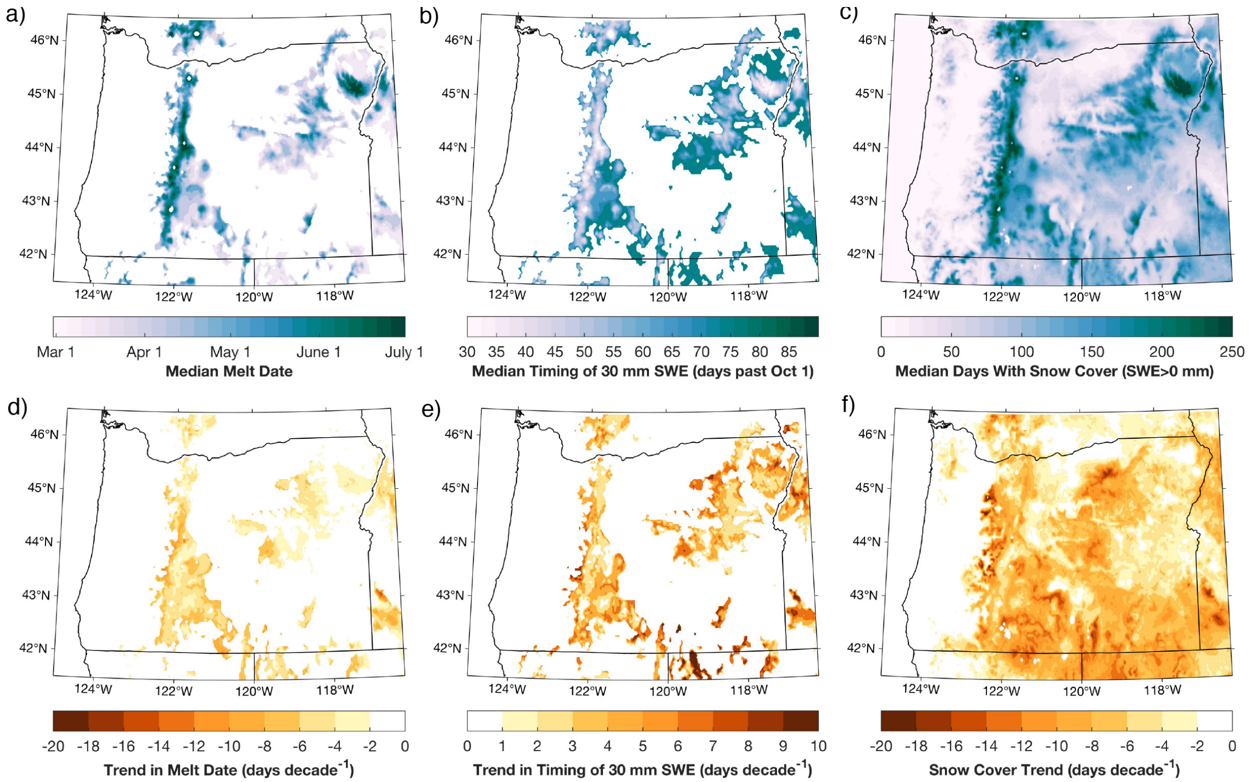

Figure 6. Additional Oregon snowpack characteristics and trends analyzed over the period 1982–2017. (a) Median timing of melt date, (b) median timing of sufficient snow for recreation (1.2 inches [30 mm] snow water equivalent [SWE]; days past 1 October), (c) median days with snow cover (SWE>0); (d–f) As in (a–c) but illustrating decadal trends. Trends were assessed with nonparametric Mann-Kendall tests with lag-1 autocorrelation removed (Hamed and Rao 1998).

Complete melting of winter snowpack—defined as the day on which SWE decreases to zero—occured in early spring (March) at lower elevations in the interior mountains (Fig. 6a) and progressively later as elevation increased. The highest elevations in the Cascade Range and Wallowa Mountains generally retained snow until late June or early July. Melting trended earlier (albeit not significant at p<0.001) in all mountain regions in Oregon (Fig. 6d), with the greatest changes (more than 16 days earlier per decade) in the northern margins of the Great Basin east of the central Cascade Range, and near the Warner Mountains and high-elevation valleys near the California-Oregon-Nevada border. Changes were smaller (2–10 days earlier per decade) along the western slopes of the Cascade Range, particularly in the central Cascade Range (north of Mt. Jefferson), in the southern and northern Blue Mountains (e.g., the Maury and Elkhorn Ranges), throughout the Steens and Warner Mountains, and along the lower elevations of the Wallowa Mountains.

The first date of sufficient snowpack for recreation was defined as the first date with 1.2 inches (30 mm) SWE (Hatchett and Eisen 2019). This value commonly is used by land managers to open areas for over-snow vehicle recreation (Hatchett and Eisen 2019). It also is a reasonable benchmark for sufficient snowpack to enjoy backcountry recreation activities. Over the period 1982–2017, snowpack usually was sufficient for recreation by early to mid-November in the higher elevations of Oregon's mountains and by mid-December at lower elevations (Fig. 6b). The timing shifted later by 3–8 days per decade (Fig. 6e), with the largest shifts along the western slope of the Cascade Range, in parts of the eastern slope of northern and central Cascade Range, and throughout the interior mountains (e.g., Blue, Wallowa, and Steens).

Most of Oregon had an average of at least 10 days of snow cover (non-zero SWE) per year from 1982–2017 (Fig. 6c). Despite low peak SWE values, often less than 3.9 inches (100 mm), much of interior southeastern Oregon had an average of 80 or more days of snow cover. However, due to sparse observations in this region, these model-based estimates should be compared against independent data from satellite-based observations or other direct measurements. Duration of snow cover increased as elevation and distance from the Pacific Ocean increased. Many of the highest-elevation and snowiest regions had more than 200 days of snow cover. The Siskiyou Mountains, northern Coast Range, and Klamath Mountains had one to two months of snow cover on average.

The number of days with snow cover decreased throughout much of Oregon (Fig. 6f). The largest declines in snow-cover duration were on the order of 12 or more days per decade and were on the west side of the central Cascade Range, Warner Mountains, and Wallowa Mountains. Widespread declines of 4–12 days per decade were observed in the inland mountain ranges and in the northern regions of the Great Basin. Changes in southeastern Oregon did not appear to be limited to high elevations. It would be quite informative to evaluate the physical drivers of declines in snow cover during the accumulation (autumn) and melting (spring) seasons with different definitions of snow cover and additional data sources.

Future projections. Oregon's snow cover and snowpack are likely to decrease further as the climate becomes warmer, which will cause a greater proportion of precipitation to fall as rain than as snow in many locations that historically received substantial snowfall during winter (Nolin and Daly 2006, Klos et al. 2014, Catalano et al. 2019, Lynn et al. 2020). Catalano et al. (2019) used projected changes in the elevation of the freezing level to quantify how the proportion of wet days with snow to all wet days will change at Snow Telemetry (SNOTEL) stations across the Northwest (Fig. 7). The proportion decreased rapidly at low to intermediate elevations, especially in the Cascade Range. For example, at most SNOTEL stations in the Oregon Cascade Range, fewer than 25% of wet days are projected to be days with snow by the mid-twenty-first century, compared to about 50% at most stations during the late twentieth to early twenty-first centuries. Such a decrease in the proportion of snow days may have a major impact in areas that rely on Cascade Range snowpack for water. The proportion of snow to rain will decrease more slowly at higher elevations and in eastern Oregon; some stations are projected to continue to have snow on at least 25% of wet days.

Runoff

Watersheds in Oregon have one of three distinctive runoff regimes: rainfall dominated, mixed rain and snow, and snow dominated. Distance from the Pacific Ocean, elevation, position on the leeward or windward side of a mountain range, vegetation, and geology affect variability in the temporal distribution of runoff in Oregon (Chang and Jung 2010). Rainfall-dominated systems occur in coastal regions and the Willamette Valley. In these areas, flow closely follows the timing of precipitation, leading to a single, extended runoff peak in winter, populated by multiple local runoff maxima corresponding to rainfall events. Mixed rain and snow systems, characterized by two runoff peaks that correspond to rainfall and snowmelt, occur in many watersheds at high elevations in the Cascade Range and mountains to the east. In snow-dominated systems above 4000 feet (1219 m) in south-central and northeast Oregon, runoff peaks in early to mid-summer. Peak flow in streams at higher elevations of the Cascade Range are delayed due to snowmelt and sustained summer flow; their continuous baseflow reflects discharge from groundwater basins with high specific yield (the ratio of the volume of water that the soil can yield by gravity to the total volume of the soil).

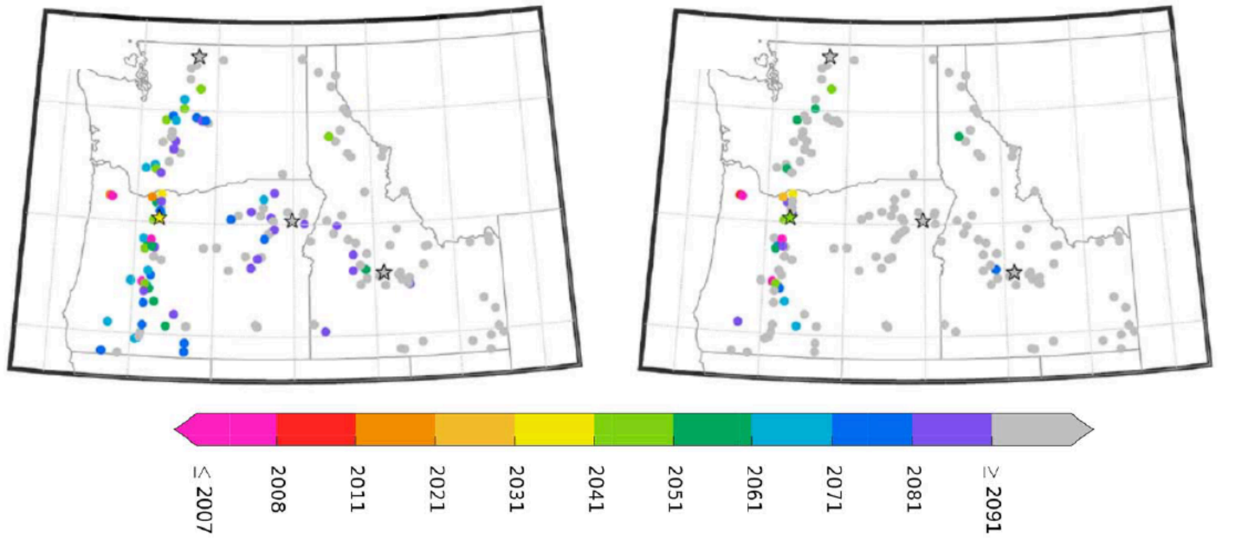

Figure 7. (Left) RCP 8.5 and (right) RCP 4.5 projections of the first decade during which the percentage of wet days that have snow falls below 25% at SNOTEL stations across the Northwest. For example, a circle with color shading corresponding to the year 2041 means that at that station, the 10-year period starting in 2041 is the first decade during which fewer than 25% of wet days will be cold enough for snow to fall. Gray circles indicate that the models do not project that the percentage of snow days will fall below 25% during the twenty-first century. Stations with stars are specific to Catalano et al. (2019), from which this figure is adapted.

Previous Oregon Climate Assessments reported that multiple studies detected trends toward earlier runoff in many snowmelt-dominated watersheds in the Northwest, consistent with a warming climate (e.g., Stewart et al. 2005, Dalton et al. 2017 and reviews therein). Observed changes in the amount and timing of streamflow, especially years with exceptionally early or high midwinter runoff (2015, for example), are eliciting responses from reservoir managers. These managers aim to assess impacts of changes in streamflow on water resources and ecosystems, with the goal of informing management actions (e.g., Cohen et al. 2020, Jones and Hammond 2020). Continued warming is projected to result in earlier streamflow, declining summer flows, and increasing winter flows, particularly for mixed rain and snow and snow-dominated basins (e.g., Dalton et al. 2017 and reviews therein). Three new studies (Burke and Ficklin 2017, Yazzi and Chang 2017, Chen and Chang 2020) projected runoff changes in specific basins in Oregon.

Burke and Ficklin (2017) reported changes in runoff volume and timing in the coastal Siletz watershed, a watershed on the central Oregon coast that provides habitat for Coho salmon (*Oncorhynchus kisutch*). They projected that wet season (November–March) flow will increase by 18% by the end of the twenty-first century under RCP 8.5. The median center timing of flow was projected to shift three days earlier by the middle of the twenty-first century and, in one global climate model, 10 days earlier by the end of the twenty-first century.

Chen and Chang (2020) investigated the effects of climate change on the runoff in the Clackamas River watershed, which provides drinking water to 350,000 people in the Portland metropolitan area. Median summer runoff in the watershed was projected to decline by 50% under the study's warmest scenario (the HadGEM2-ES climate model assuming RCP 8.5). In addition, extreme high flows, defined by the 90th percentile flow volume, were projected to increase by up to 19%, and extreme low flows, defined by the seven-day low flow, were projected to decrease by as much as 20 cubic meters per second by the middle and late twenty-first century (Chen and Chang 2020). The center timing of flow was projected to shift two to three weeks earlier by the 2080s (2070–2099) under the study's warmest scenario. Chen and Chang (2020) also found that land-cover change had minimal impact on watershed-level runoff. Similarly, in the snow-dominated upper Umatilla River in eastern Oregon, which is the main source of irrigation water in that river basin, the center timing of flow was projected to occur nearly one month earlier (Yazzi and Chang 2017).

Projections of future streamflow have several sources of uncertainty, including the selection of climate models, emission scenarios, downscaling methods, and hydrologic model structure and parameters (Praskievicz and Chang 2009). In the Northwest, differences among climate models and representative concentration pathways (RCPs) are the greatest sources of uncertainty in projections of the volume and timing of annual runoff, whereas differences among hydrologic models are the greatest source of uncertainty in projections of low flows in many locations (Fig. 8; Chegwidden et al. 2019). Information about the greatest sources of uncertainty in future hydrological projections for different flow metrics and locations (e.g., Chegwidden et al. 2019) can inform selection of the most appropriate set of hydrological projections for a given application. For the majority of the Columbia River Basin, applications might consider the timing of annual runoff and analyze results among multiple representative concentration pathways, because difference among the latter are the largest source of uncertainty (Fig. 8). In the Willamette Basin, however, it may be sensible to prioritize analysis of results among multiple global climate models, because difference among those models are the greatest source of uncertainty in that geographic area (Fig. 8).

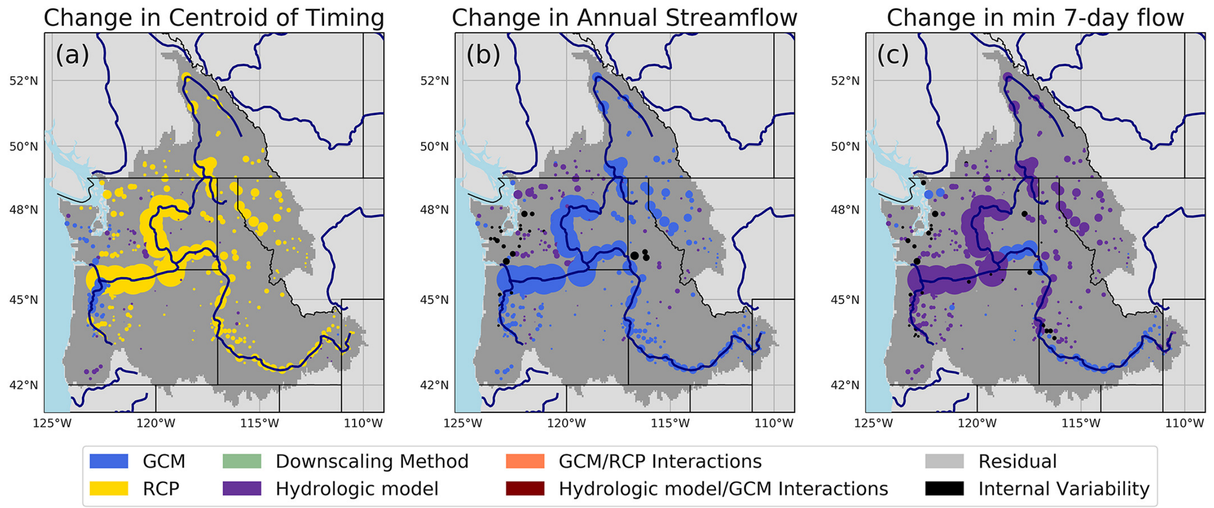

Figure 8. The dominant source of uncertainty in projected changes in the (a) timing and (b) volume of annual runoff and (c) low flows from the 1980s through the 2080s. Marker sizes are scaled by the mean annual historic flows without regulation or irrigation. Source: Chegwidden et al. 2019.

Stream Temperature

Stream temperature is sensitive to changes in air temperature, but also is affected by vegetation cover and water source. In open water, a 1.8°F (1.0°C) increase in air temperature generally leads to 1.1–1.4°F (0.6–0.8°C) increase in water temperature (Morrill et al. 2005), although the sensitivity of stream temperature to air temperature varies on the basis of factors such as water depth, mixing of surface and shallow subsurface water, wind, humidity, and cloud cover. Additionally, riparian vegetation can provide shade that reduces stream temperature. Groundwater input also affects stream temperature because the temperature of groundwater is fairly constant throughout the year, whereas the temperature of surface water fluctuates seasonally. For example, in the upper Middle Fork John Day River in northeast Oregon, a mature riparian forest with 79% effective shade—the percentage of direct solar radiation attenuated and scattered by riparian vegetation before reaching the stream surface—can decrease the seven-day average daily maximum stream temperature (a measure commonly applied in regulation of water temperatures) by ~12.6°F (7.0°C) via changes in air temperature and discharge (Wondzell et al. 2019).

Stream temperature generally is projected to increase across Oregon. Assuming the A1B emissions scenario (an older scenario that falls between RCP 4.5 and RCP 8.5), by the 2080s (2070–2099), relative to the 2000s (1993–2011), August average stream temperature was projected to increase by about 4°F (2.2°C) in most parts of Oregon (Isaak et al. 2017). The increase in stream temperature was projected to be slightly lower in southeastern Oregon.

In the Willamette River Basin, stream temperature was projected to increase by 1.8–7.2°F (1.0–4.0°C) by the 2080s according to three representative climate change scenarios that were based on three global climate models and RCP 8.5. The magnitude of change depended on the climate scenarios and local geology. With the same climate change scenario, the temperature increase was minimal in groundwater-fed streams at high elevations in the Cascade Range, whereas the increase was greatest in low-elevation streams that are fed by surface water (Chang et al. 2018).

In a central Oregon Coast watershed, maximum stream temperature was projected to increase by 5.4°F (3°C) in the mainstem of the North Fork of the Siletz River by the 2080s (2070–2099) under RCP 8.5 as simulated by one global climate model (HadGEM2-ES365) (Lee et al. 2020).

Recent Advances in Climate Science

Three of the areas of climate science that are developing rapidly are simulations of the future climate, prediction of weather conditions three to four weeks into the future (subseasonal-to-seasonal forecasting), and attribution of extreme weather events.

Simulations of Future Climate

For decades, the assessments of the Intergovernmental Panel on Climate Change (IPCC) have been supported by the Coupled Model Intercomparison Project (CMIP). New simulations from CMIP6 (Eyring et al. 2016) have been distributed since 2019 to support development of the IPCC's Sixth Assessment Report, currently scheduled for release in April 2021. In the aggregate, the CMIP6 models estimate a higher equilibrium climate sensitivity (ECS)—the increase in temperature after the climate system reaches equilibrium following a doubling of atmospheric carbon dioxide concentrations—than the CMIP5 models (Fig. 9, Forster et al. 2020). Cloud feedbacks and cloud-aerosol interactions most likely are the primary contributors to the increased ECS (Meehl et al.

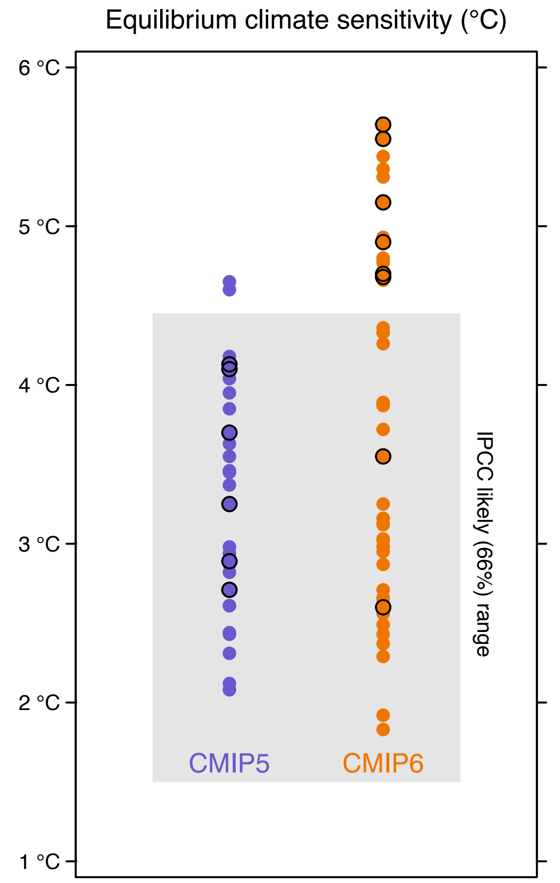

Figure 9. The equilibrium climate sensitivity (ECS) from 30 CMIP5 and 47 CMIP6 global climate models. Black open circles correspond to the models listed in Table 3, except CMCC-CM and HadGEM2-CC, for which ECS values were not found in the literature. Figure adapted from Forster et al. (2020). ECS values from Meehl et al. (2013) and Zelinka et al. (2020).

2020, Zelinka et al. 2020). As of December 2020, a vigorous scientific debate continues about the plausibility of the higher ECS values in the new CMIP6 models. Some scientists argue that the higher ECS values (or the related transient climate response) exceed observational constraints (e.g., Nijsse et al. 2020). Others critique the observational constraint, noting that the warming during 1975–2013 ended with the so-called hiatus, which may have caused the CMIP6 models to overestimate the warming during that period. Regardless, the IPCC long has assessed ECS with a probability distribution. For instance, the grey “likely” range in Fig. 9 means that there is a 66% probability that ECS is within the range of about 1.5–4.5°C, and a 34% probability that ECS is outside that range. The probability that ECS exceeds 4.5°C was not quantified explicitly by the IPCC, but is physically possible. However, it is “very unlikely”—probability less than 10%—that ECS is greater than 6°C (IPCC 2007).

The potential changes in ECS do not affect the scenarios of greenhouse gas concentrations. In the CMIP6 models, the representative concentration pathways (RCPs) that provided estimates of greenhouse gas emissions for CMIP5 have been augmented by shared socioeconomic pathways (SSPs) that describe more explicitly the social and economic scenarios corresponding to each RCP. Here, RCP 4.5 corresponds to SSP2-45, and RCP 8.5 to SSP5-85.

CMIP5	CMIP6
CanESM2	CanESM5
CESM1-BGC	CESM2
CESM1-CAM5	CESM2-WACCM
CMCC-CM	CMCC-CM2-SR5
CNRM-CM5	CNRM-CM6-1
HadGEM2-CC	HadGEM3-GC31-LL
IPSL-CM5A-LR	IPSL-CM6-LR
MIROC5	MIROC6

Table 3. Model pairs from the fifth and sixth phases of the Coupled Model Intercomparison Projects (CMIP5, CMIP6) that were used to create Figure 10.

For this Assessment, CMIP6 outputs were obtained from global climate models that most clearly corresponded to those used in the CMIP5-based analysis for the Northwest (Rupp et al. 2017; Fig. 1a). The CMIP5 models within the selected pairs (Table 3) were among the 10 best-performing models as evaluated by Rupp et al. (2013a), or frequently were used in related studies (e.g., the IPSL-CM5A-LR and MIROC5 models). Also, data for both the historical period and the twenty-first century were available for the selected CMIP6 models. Where multiple versions of a model were available, the version that seemed most similar to the CMIP5 version, given readily available documentation, was chosen. The eight CMIP6 models were used to analyze past and future annual mean temperature in Oregon (Fig. 10), similar to Figure 1a. The CMIP5 versions of these models have a somewhat higher rate of warming than the 35-member average of Rupp et al. (2017).

Another way to parse the CMIP6 data is to draw a direct statistical connection between ECS and temperature change in Oregon (Fig. 11). The CMIP5 projected temperature change for Oregon (Rupp et al 2017) was regressed on each model’s ECS value for each RCP and future period. The regression equations then were applied to the ECS values of the CMIP6 models from Zelinka et al. (2020).

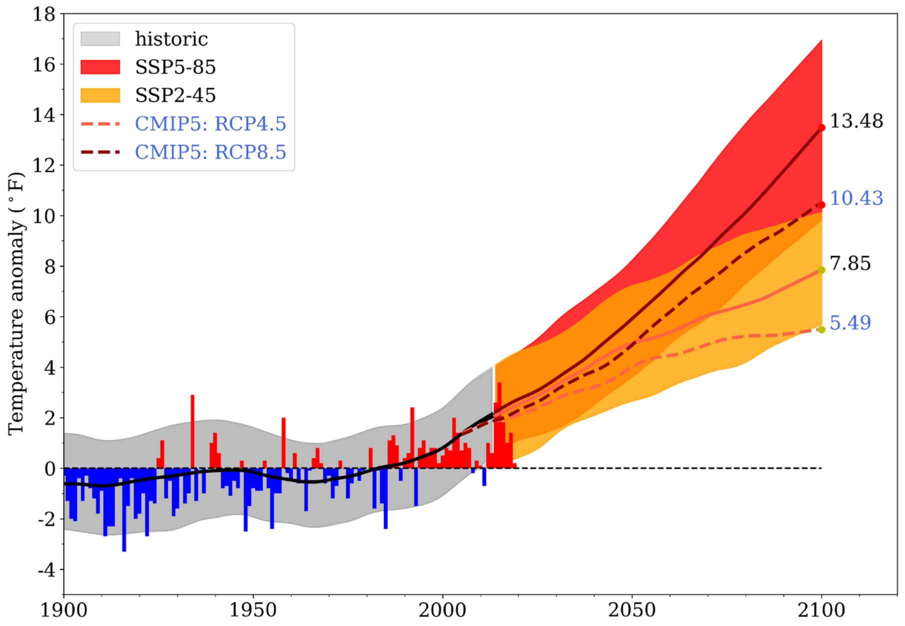

Figure 10. Annual mean temperature in Oregon as observed (blue and red bars; relative to the 1970–1999 average, from NOAA Climate at a Glance) and as simulated by the CMIP6 models for the past (heavy black curve and grey shading). The colored bands and solid curves indicate the average of the two CMIP6 scenarios for 2015–2100, and the dashed curve indicates the corresponding results for CMIP5 (2006–2100). Shaded regions denote the range between the smoothed minimum and maximum annual mean temperature for the eight models. The modeled time series were smoothed with a lowess filter. Mean values for the eight models are printed to the right of the curves and represent the warming relative to 1970–1999.

Consistent with the increase in ECS (Fig. 9), the CMIP6 models suggested higher rates of warming, given either emissions scenario, than their predecessors. Under the RCP 8.5 scenario, the eight CMIP6 models used here, which coincidentally included a disproportionate number with high ECS, led to a 3°F (~1.7°C) greater warming by the end of the twenty-first century than the CMIP5 models. Preliminary estimates that were based on a much larger set of models generally indicated smaller differences in warming between the CMIP5 and CMIP6 models (Fig. 11). Nevertheless, for Oregon and globally, the CMIP6 models suggest that the climate may warm more than expected under the CMIP5 models, if the high ECS values are accurate.

Subseasonal-to-Seasonal Forecasting

Skillful weather forecasts require one to obtain an accurate and thorough estimate of the current state of the atmosphere by assimilating as many observations as possible. Small errors in the initial state of weather propagate, eventually (usually around 10 days) leading to a forecast that is no better than random chance. Seasonal climate prediction, by contrast, aims at a statistical description of the next few months, and rests in large part on the evolving state of the tropical ocean, especially the central and western Pacific Ocean. Between the time scales of skillful weather forecasts and skillful seasonal forecasts are the subseasonal-to-seasonal scales. Recent progress on probabilistic forecasts with some skill on these time scales for the Northwest builds on the work of Bond and Vecchi (2003), who were the first to demonstrate a link between the tropical weather variability known

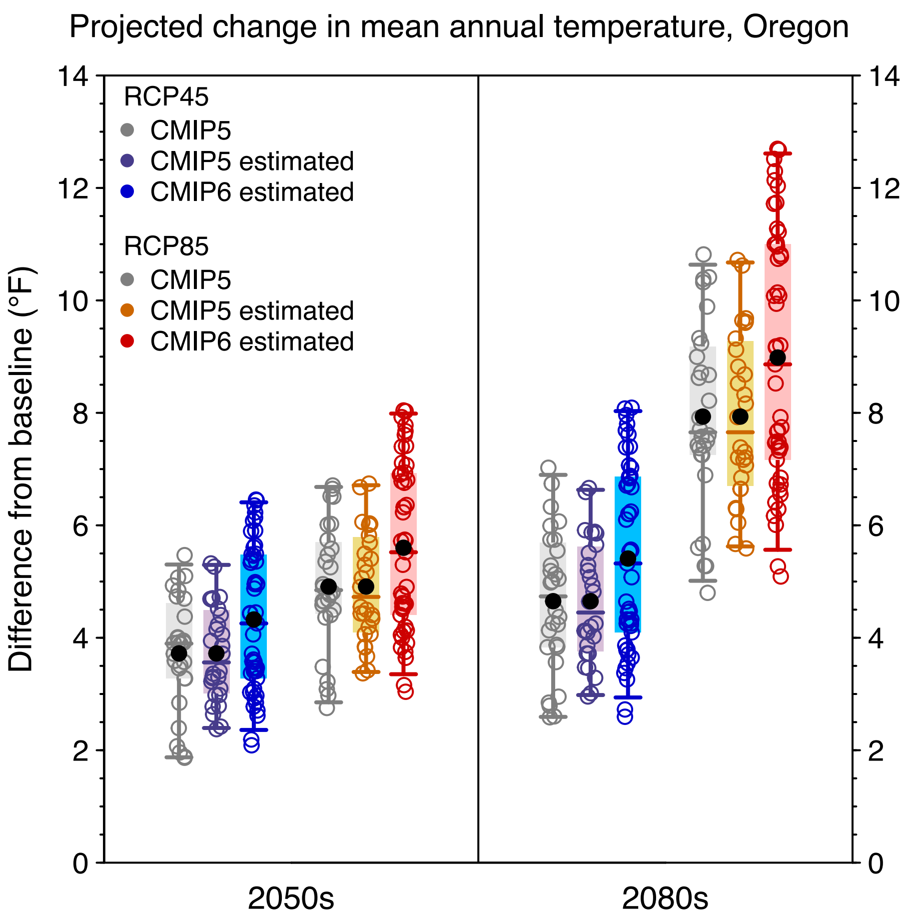

Figure 11. Projected change in Oregon mean annual temperature as the difference between a baseline period (1970–1999) and two future periods (2040–2069, or the 2050s; and 2069–2098, or the 2080s). Estimates were based on direct climate model outputs (gray symbols) or estimates derived from ECS (colored symbols) from CMIP5 (28 models) and CMIP6 (47 models) under RCP 4.5 and RCP 8.5, as described in the text.

as the Madden-Julian oscillation and weather in the Northwest. They discovered that certain phases of the Madden-Julian oscillation corresponded to a heightened risk of flooding in the Northwest. Given the inherent 40- to 50-day duration of the oscillation, their results suggested potential predictability of flooding of at least a few weeks.

Advances in research, observations, and modeling are propelling improvements in the predictability of climate at temporal extents between one week and one month. Perhaps the most comprehensive analysis of subseasonal modeling included seven global atmospheric models (some of which are used in operational weather forecasts) and 17 years of retrospective forecasts. This analysis evaluated forecasts for the third week (the average of days 15 through 21) after the forecasts were made (Pegion et al. 2019). Each of the models made skillful forecasts of Northwest temperature, and the model average was even more skillful. Although similar analysis of precipitation forecast skill was not presented, the models appeared to be capable of forecasting large precipitation anomalies. Pegion et al. (2019) provided an example in which the third week of forecasts of precipitation in October 2018 indicated large wet anomalies. These anomalies coincided with the formation and landfall of Hurricane Michael in the southeastern United States.

Seasonal-to-subseasonal forecasting has the potential to improve climate adaptation. Increasing the advance warning of weather anomalies, such as rapidly developing droughts (Pendergrass et al. 2020) or heat waves, floods, or windstorms, increases preparation time and may improve outcomes. As an example, federal management of reservoirs throughout the year is determined by seasonally dependent reservoir rule curves. These curves describe the desired elevation (amount of water) in each reservoir, and typically are quite low during flood season. However, the rule curves

were developed decades ago, when weather forecasts were accurate only a few days in advance. Incorporating a modern understanding of forecast skill in the 7–10 day (or 15–21 day) time horizon would allow reservoirs to be maintained at higher elevation and avoid a situation in which reservoirs cannot be refilled at the end of flood season (as was the case throughout Oregon in 2015). Such adjustments would help mitigate the stresses of droughts and floods in a changing climate.

Attribution of Climate Events

Attribution of climate phenomena "is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with formal assessment of confidence" (IPCC 2018). Increases in global average temperature since the mid-twentieth century were attributed to human activity by the mid-1990s (e.g., Hegerl et al. 1997). Attribution of seasonal temperature and precipitation in the Northwest suggested that only human activity could account for the warming in each season, but did not indicate that changes in precipitation were attributable to human activity (Abatzoglou et al. 2014). Armal et al. (2018) investigated trends in extreme daily precipitation across the United States. They detected a trend at 35% of Northwest weather stations, and found that most trends could be explained by anthropogenic forcing and natural modes of climate variability.

During the past decade, the focus of attribution research shifted from annual and seasonal means over large areas to human influences on the magnitude or likelihood of specific extreme events or classes of extreme events (e.g., Herring et al. 2020, Swain et al. 2020). NASEM (2016) made highly relevant points about framing questions of attribution, the capabilities for attribution of different types of events, and the fact that basic principles of physics suggest that as climate changes, many types of extreme events will become more likely. Two of these points are discussed here.

First, asking whether climate change caused a certain event is less useful than asking about the change in the likelihood of the event as a result of human activities. Some studies have focused on an individual event and simulated that event under specific meteorological conditions, then created a counterfactual—an alternate simulation or simulations—in which the meteorological conditions were changed to reflect understanding of the physical influence of elevated greenhouse gases. For instance, to study human influence on rainfall intensity in Hurricane Harvey, which deposited as much as 52 inches (1.3 m) of rain over part of Texas, including Houston, in August 2017, van Oldenborgh et al. (2017) subtracted the warming of the ocean surface estimated with the EC-Earth2.3 climate model from the observed ocean temperatures, and ran simulated weather forecasts with a moderately high-resolution atmospheric model. Another approach is to define an extreme event, run numerous simulations, and then compare how often the event occurred with and without greenhouse gas forcing. This approach was applied to the attribution of warm and dry conditions during the 2011 Texas drought (Rupp et al. 2012, 2015), low precipitation in the central United States in 2012 (Rupp et al. 2013b), changes in Northern Hemisphere snow cover in spring (Rupp et al. 2013c), extreme heat in central California (Mera et al. 2015), and exceptionally low spring snowpack in the Northwest in 2015 (Mote et al. 2016).

Second, by considering both the physical effects of climate change on the event type and the confidence in attribution of specific events, NASEM (2016) delineated the capacity for attribution of different types of events on the basis of the expected magnitude of change and the confidence with which models can simulate those events. Attribution is most feasible for cold events, which are becoming less common as concentrations of greenhouse gases increase, followed by heat events, which are becoming more common. Attribution of droughts and extreme rainfall is moderately feasible, and somewhat less feasible for extreme snow and ice storms and tropical cyclones. Attribution of extratropical cyclones, fire, and severe convective storms is difficult.

Previous Oregon Climate Assessments (e.g., Dalton et al. 2017) reported on formal attribution studies in the Northwest, including average and seasonal temperature and precipitation (Abataoglou et al. 2014), fuel aridity related to area burned by wildfire in the western United States (Abatzoglou and Williams 2016), low snowpack in 2015 (Mote et al. 2016), and acidity of coastal ocean water (Feely et al. 2016). Williams et al. (2020) analyzed the contribution of anthropogenic climate change to the particularly dry conditions of the early twenty-first century in an area covering the southwestern United States and most of Oregon. The period 2000–2018 in this geographic region was the second-driest 19 years since 800 CE, and climate model simulations suggested that 47% of the observed dryness in soil moisture was driven by the effect of anthropogenic climate change on temperature, humidity, and precipitation (Williams et al. 2020).

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Extreme Heat

Meghan Dalton and Paul Loikith

Influence of Climate Change on Extreme Heat Events

Warming temperatures are increasing the frequency and intensity of extreme heat events. Extreme heat can include days with maximum temperatures over a threshold, seasons with temperatures well above average, and heat waves, or multiple days with temperature above a threshold. Heat waves occur periodically as a result of natural variability, but human-caused climate change is increasing their severity (Vose et al. 2017). Additionally, 82% of the increase in the frequency of hot summers—average June, July, and August temperatures more than two standard deviations above a baseline—over the western United States from 2000–2010 relative to 1978–1999 may be attributable to anthropogenic climate change (Kamae et al. 2017). Changes in extreme temperatures due to climate change can result directly from increases in temperature. Changes in extreme temperatures also can be an indirect result of changes in the weather patterns that lead to temperature extremes. Atmospheric conditions that drive extreme heat events in Oregon include upper-level ridges of high pressure and offshore flows; the specific atmospheric patterns conducive to heat events vary among the western, central, and eastern portions of the state (Loikith et al. 2017). Previous Oregon Climate Assessments reported on research that projected a weakening of summer atmospheric ridges and fewer days with strong offshore flow events, particularly in western Oregon (Brewer and Mass 2016a, b; Dalton et al. 2017). This suggested that although increases in average temperatures will lead to a larger number of heat events, and more severe extreme heat events, across the state, the increase may be greater in eastern Oregon than in western Oregon (Dalton et al. 2017). However, the degree to which future changes in warm temperature extremes in Oregon and the Northwest will be affected by changes in these weather patterns is still an active area of research.

Observed Trends in Extreme Heat

The frequency and magnitude of very hot days is increasing across Oregon. Very hot temperatures can be defined on the basis of relative thresholds, such as days on which the maximum temperature is above the 90th percentile of some reference period, or absolute thresholds, such as days on which the maximum temperature is above 90°F (32°C). Medford, Pendleton, and Portland, Oregon, have different climates, but annual variability in temperature has been considerable in all three, and the number of days exceeding

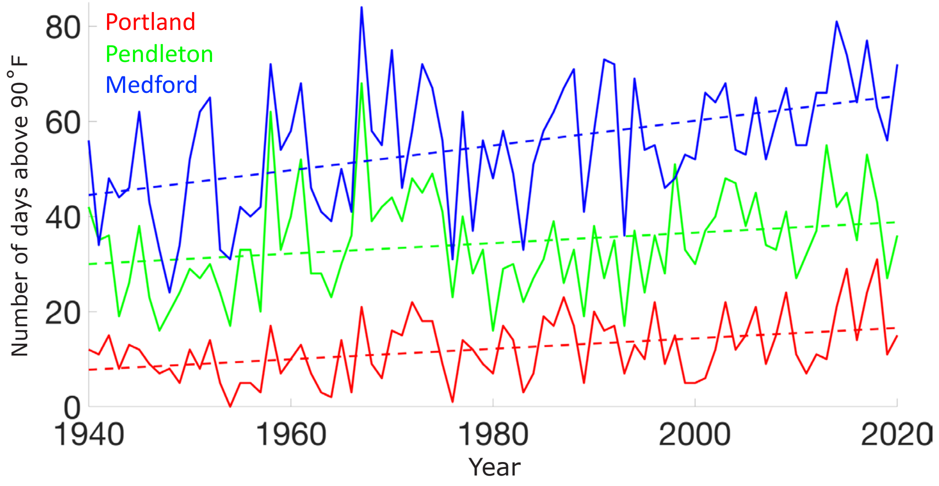

Figure 1. Number of days per year on which the daily high temperature exceeded 90°F at Medford, Pendleton, and Portland. Data source: NOAA National Centers for Environmental Information, www.ncdc.noaa.gov/ghcnd-data-access.

90°F increased markedly since the mid-twentieth century (Fig. 1). Since 1940, the number of days exceeding 90°F increased by over eight days per year in Portland and Pendleton, and 21 days per year in Medford. The number of 90˚F days in Portland in 2015 (29) and 2018 (31) broke records. These increases are representative of other cities across the state, with the exception of those at the immediate coast and relatively high elevations, where the number of days above 90°F is too small to observe a trend.

Previous Oregon Climate Assessments reported increasing trends in the number of summer extreme heat events as defined by minimum temperature thresholds (Bumbaco et al. 2013, Mote et al. 2013, Oswald and Rood 2014, Dalton et al. 2017). Recent publications are consistent, indicating that trends in summer extreme heat events as defined by nighttime minimum temperatures are stronger than those based on daytime maximum temperatures (Oswald 2018, Thomas et al. 2020). Over the period 1978–2015, the number of summer minimum temperature heat waves increased significantly over most of Oregon, except parts of eastern Oregon (Oswald 2018). The number of summer maximum temperature heat waves over southeastern Oregon also increased significantly (Oswald 2018).

Projections of Future Extreme Heat

Hot summer days are projected to become more frequent in Oregon under continued global emissions of greenhouse gases, and overnight lows will continue to become warmer (Dalton et al. 2017, Mote et al. 2019). The frequency, duration, and intensity of extreme heat events is expected to increase. Not only are summers expected to warm more than annual average temperatures, but the hottest days in summer are projected to warm more than the mean summer temperature over the Pacific Northwest (Dalton et al. 2017). The hot summers of 2015 and 2018 are salient examples of summer temperatures that are expected to become relatively common by the middle of the twenty-first century.

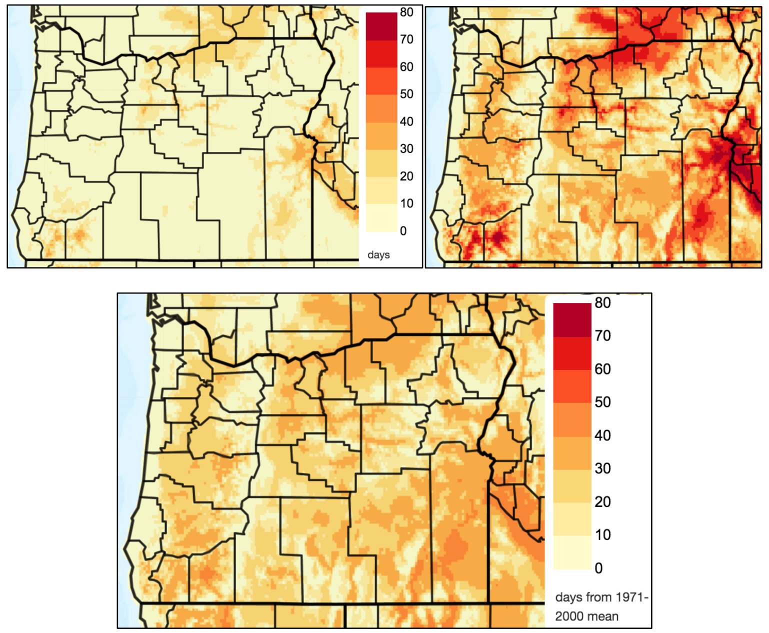

Figure 2. Number of days from April through October with a heat index ≥90°F in historic (1971–2000, top left) and future (2040–2069, top right) periods under RCP 8.5, and the change between those periods (bottom). Data are means of 18 downscaled models from the Coupled Model Intercomparison Project Phase 5. Source: Climate Toolbox, climatetoolbox.org/tool/climate-mapper (Dahl et al. 2019).

The fourth Oregon Climate Assessment reported that by the mid-twenty-first century under RCP 8.5 (a scenario that represents a continuation of current levels of greenhouse gas emissions throughout the twenty-first century, or a relatively high amount of warming), the number of days per year with temperatures above 86°F (30°C) would increase by at least 30 at most locations in Oregon, except at high elevations and the coast (Mote et al. 2019). New research on projected increases in heat index days (Dahl et al. 2019) provides insight on the human health impacts of extreme heat. The heat index is a measure of perceived heat that reflects both temperature and relative humidity. The National Weather Service issues heat warnings when the heat index exceeds given local thresholds. As relative humidity increases, a given temperature can feel hotter. Across Oregon, heat waves rarely are humid (Rastogi et al. 2020), and the heat index generally is similar to the actual temperature. By the mid-twenty-first century under RCP 8.5, the number of days per year with a heat index greater than or equal to 90°F is projected to increase by at least 15 days across the majority of counties in Oregon (Fig. 2, Table 1).

Effects of Extreme Heat on Public Health and the Built Environment

Increases in the frequency of extreme heat events, and even small increases in average summer temperatures, are expected to increase the incidence of heat-related illnesses and deaths, particularly among the elderly; children; people with chronic illnesses; people with low incomes; Black, Indigenous, and People of Color; and outdoor workers (Ebi et al. 2018; *Public Health*, this volume). Excess mortality from heat waves is likely in cities and countries around the world (Guo et al. 2018). In the United States, without any adaptation, excess heatwave-related deaths were projected to increase by an average of 422% by 2031–2080 relative to 1971–2020 under RCP 8.5 and a median population scenario. With full adaptation measures, including a spectrum of interventions from individual to public policy, excess heatwave-related deaths were projected to increase by 57% (Guo et al. 2018). Increases in projected excess heatwave-related deaths in Portland, Oregon were slightly less than the United States average (Guo et al. 2018).

County	Historical baseline (1971–2000)	Mid-twenty-first century RCP 8.5 (2040–2069)	Change	County	Historical baseline (1971–2000)	Mid-twenty-first century RCP 8.5 (2040–2069)	Change
Baker	5	27	22	Lake	3	24	21
Benton	4	25	21	Lane	4	24	20
Clackamas	2	15	13	Lincoln	1	6	5
Clatsop	1	6	5	Linn	3	22	19
Columbia	2	16	14	Malheur	12	45	33
Coos	1	7	6	Marion	3	20	17
Crook	4	26	22	Morrow	12	38	26
Curry	3	15	12	Multnomah	4	23	20
Deschutes	3	21	18	Polk	4	23	19
Douglas	6	28	22	Sherman	13	42	29
Gilliam	14	43	29	Tillamook	0	4	4
Grant	3	21	18	Umatilla	10	35	24
Harney	4	30	26	Union	3	20	17
Hood River	2	12	10	Wallowa	4	21	18
Jackson	9	33	24	Wasco	9	34	24
Jefferson	9	33	24	Washington	4	21	17
Josephine	13	40	26	Wheeler	7	28	22
Klamath	2	20	17	Yamhill	5	24	19

Table 1. Averaged multiple-model mean values of and changes in the number of days from April through October with a heat index ≥90°F in historical (1971–2000) and future (2040–2069) periods under RCP 8.5. All changes are increases. Data derived from 18 downscaled climate models from the Coupled Model Intercomparison Project Phase 5. Source: Climate Toolbox, climatetoolbox.org/tool/climate-mapper (Dahl et al. 2019).

Increasing access to air conditioning often is touted as a means of increasing resilience to extreme heat events. At present, about 68% of single-family homes and manufactured homes in Oregon have cooling systems, and about 25% of multifamily residences have cooling systems (NEEA 2019). The areas in which extreme heat historically was most common, such as southern and eastern Oregon, have a larger proportion of homes with cooling systems. However, heat also can be extreme in western Oregon, and such extreme heat is becoming more frequent as climate changes. The number of residences in Oregon with air conditioning is increasing, which can improve health outcomes. However, air conditioning also can increase emissions of greenhouse gases that contribute to climate change. Passive survivability in building design can be an alternative to increasing air conditioning (*Built Environmen*t, this volume). Additionally, heat waves can increase the demands on electric power for cooling, increasing the risk of cascading failures within the electric power network (Clarke et al. 2018). *Built Environment* (this volume) discusses an extreme heat event in summer 2020 that challenged the West Coast's electricity supply. Urban heat islands are addressed in *Built Environment*, *Public Health*, and *Social Systems* (this volume).

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Drought

Larry O'Neill, Benjamin Hatchett, and Meghan Dalton

Introduction

Drought is a natural hazard with significant social, economic, and ecological impacts. Persistent drought is common in the Northwest (Gedalof et al. 2004, Knapp et al. 2004, Bumbaco and Mote 2010, Xiao et al. 2016), and Oregon is among the more drought-prone states (e.g., Cook et al. 1999). Over the last 20 years, the incidence, extent, and severity of drought has increased in both the western United States in general and the Northwest in particular compared with the twentieth century (e.g., Dalton et al. 2017, Williams et al. 2020). These droughts have had numerous adverse impacts on agriculture, water availability, recreation, ecosystems, and wildfire risk. The likelihood of continued increases in drought severity and duration in the twenty-first century raises questions about how best to prepare for and mitigate the impacts of drought and how to better understand drought and its causes. This chapter highlights recent advances in the understanding of drought in Oregon and discusses how climate change is projected to influence drought.

The simplest conceptual definition of drought is "insufficient water to meet needs" (Redmond 2002). Drought broadly may be defined as a sustained imbalance of moisture supply and demand at the surface relative to long-term average conditions. Precipitation supplies moisture, whereas evapotranspiration creates a moisture demand. Drought severity depends on the magnitude and duration of moisture deficiency and the size of the affected area. Four primary classes of drought used widely in monitoring and research distinguish between impacts and physical causes: meteorological, hydrological, agricultural, and socioeconomic (Wilhite and Glantz 1985, Rasmussen et al. 1993). Meteorological drought typically is defined by lack of precipitation, or by evaporative demand that exceeds precipitation. For Oregon, the minimum period of time for consideration of meteorological drought operationally is about 90 days. Hydrological drought occurs when prolonged meteorological drought affects surface or subsurface water supply, such as streamflow, reservoir and lake levels, or groundwater levels. Hydrological drought tends to evolve more slowly than meteorological drought, with extents longer than six months. Agricultural drought occurs when meteorological and hydrological drought impacts agricultural production, and usually reflects precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits, and reduced availability of irrigation water.

The latter three drought classes largely reflect physical phenomena. Socioeconomic drought, by contrast, occurs when meteorological, hydrological, or agricultural drought reduces the supply of some economic or social good or service. Examples include lower crop yields or reductions in outdoor recreation. Socioeconomic drought often affects state and federal drought declarations. In addition to these primary drought designations, three other drought designations—ecological, flash, and snow—were proposed more recently to reflect more-specific drivers and impacts of drought. Ecological drought is defined as "[a]n episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems" (Crausbay et al. 2017). Like agricultural drought, ecological drought usually is caused by meteorological and hydrological drought. Vegetation and soil types affect likelihood of ecological drought.

Flash drought refers to relatively short periods of warm surface temperatures, low relative humidities and precipitation deficits, and rapidly declining soil moisture. These droughts tend to develop and intensify rapidly within a few weeks (e.g., Otkin et al. 2018, Pendergrass et al. 2020), and may be generated or magnified by prolonged heat waves (e.g., Mo and Lettenmaier 2015, Rupp et al. 2017, Chen et al. 2019).

Snow droughts are defined when snowpack—or snow water equivalent (SWE)—is below average for a given point in the water year, traditionally 1 April (Harpold et al. 2017, Hatchett and McEvoy 2018). Years with low SWE on 1 April often are followed by summers with low river and stream flows. The low flows sometimes lead to or exacerbate water supply deficiencies, especially in snowmelt-dominated basins. Although the idea of snow drought has existed for many years (e.g., Wiesnet 1981), it was further developed in Oregon (Sproles et al. 2017) and the Northwest following the 2015 water year, in which below-average snowpack counterintuitively corresponded with above-average precipitation (Mote et al. 2018). This type of snow drought is classified as warm snow drought. Dry snow drought is classified on the basis of below-average snowpack and precipitation (Harpold et al. 2017).

The dimensionless Standardized Precipitation-Evapotranspiration Index (SPEI) is a key quantitative metric for assessing the occurrence and severity of meteorological and hydrological drought. The SPEI compares the net water balance between precipitation and potential evapotranspiration (evapotranspiration from a large area with uniform vegetation and unlimited soil water) between a recent period of time and a historical period (Vicente-Serrano et al. 2010). The SPEI allows for comparison of drought severity in different locations and times and for identification of different drought types (e.g., Ahmadalipour et al. 2017), including consideration of the role of temperature in drought assessment (Vicente-Serrano et al. 2010). The 12-month SPEI is a reliable predictor of annual streamflow in the Northwest (e.g., Abatzoglou et al. 2014, Peña-Gallardo et al. 2019) and water levels in lakes and reservoirs (e.g., McEvoy et al. 2012).

Meteorological droughts generally build over seasonal or longer periods of time in the Northwest, but they often end relatively abruptly. Precipitation from atmospheric rivers terminates an estimated 60–74% of persistent droughts in the Northwest (Dettinger 2013). Some colloquially refer to atmospheric rivers as drought busters in recognition of their ability to erase large precipitation deficits over a period of time as short as a few days. Along the west coast of the United States, atmospheric rivers are considered critical in terminating droughts. However, atmospheric rivers can create another natural hazard—floods (*Floods*, this volume).

Historical Trends in Drought Severity and Extent

From 2000 through 2020, an average of 37% of Oregon experienced drought of at least moderate intensity, as classified by the U.S. Drought Monitor (USDM), and extreme drought affected nearly 7% of the state (Fig. 1). The USDM provides a consistent overview of drought conditions in the United States. It combines multiple indicators of dryness, including precipitation, snowpack, streamflow, soil moisture, groundwater, and evapotranspiration, at multiple temporal extents, into a single drought severity classification (Svoboda et al. 2002). The total area of Oregon affected by drought varied significantly over the last 20 years, and multiple-year droughts were common (Fig. 1). The impacts of conditions consistent with the USDM's most intense drought categories, extreme (D3) and exceptional (D4), often are widespread and severe across multiple sectors. Major impacts observed in Oregon during these most intense droughts included widespread losses of major crops and pastures, loss of snow- and water-based outdoor recreation, and shortages of water in reservoirs, streams, and wells. In the last 20 years, Oregon experienced exceptional drought only once, from July 2003 through January 2004 in southeast Oregon. This drought affected an average of 5% of the state. Extreme drought occurred during five distinct episodes: portions of 2001, 2004–2005, 2014–2015, 2018, and 2020 (see Box 1).

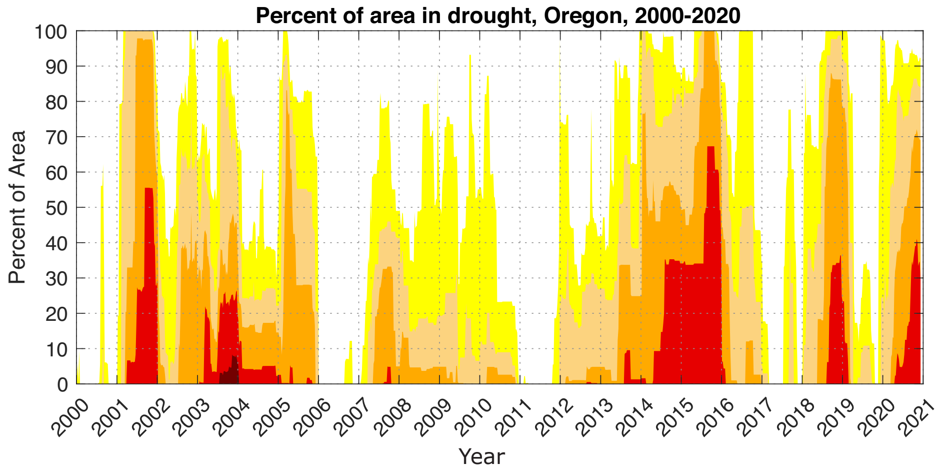

Figure 1. Percentage of Oregon's area in drought according to the U.S. Drought Monitor (droughtmonitor.unl.edu). The five drought classifications are abnormally dry (D0, light yellow), moderate drought (D1, tan), severe drought (D2, orange), extreme drought (D3, red), and exceptional drought (D4, dark red). White corresponds to neutral conditions.

The USDM drought categorization has many uses, but is not suitable as an objective definition of drought when analyzing long-term historical conditions or future climate projections. A better metric for the latter applications is the SPEI, which is a key indicator of water supply and demand as reflected in the USDM. In 14 of the last 20 years, the statewide annual SPEI was negative, indicating dry conditions (Fig. 2). In six of these years, SPEI was less than -0.8, indicating widespread, moderate-to-severe meteorological and hydrological drought (Fig. 2). In Oregon and the southwestern United States, the period 2000–2018 was the second-driest 19 years since 800 CE (Williams et al. 2020). Climate model simulations also suggested that 47% of the dryness in soil moisture observed from 2000 through 2018 was driven by the effect of anthropogenic climate change on temperature, humidity, and precipitation (Williams et al. 2020).

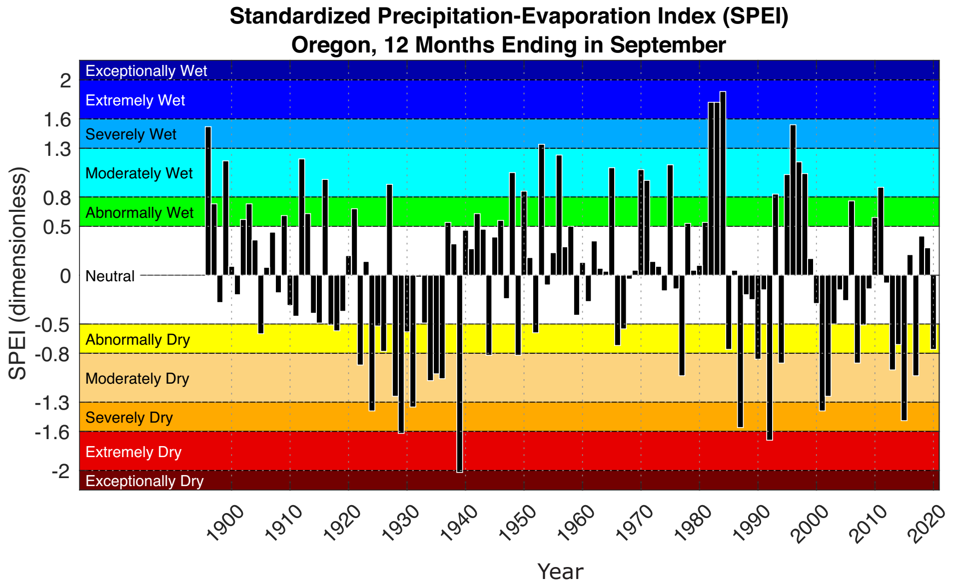

Figure 2. Time series of water year Standard Precipitation-Evapotranspiration Index (SPEI) for Oregon. Negative values follow the U.S. Drought Monitor's drought classifications, and positive values follow the Climate Toolbox U.S. Water Watcher tool (climatetoolbox.org/tool/US-Water-Watcher). Data Source: West Wide Drought Tracker, wrcc.dri.edu/wwdt/time/, with the following selections: Oregon, SPEI, 1895–2020, September, 12-month; accessed 19 December 2020.

Persistent and severe drought has been a feature of Oregon's climate over the past 20 years (Fig. 1, 2). These droughts were caused by different conditions, such as low winter precipitation and snowpack (2001), low summer precipitation and high winter temperature (2003), and low snowpack and low winter precipitation (2005) (Bumbaco and Mote 2010). Low

Box 1. Oregon drought during water year 2020

During water year 2020, most of Oregon was in the midst of a historically significant drought (Fig. B1). The exception was northeast Oregon, which received well above average precipitation and flooding associated with a powerful atmospheric river event (*Floods*, this volume). Statewide, water year 2020 was the 13th driest and 10th warmest among the 125 years of record (1895–2020; NCEI 2020).

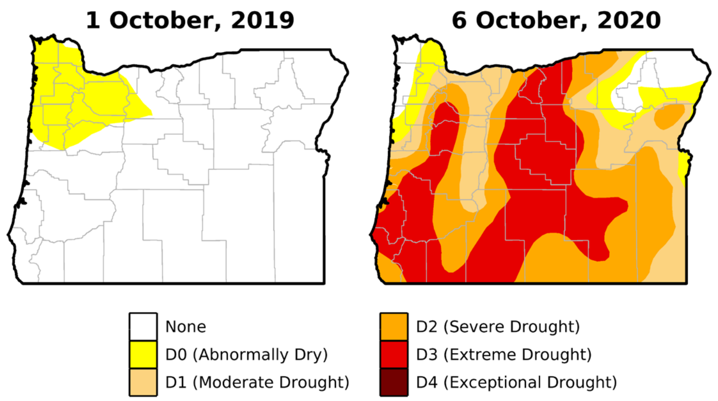

Figure B1. Progression of drought severity throughout water year 2020 as depicted by the weekly U.S. Drought Monitor for (left) 1 October, 2019 and (right) 6 October, 2020.

Fifteen counties in southwest and central Oregon, in which the water year was the 11th driest on record, were granted state-level drought declarations (Fig. B2) due to impacts on surface water availability and agricultural and livestock production.

Although precipitation across much of the state was well below average, snow water equivalent (SWE) in the north and central Cascade Range was only slightly below normal on 1 April. In southern Oregon, by contrast, precipitation and 1 April SWE were well below normal, and therefore the drought in that region had a significant snow drought component. The snowpack melted out one to three weeks early in the Klamath and Rogue River Basins, which elevated streamflows to near normal for a few weeks. Early meltout also occurred in the Willamette River Basin as a result of anomalously high temperatures throughout Oregon from mid-April through mid-May.

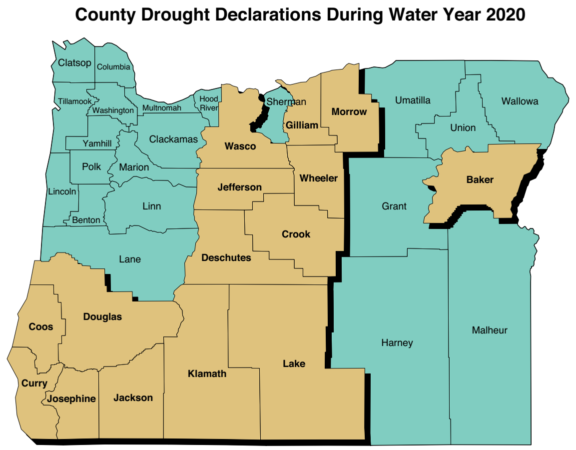

Figure B2. Counties with state-level drought declarations in September 2020 (tan shading). Fifteen counties had governor-approved drought declarations during water year 2020.

see **Water Year 2020**, page 42

precipitation contributed to each drought, but temperature and snowpack also affected drought severity and impacts, including the propagation of meteorological drought to hydrological and agricultural drought (Bumbaco and Mote 2010). Multiple studies have associated cooler sea surface temperatures in the eastern Pacific Ocean during La Niña with the 1998–2004 drought in the western United States (e.g., Hoerling and Kumar 2003, Seager 2007), and with other historical droughts in that region (e.g., Herweijer et al. 2006, Cook et al. 2007).

A number of severe droughts, with different causes, occurred in Oregon since 2010. The most severe of these droughts occurred from 2013–2015 and reflected very low winter precipitation (2014 water year) and snowpack (2015 water year). During water year 2014, SWE was near normal at high elevations and slightly above normal at low elevations (Fig. 3a). During the warm snow drought in water year 2015, precipitation was above normal (Sproles et al. 2016), but SWE was well below normal throughout the state (Fig. 3b), driven by warm temperatures that caused precipitation to fall primarily as rain (Mote et al. 2016) and earlier snowmelt. The water year 2015 drought possibly was accelerated by a snow albedo feedback whereby more sunlight is absorbed by bare ground than by snow, which further increases the surface air temperature and melts the snow (Walton et al. 2017). Water years 2014 and 2015 illustrate two types of snow droughts that may become more common in a warmer climate. First, the snow season may begin later and end earlier, with below-normal peak SWE (e.g., 2014 [Fig. 3a] and, to a lesser extent, 2020). Second, warm temperatures may cause more precipitation to fall as rain and less as snow, resulting in shorter snow-covered durations with smaller peak snowpacks (e.g., 2015, with greater negative SWE anomalies than 2014; Fig. 3b).

Anticipated Impacts of Climate Change on Drought

Climate models project warmer and drier summers for Oregon, and decreases in mountain snowpack due to warmer winter temperatures (*State of Climate Science*, this volume). These factors increase the likelihood of one or more types of drought. Snow drought, for instance, is projected to occur more frequently under a warmer climate as the proportion of precipitation falling as snow decreases. These conditions are projected to increase winter runoff and decrease runoff during spring and summer (e.g., Vano et al. 2015b).

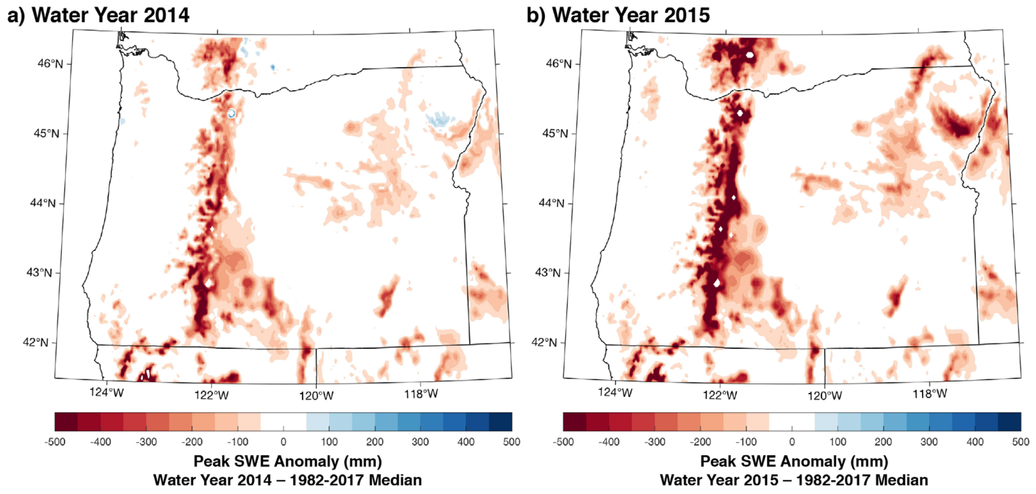

Figure 3. Peak snow water equivalent (SWE) anomalies calculated as differences from the water years 1982–2017 median peak SWE for two recent water years with notable snow drought: (a) water year 2014 and (b) water year 2015. Figure created by Benjamin Hatchett from a 4 km resolution reanalysis of daily SWE from Broxton et al. 2016.

It is still an open question whether conditions similar to the 2015 snow drought may become common by the middle of the twenty-first century (Cooper et al. 2016, Dalton et al. 2017). A sensitivity analysis of historical climate data suggested that for every 1.8°F (1°C) of warming, peak SWE decreases up to 30% (Cooper et al. 2016). Recent work also suggested that effects of anthropogenic forcing on spring snowpack trends since 1980 may have been mitigated by natural variability forced by large-scale changes in atmospheric circulation, which were driven by Pacific sea surface temperatures (Siler et al. 2019). The latter study noted that declines in the snowpack of the western United States may accelerate once the cycle of natural variability shifts from its current mode. Ultimately, projections suggest a decrease in winter snowpack of upwards of 60% by 2050 under RCP 8.5 (a scenario that represents a continuation of current levels of greenhouse gas emissions throughout the twenty-first century, or a relatively high amount of warming) (Fyfe et al. 2017). As climate change reduces mountain snowpack, seasonal drought will become less predictable in the western United States, including Oregon (Livneh and Badger 2020), and snow droughts will increase the likelihood of hydrological or agricultural drought during the following spring and summer (e.g., Koster et al. 2010, Wood et al. 2016).

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Southwest Oregon was first region to experience significant impacts from the drought. Irrigation allocations at the beginning of March were about one-third of normal, leading many producers in the Klamath Basin, for instance, to curtail planting or to rotate to less water-intensive crops. The Oregon Department of Forestry announced an early start of the wildfire season in southwest Oregon due to elevated wildfire risk from dry and warm conditions.

Late spring rainfall was insufficient to alleviate large precipitation deficits across the state, although it delayed drought impacts until mid to late summer across much of western Oregon. Compounding the low winter precipitation east of the Cascade Range was the lack of rainfall during the typical North American monsoon season (July–September). On average, eastern Oregon receives 10–30% of its annual precipitation during these months. The South Central Oregon Climate Division (Fig. B3, CD7) received 0.42 inches (1 cm) of rain from July–September 2020 compared with an average of 1.6 inches (4 cm); this ranks as the fifth driest July–September in the 125-year period of record (NCEI 2020). Additionally, the two-month period August–September 2020 was the third warmest on record for CD7, where average temperatures were 5.0°F (2.8°C) warmer than normal. The low precipitation and high temperatures resulted in extremely dry soil, consistent with flash drought. The most acute impacts were reported in Malheur County. The lack of monsoonal thunderstorms minimized summer lightning activity in eastern Oregon, and lightning did not spark wildfires in the dry vegetation.

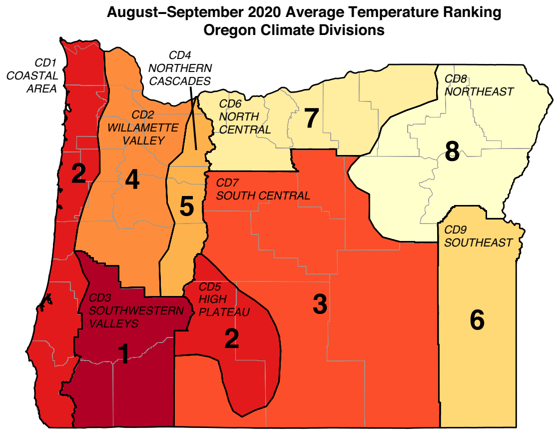

Figure B3. Rank of August–September average temperature over the past 125 years by state climate division (CD). A rank of 1 indicates the warmest average on record. Official rankings from the NOAA National Centers for Environmental Information published December 2020 and retrieved on 19 December 2020.

Conditions consistent with flash drought, driven by near record-high temperatures and dryness, also affected western Oregon during late summer (Fig. B3). The Southwest Oregon Climate Division (CD3) recorded its warmest August–September on record, the Willamette Valley Climate Division (CD4) its fourth warmest, and the Coastal Climate Division (CD1) its second warmest. These conditions contributed to the rapid expansion of wildfires throughout western Oregon during September.

The drought led to a number of very low reservoir levels. Wickiup Reservoir in the central Cascade Range, for instance, was at 1% of capacity by mid-September, a historical low. Delivery of irrigation water from Prineville Reservoir was curtailed in late August due to low water levels and the need to maintain minimum flow requirements on the Deschutes River. Even with irrigation curtailments, reservoirs in southwest Oregon ended water year 2020 at less than 15% of capacity, meaning essentially no carryover into water year 2021.

The social and economic impacts of snow drought may be considerable in basins that rely more heavily on irrigation water derived from snowmelt runoff. In the Columbia River Basin, for example, snowmelt runoff accounts for about 25% of total surface water allocated to irrigation (Qin et al. 2020). The Willamette River Basin also is vulnerable to projected decreases in Cascade Range snowpack and snowmelt runoff, with increased incidence of short-term agricultural drought during summer (Jung and Chang 2012). Short-term drought during the growing season may have major effects on agricultural productivity if water for irrigation becomes limited. Watersheds in the Northwest that receive both rain and snow, and in which snowmelt contributes substantially to streamflow during sprng and summer, are the most sensitive to projected winter warming (Vano et al. 2015a). The frequency of hydrological drought is projected to increase in such watersheds.

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Wildfire

Andrés Holz, Jessica Halofsky, William Nanavati, Laura Platt, and Kelly Gleason

Fire is a natural and recurring ecological disturbance that affects and responds to changes in climate, atmospheric chemistry, vegetation, and human activities, from recreation to industry to housing (Bowman et al. 2009, Flannigan et al. 2009, Archibald et al. 2018). As an ecological process and evolutionary driver, fire affects vegetation structure, plant communities, and species' identities or traits that allow plants to better survive or adapt to different types of fire over time (Agee 1993, McKenzie et al. 2004, Walsh et al. 2015, He et al. 2019, McLauchlan et al. 2020). The total area burned in Oregon during summer and autumn 2020 was among the largest in recorded history. During the 2020 fire season, five wildfires over 100,000 acres (~400 km^2), ignited by lightning and human activity, burned in wildlands and the wildland-urban interface. These and other fires across the western United States led to the displacement of thousands of people and loss of structures and infrastructure, and contributed to hazardous air quality in many parts of Oregon and the Northwest. Given these recent extreme events, this chapter provides historical and scientific context for wildfires in the state and region, and explore projections of wildfire under likely future climate conditions.

Wildfire Regimes in Oregon

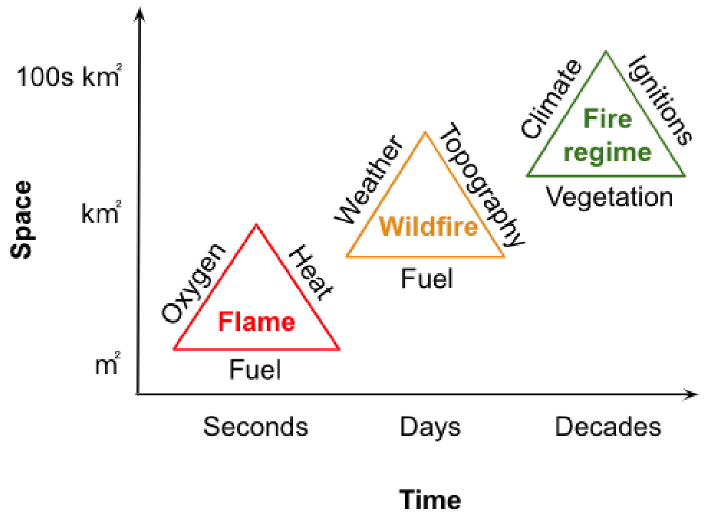

Figure 1. Nested controls on wildfires. Adapted from Moritiz et al. 2005.

Wildfire is driven by nested controls that vary across spatial and temporal scales (Fig. 1). At the finest resolutions, fuel, oxygen, and heat control an ignition or flame. Winds and other weather conditions, fuels, and topography affect expansion of fire and fire intensity (amount of heat; Rothermel 1972, Pyne 1996). Over decades to centuries, fire regimes (attributes of fires over space and time, such as frequency, size, and severity) are influenced by climate, which affects the weight (biomass) and dryness of fuel; vegetation type or species identities of plants; and the frequency, type, and timing of ignitions (Moritz et al. 2005, Parisien and Moritz 2009) (Box 1). This chapter introduces some foundational terms and concepts in wildfire science and reviews fire trends in Oregon.

Individual wildfires are produced by interactions between fine-scale flame dynamics and larger-scale fire regime dynamics, and are enabled by four factors that are synchronized (Bradstock 2010): sufficient fuel biomass, dry fuels, weather that is conducive to fire expansion, and ignitions. Understanding the interactions among these four factors is necessary to project how wildfires may respond to climate change and to consider whether and where fuels management may be effective.

Across the western United States, a steady increase in fire activity has been observed and linked to climate change (e.g., Westerling et al 2006, Abatzoglou and Williams 2016) and management legacies, such as fire suppression (Haugo et al. 2019) and the introduction of invasive grasses (Kerns et al. 2020). In this region, the number of wildfires ignited by lightning has increased rapidly, whereas human-set fires have increased moderately since the early 1990s (Balch et al. 2017). From 1984 through 2018, annual area burned in Oregon increased (Fig. 2), and projected climate change is expected to greatly increase the occurrence and future risk of large wildfires throughout Oregon, the Northwest, and the western United States (Littell et al. 2010, Stavros et al. 2014, Ager et al. 2017).

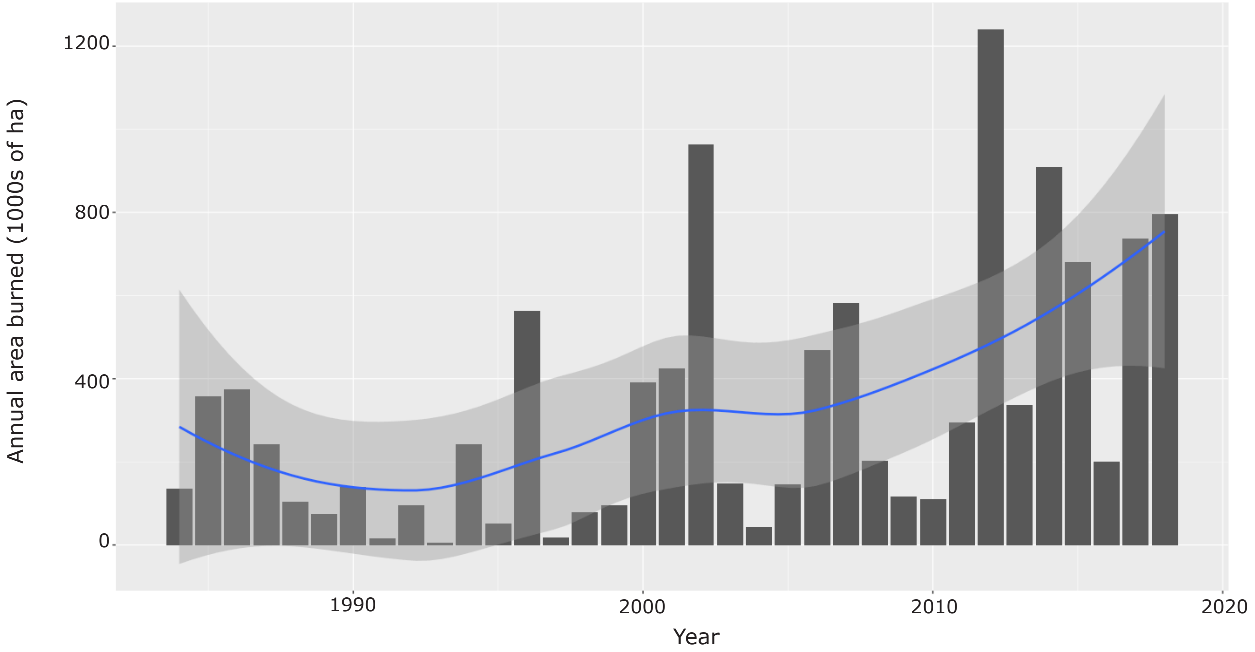

Figure 2. Annual area burned in Oregon from 1984–2018. Fires smaller than 988 acres (400 ha) were omitted. Data source: Monitoring Trends in Burn Severity (Eidenshink et al. 2007).

The concept of fire regimes is useful for characterizing how fire activity varies as precipitation or plant productivity varies along a gradient from low to high. At one end of the gradient are fuel-limited fire regimes, or those in which fire activity is constrained by the amount of contiguous biomass. Fires often are fuel-limited in regions that are dry and have low productivity. For example, fuels usually are limited in sparse shrublands (and some very dry, scattered, and unproductive low-elevation forests) east of the Cascade Range. In contrast, the dense forests of the Coast Range and intermediate to high elevations in the western Cascade Range are flammability-limited: fuels are abundant, but conditions usually are too wet for fire. Forests at intermediate and low elevations in western and southwestern Oregon (e.g., the Willamette Valley), and at intermediate elevations in the Blue Mountains east of the Cascade Range, are characterized by abundant fuels, seasonal aridity, and mixed fire regimes (Perry et al. 2011, Stine et al. 2014, Spies et al. 2018) (Fig. 3).

Limitations to fire activity in both fuel- and flammability-limited ecosystems can be overcome by short-term variability in climate (conditions over a month or longer) and weather (conditions over less than a month). For example, numerous studies in fuel-limited ecosystems have reported that years with above-average precipitation can lead to increased biomass and contiguity of fine fuels and an unusually active fire season. By contrast, in flammability-limited ecosystems, high fire activity often corresponds to extreme heat, spring and summer drought conditions, or strong and dry winds (Littell et al. 2009, Holz et al. 2012, McKenzie et al. 2019).

Conceptually, it is sensible to assume a negative linear relation between fire frequency and severity: as more fires occur in an area, less fuel is available for future fires. Conversely, as the fire-free period becomes longer, fuels can accumulate. However, this assumption ignores nonlinear variation in flammability following fire events. For instance, in the aftermath of a fire, fuel amount might increase rapidly until canopy closure, after which fuel accumulation continues but flammability decreases (Agee and Huff 1987, Spies et al. 1988). Alternatively, succession (long-term development of a plant community) can be interrupted by new and frequent fires (Whitlock et al. 2014, Busby et al. 2020). In dry montane forests, in which the majority of trees that do not require fire for reproduction germinate from seeds, succession can be limited by aridity, and relatively flammable grasses and shrubs can dominate in the early years or decades following wildfire (Davis et al. 2019).

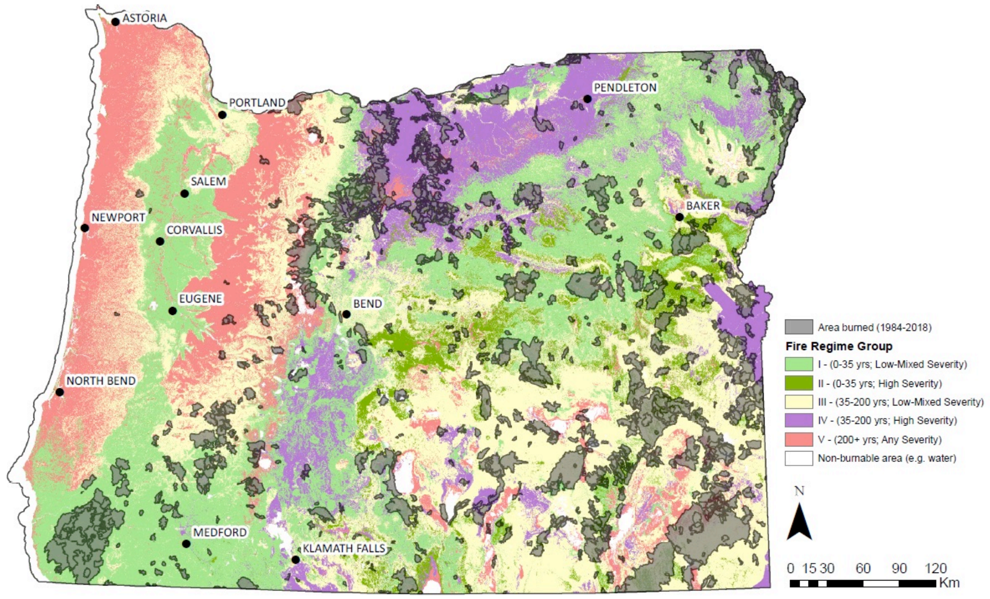

Figure 3. Total area burned in Oregon from 1984–2018 and fire regime groups. Fires smaller than 988 acres (400 ha) were omitted. Data sources: Monitoring Trends in Burn Severity (Eidenshink et al. 2007), LANDFIRE (2010).

Different ecosystems in Oregon have different fire regimes, which can be summarized on the basis of mean fire frequency, size, or seasonality, or other criteria. Below is a summary of Oregon's fire regimes on the basis of burn severity, or the percentage of trees killed by wildfire (Agee 1998): low (less than about 20%), high (more than about 70%), or mixed (about 20–70%). This chapter does not aim to characterize fire regimes in different regions of Oregon in great detail.

Low-severity fires are common at both ends of the precipitation gradient—in both fuel-limited and flammability-limited systems. In fuel-limited ecosystems, fires generally have low severity, cover large areas, and are fairly frequent (Heyerdahl et al. 2019). Years in Oregon in which the area burned was relatively high followed autumns and winters with above-average precipitation, which enabled accumulation of fine fuels, thereby connecting formerly fragmented vegetation and facilitating fire spread. Such climate-vegetation-fire dynamics sometimes are related to the El Niño–Southern Oscillation, as explained below (Heyerdahl et al. 2002, Johnston et al. 2017). Low-severity fires also occur in some moist forests in the Oregon Coast Range (Impara 1997) and western Cascade Range (Reilly and Spies 2016), where only fine fuels in the understory and small trees become dry enough to burn (Keeton and Franklin 2004, Tepley et al. 2013, Meigs et al. 2020).

Following decades of fire suppression that coincided with a relatively cool and wet climate (Higuera et al. 2015), the density and flammability of many low- to mid-elevation dry forests and woodlands in Oregon has increased (Haugo et al. 2019). For example, fire suppression in low elevation,

Box 1. Climate-wildfire relations in Oregon

Characteristics of fire and its ecological effects reflect relations among climate, people, and fire (Whitlock et al. 2010). Paleoecological and dendrological data, ethnographic accounts, and historical observations help elucidate these relations (Table B1). Indirect evidence does not explicitly describe ecological or climate change. Direct evidence includes qualitative and quantitative historical data and remotely sensed observations.

	Spatial resolution	Spatial extent	Temporal resolution	Temporal extent	Ecological inference	Effort needed
Paleoecology	Low	Low	Moderate	Very high	Indirect	High
Ethnographic & historical accounts	Variable	Moderate	Very high	Variable	Variable	Variable
Dendrology	Variable	Low	High	High	Direct	High
Aerial photographs	High	High	Low	Moderate	Indirect	Low
Satellite images	Very high	Very high	Very high	Very low	Indirect	Very low
Historical surveys	Low	High	Low	Low	Indirect	Moderate

Table B1. Forest structure and fire regime reconstruction methods. Adapted from Yokom-Kent 2014, Daniel et al. 2017, and Naficy 2019.

Paleoecological records

Sedimentary pollen and charcoal indicate changes in vegetation and fire activity over tens of thousands of years in the Northwest (Whitlock 1992, Walsh et al. 2015). Following the Pleistocene, about 12,000 years before present (BP), fire activity increased greatly as temperatures increased and forests established. Fire activity was high from 10,000–8000 BP as summer insolation (incoming solar radiation) peaked. Decreases in tree density from 9500–7500 BP may reflect increased fire activity and warm, dry summers. From 8000–4000 years BP, fire activity greatly decreased during a period of lower summer insolation and increased precipitation or lower evapotranspiration. By the end of this period, forest composition was similar to contemporary composition. Fire activity increased after 4000 years BP as a result of continued moisture variability, higher fuel loads, and Indigenous use of fire (Whitlock 1992, Walsh et al. 2015).

Tree-ring records

Tree-ring (dendrological) records can be used to reconstruct the past several hundred years of forest structure and composition, and of wildfires and climate, at seasonal to annual resolution (Table B1). These records suggest that fires were widespread west of the Cascade Range between the 1400s and 1650, possibly associated with warm, dry conditions and Indigenous fire use. Area burned decreased from 1650–1800, likely related to cool, wet conditions and reduction in population sizes of Native Americans, and then increased from 1800–1910, coincident with Euro-American settlement. Then, through the early 2000s, displacement of Native Americans and discontinuation of Indigenous fire use, fire suppression, and cool, wet conditions reduced fire activity (Boyd 1999, Weisberg and Swanson 2003, Noorgard 2014). Exceptions were the large fires during the twentieth century (e.g. Yacolt, 1902; Tillamook, 1933) that resulted from logging operations and extreme easterly winds. Increases in fire incidence since the early 2000s coincided with decreases in fuel moisture (Abatzoglou and Williams 2016).

Most dendrological reconstruction in the eastern Cascade Range has focused on dry, mixed-conifer forests within the Blue Mountains and relatively wet forests at the margins of drier forests. This work assessed variability in fire frequency among forest types and effects of fire suppression on forest structure. Results indicated that fire frequency was about 10–50 years in mixed-conifer forests

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historically open ponderosa pine (*Pinus ponderosa*) forests led to dense fuels and establishment of shade-tolerant tree species, such as grand fir (*Abies grandis*) and white fir (*A. concolor*), throughout the tree canopy, connecting fuels vertically from the ground to the crown. As a result, the intensity and severity of fires in the last three to four decades has increased (Hessburg et al. 2015, Haugo et al. 2019). Due to changes in climate and fire severity (Marlon et al. 2012), some dry forests and woodlands at low to intermediate elevations in eastern Oregon may not be able to reestablish naturally, and could transition to more-flammable shrublands or grasslands (Davis et al. 2019, 2020; Rodman et al. 2020). Fire suppression in wet ecosystems in the western Cascade Range has played a relatively minor role in driving fire patterns in these ecosystems (Spies et al. 2018).

Increases in fire severity also have been observed in arid shrubsteppe in central and eastern Oregon. In these ecosystems, the rapid expansion of non-native invasive grasses, such as cheatgrass (*Bromus tectorum*) and ventenata grass (*Ventenata dubia*), has increased fine-fuel biomass and spatial continuity of fuels (Balch et al. 2013, Kerns et al. 2020, Tortorelli et al. 2020). Formerly sparse sagebrush ecosystems continue to be colonized by cheatgrass, which has resulted in increases in area burned of up to 200% since 1980 (Bradley et al. 2018). Expansion of cheatgrass leads to a positive feedback loop in which increases in fire frequency and extent facilitate further increases in the distribution and density of cheatgrass. Any ground disturbance, whether from livestock grazing (Williamson et al. 2020), tree thinning, or fire, can facilitate the colonization and increase in abundance of cheatgrass. Expansion of the shade-intolerant cheatgrass tends to be more likely in areas in which native grasses and forbs are sparse, which sometimes reflects a history of intensive livestock grazing (e.g., Kerns and Day 2017). *Ventenata dubia* can colonize relatively bare or open areas in ponderosa pine and mixed conifer forests.

High-severity fires dominate wet, cool forests, including remnant old-growth forests, in Oregon's Coast Range and western Cascade Range. Some shrublands and grasslands in central, eastern, and southwest Oregon also burn at high severity, but more frequently than forests (Fig. 3). High-severity wildfires in wet, cool forests

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(Heyerdahl et al. 2001, 2019; Merschel et al. 2014, 2018; Johnston 2016; Platt 2020). It appears that all dendrological reconstructions of fire history at low to intermediate elevations are consistent with other evidence that fire frequency decreased after 1910–1930 coincident with the federal implementation of fire suppression (Hessburg et al. 1999).

The high temporal resolution of dendrological records also allows for better understanding of the interactions between annual and decadal climate variability and fire activity. Annual variation in the El Niño-Southern Oscillation and decadal variation in the Pacific Decadal Oscillation cause similar changes in climate throughout the Northwest. Relatively warm winters and low snowpack are likely during the positive phases of these oscillations, as are increases in fire activity (Heyerdahl et al. 2002), whereas relatively cool, wet winters and high snowpack are likely during the negative phases (La Niña and PDO-) (Heyerdahl et al. 2008, Littell et al. 2016).

Comparisons to other records

Comparison of paleoecological and dendrological records to past land surveys (e.g., Public Land Surveys); historical and ethnographic records; and time-series of satellite, aerial, and land-based images allows for better understanding of interactions among climate, vegetation, fire, and humans. Fire has been a consistent, major disturbance process in the Northwest. Although changes in vegetation and fire activity following the Pleistocene likely were driven by a warming climate and increased atmospheric concentrations of carbon dioxide, Indigenous fire use likely influenced fire dyamics and vegetation during the past 4000 years. Archaeological, ethnographic, and historical records suggest that Indigenous use of fire led to frequent (less than about 5–35 years), low-severity surface fires in shrubsteppe, grassland, and dry low- to intermediate-elevation forests in central and eastern Oregon, and across the Willamette and Klamath-Siskiyou Basins (Boyd 1999, Steen-Adams et al. 2019).

The reduction in intentional ignition following the displacement of Tribes and fire suppression coincided with cool conditions, resulting in a marked decrease in fire activity and increases in the density of trees and shrubs (Whitlock 1992, Weisberg and Swanson 2003, Hessburg et al. 2007, Walsh et al. 2015). These interpretations and observations are consistent with the hypothesis that the absence of fire from much of the Northwest altered vegetation composition and structure and reduced the frequency of wildfires (Marlon et al. 2012).

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typically are infrequent and large, facilitated by extremely dry and warm springs and summers or high winds (Hemstrom and Franklin 1982, Spies et al. 2018). East of the Cascade Range, most wildfires are ignited by lightning, whereas west of the Cascade Range, most are ignited by human activity (Balch et al. 2017). Dry, cloud-to-ground lightning strikes are rare on the west side of the Cascade Range because of the strong maritime effect of the Pacific Ocean (Spies et al. 2018, Kalashnikov et al. 2020).

In western Oregon (western Cascade Range and Coast Range), extensive clearcutting followed by the planting of Douglas-fir (*Pseudotsuga menziesii*) plantations has reduced the spatial heterogeneity and overall variability in forest structure (Tyler and Peterson 2004, Donato et al. 2020). In older, more-complex stands, the sizes of trees usually are diverse and the understory is shady. In young plantations, by contrast, trees tend to be denser and to have more branches, which allows for greater horizontal and vertical spread of fire (Agee 1993, Stephens et al. 2005). Although the canopies of young plantations are not fully closed, the small-diameter trees readily become dry, which increases their ability to carry fires and elevates the risk of high-severity fires (Thompson et al. 2007, Zald and Dunn 2018). Logging and the post-fire planting of trees have reduced the extent of both mature or old-growth forest and early successional vegetation in forests west of the Cascade Range in Oregon and Washington (Franklin and Johnson 2013, Swanson et al. 2014). Consequently, the extensive, homogenous patches of young tree plantation and closed-canopy, mid-successional Douglas-fir and western hemlock (*Tsuga heterophylla*) currently present in western Washington and Oregon occupy a larger area than in the past (Davis et al. 2015, DeMeo et al. 2018, Donato et al. 2020). In these historically more heterogeneous forests, the suppression of active fires may be ineffective and considerably more hazardous for fire crews during extremely hot and dry conditions that often are associated with strong easterly winds, such as those that fueled much of the 2020 fire season (Higuera and Abatzoglou 2021).

Mixed-severity fire regimes are the most complex and least understood across the western United States (Agee 1993, 2005; Tepley et al. 2013). These fire regimes are characterized by local differences in burn intensity and plant mortality (Agee 2005, Naficy 2016). The life histories of the plants that occur in regions with mixed-severity regimes are distinct in terms of fire resistance (Stevens et al. 2020) and vary as a function of water availability, which is affected by topography (Tepley et al. 2015). Fire histories in these systems are difficult to determine because most fire-history reconstruction techniques were developed for low- or high-severity regimes (Agee 2005; but see Hagman et al. 2019, Platt 2020). For example, in systems with infrequent, high-severity fires, the dates of past fires are estimated by pairing individual fire events with data on the ages of trees that colonized and established following that fire (Box 1). In systems with frequent, low-severity fires, fire occurrences typically are evident by scars on individuals of fire-resistant tree species. In contrast, in systems with mixed-severity fire regimes, species with traits that enable resistance or recovery are not uniformly distributed, leaving researchers unable to reconstruct fire activity on the basis of one method alone, and therefore reducing the number of samples from a given site. Additionally, dominant tree species in many areas characterized by mixed-severity fires decay relatively rapidly, limiting the potential use of dendroecology to reconstruct fire histories (Tepley and Veblen 2015). Novel research approaches aim to overcome challenges to reconstruction of fire frequency and severity in dry and cold (Hagman et al. 2019) or moist (Platt 2020) mixed-conifer forests.

Projections of Future Fire Dynamics

Empirical Models

Different types of models are being applied to project future fire dynamics in Oregon. Many empirical models, some reported in previous Oregon Climate Assessments, use the statistical relation between observed climate and area burned over the past 100 years to predict future area burned on the basis of projected temperature and precipitation, which usually are derived from global climate models. Empirical models can be applied at either global (Krawchuk et al. 2009, Moritz et al. 2012) or regional extents, such as the western United States (McKenzie et al. 2004, Littell et al. 2010, Yue et al. 2013, Kitzberger et al. 2017). Empirical models at all extents consistently project that the area burned in Oregon will increase. For example, McKenzie et al. (2004) projected that, with a mean temperature increase of 3.6°F (2°C), the area burned in Oregon will increase more than 200%. Assuming the A1B emissions scenario (medium emission levels), Kitzberger et al. (2017) also projected a 200% increase in median annual area burned in Oregon, including the Cascade Range, from 2010–2039 compared to 1961–2004. Other empirical models for Idaho, Montana, Oregon, and Washington, which were based on projections from two global climate models and the A1B scenario, suggested that area burned will double or triple by the 2080s (Littell et al. 2010).

Results of different empirical models also consistently suggest that the incidence of very large fires, often defined as the largest 5–10% of fires or fires that burn more than 12,350 acres (5000 ha), will increase in the future (Barbero et al. 2015). For example, empirical models developed by Barbero et al. (2015) under RCP 8.5 (a scenario that represents a continuation of current levels of greenhouse gas emissions throughout the twenty-first century, or a relatively high amount of warming) suggested that across the western United States, including Oregon, the annual probability of very large fires will increase by 200–400% by 2041–2070 compared to 1971–2000. Models by Davis et al. (2017) suggested that under RCP 4.5 (a lower-emissions and warming scenario), the proportion of forests in which conditions are consistent with large wildfires (more than 100 acres, or 40 ha) will increase by over 20% during the twenty-first century for nearly all major regions in Oregon, although less so for the Coast Range. The largest projected increases were in the Blue Mountains, Klamath Mountains, and eastern Cascade Range.

Impact of wildfires on runoff

Wildfires affect water balance, water quality, fluvial and riparian systems, and water infrastructure. Reduction in the extent of the vegetation canopy reduces water interception and storage by the canopy, allowing more precipitation to fall on the soil. In conjunction with reductions in the volume and extent of litter and live vegetation, and therefore evapotranspiration, the additional precipitation increases direct runoff for at least the first few years following a wildfire. In subalpine and alpine watersheds, less canopy interception may lead to greater snow accumulation.

After a wildfire, increased light transmission through the canopy and decreased reflectivity of the snow, a result of deposition of light-absorbing particles such as black carbon and burned debris, increases net shortwave radiation, which drives earlier snowmelt. This is somewhat offset by the decreased net longwave radiation due to the loss of canopy, but overall, wildfire increases the net snowpack energy balance and warms the snowpack (Gleason et al. 2019). In burned forested areas across 11 western states (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming), snow disappeared five days earlier on average, and this shift in snowmelt persisted for more than ten years following fire (Gleason et al. 2019).

Soil hydrophobicity (repelling rather than absorption of water by soil) also is likely to increase after a wildfire, resulting in less infiltration and more direct runoff. Changes in hydrophobicity depend on burn severity and vegetation composition, but overall reduce the lag from snowmelt to streamflow, increase overland flow, and increase peak streamflow. These changes are likely to increase erosion and contribute to earlier drying of soils and vegetation and reductions in late-season flows. As a result, water shortages in the dry season, and differences in seasonal flows in many parts of Oregon, may be exacerbated.

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Future fire severity will depend partly on vegetation composition and structure. In the near term, high tree density may increase fire severity in dry forests (Cassell et al. 2019). Over the long term, fire severity in dry forests may remain similar or increase slightly (Parks et al. 2016).

Mechanistic Models

Mechanistic models use knowledge of physical and biological processes and their interactions to simulate future ecosystem attributes, such as vegetation composition and structure, vegetation productivity, fire frequency and severity, and carbon storage. These models account for potential interactions between vegetation and fire as the climate changes to conditions for which there is no past analog. Thus, they incorporate negative and positive feedbacks between fuel levels and fire frequency, and potential changes in the relation between climate and fire in the future, which are phenomena not captured by the empirical models described above. These models also integrate the potential increase in primary productivity, and in turn fuel loads, as a result of increased atmospheric carbon dioxide concentrations. Examples of process-based models that simulate fire are LANDIS-II (Scheller and Mladenoff 2008) and MC1 (Bachelet et al. 2001) and MC2 (Bachelet et al. 2015).

In an application of the LANDIS-II model to the Oregon Coast Range, area burned over the twenty-first century did not increase substantially relative to historical area as climate changed, but fire severity and the incidence of extreme fire weather increased (Creutzburg et al. 2017). By contrast, LANDIS-II suggested a large increase in fire frequency, size, and severity in dry forests in the southern Blue Mountains of central Oregon (Cassell et al. 2019).

An application of MC1 to the western three-quarters of Oregon and Washington, which assumed an A2 emissions scenario (high emissions), projected a 76–310% increase in annual area burned and a 29–41% increase in burn severity (measured as aboveground carbon released by fire) by 2100, with the degree of increase depending on the climate model used as input (Rogers et al. 2011). As reported in the third Oregon Climate Assessment (Dalton et al. 2017), more-recent simulations with the MC2 model, which incorporated climate scenarios from the fifth phase of the Coupled Model Intercomparison Project, also projected increases in fire frequency across all forest-dominated ecosystems in Oregon, with or without fire suppression (Sheehan et al. 2015).

At the subregional level, MC1 projected increases in fire frequency and extent over approximately 250,000 acres (1 million ha) of forests in central Oregon (Halofsky et al. 2013, 2014). The latter work projected that more than three-quarters of those forests will burn repeatedly from 2070–2100, particularly given hot and dry climate scenarios. The projected fire regime for central Oregon would be a significant change from that of the last century, and likely would result in substantial changes in vegetation. Similarly, MC2 simulations suggested that across south-central Oregon, fire will become more frequent in most vegetation types, especially dry and wet forests, and that fire severity in forests will be similar to or increase slightly compared to historical fire severity (Case et al. 2019).

Turner et al. (2015) projected increased fire frequency in the Willamette Valley under RCP 8.5. Average annual area burned was projected to increase 900% by 2100 relative to 1986–2010, but during the latter period, the total area burned was small (0.2% of the Willamette Valley per year). With smaller temperature increases, average area burned was slightly above historical levels. Mechanistic models consistently suggest that fire frequency and area burned in Oregon will increase. Fire severity also may increase, depending in part on forest composition, structure, and productivity over time. In highly productive ecosystems such as forests west of the Cascade Crest, both fire frequency and severity may increase (Rogers et al. 2011, Halofsky et al. 2018a, McEvoy et al. 2020).

Potential Interactions between Wildfire and Other Disturbances

Fire interacts with other stressors to trees, including drought, insect outbreaks, and pathogens, that can lead to substantial ecological changes (McKenzie et al. 2008). For example, water and vapor-pressure deficits are expected to increase as the climate becomes warmer, indirectly mediating increases in the frequency, extent, and severity of fire (McKenzie et al. 2004, McKenzie and Littell 2017) and insect outbreaks (Logan and Powell 2009). Effects on trees of colonization and herbivory by some insects, such as bark beetles, tend to increase among species during prolonged droughts or warm winters (Logan and Bentz 1999, Carroll et al. 2004, Hicke et al. 2006). Nevertheless, there is little evidence that fire occurrence or severity increases following bark beetle outbreaks in Oregon's forests (especially if trees are needleless when burned) (Agne et al. 2016, Meigs et al. 2016).

Options for Adapting to Fire

Many current management practices, such as manipulation of stand density and efforts to control non-native invasive species, can decrease the magnitude of ecological change following wildfire and as climate continues to change (Peterson et al. 2011a, b; Tepley et al. 2020). Effects of wildfires on public health and human communities, and potential actions to alleviate those effects, are addressed in *Built Environment*, *Public Health*, and *Social Systems* (this volume).

In ponderosa pine and dry mixed conifer forests east of the Cascade Range and in southwest Oregon, thinning and hazardous fuels treatments may decrease crown fire potential (Agee and Skinner 2005, Safford et al. 2012, Martinson and Omi 2013, Shive et al. 2013). Reducing tree density can decrease competition among trees for water and light and increase growth and vigor of the remaining trees, which in turn increases their resilience to drought (D'Amato et al. 2013, Clark et al. 2016, Sohn et al. 2016, Bottero et al. 2017, Vernon et al. 2018).

Prescribed fire also can be used to reduce tree densities in dry forests and increase resilience to wildfire and drought (Johnson et al. 2007, Peterson et al. 2011a). Prescribed fire is likely to be most effective in vegetation types that evolved with frequent, low- to mixed-severity fire and from which fires have been excluded, such as dry and mesic forests and oak woodlands. Additionally, prescribed fire can be used to promote fire-dependent native species in meadows, fens, and areas dominated by huckleberries (*Vaccinium* spp.) or beargrass (*Xerophyllum tenax*). Such use of fire could follow traditional practices by Indigenous peoples (e.g., Steen-Adams et al. 2019; *Tribal Cultural Resources*, this volume).

To reduce fire size and intensity across large areas, the spatial extent of both thinning and prescribed fire would need to increase considerably and to be maintained (Agee and Skinner 2005, Peterson et al. 2005). However, in many cases, the extent of fuel treatments is limited by financial resources, agency capacity, and air quality regulations (Melvin 2018). Thinning, followed and maintained by regular prescribed fire treatments, can be prioritized in areas where trees have expanded in response to fire suppression, such as in dry forests dominated by grand or white fir; where drought stress is expected to be greatest (e.g., on south-facing slopes and on sandy and other soils with low water-holding capacity), and in the wildland-urban interface (Halofsky et al. 2020).

In wetter forests west of the Cascade Range, such as intermediate- to high-elevation and coastal forests, thinning and hazardous fuel treatments are unlikely to reduce fire severity appreciably, and due to the high productivity of these forests, thinning would need to be practiced repeatedly to be effective. Major fires in these systems typically are infrequent and occur during severe drought and high winds, resulting in large, high-severity events (Halofsky et al. 2018b; Higuera and Abatzoglou 2020). Promoting diverse species composition, genetics, and vegetation structure may increase resilience to wildfire and other disturbances (Stephens et al. 2010), although vegetation cover and forest structure west of the Cascade Range is relatively homogeneous (Donato et al. 2020).

Increases in temperature and decreases in water availability may reduce natural post-fire regeneration, especially in topographic settings or forest types that already are water-limited. It may be possible to supplement natural regeneration after fire in some locations, such as those further than 650 feet (200 m) from living trees, and where costs are not made prohibitive by remoteness or topography (North et al. 2019). Information on species-specific dispersal traits and topography can help to create potential refugia from disturbances (Krawchuk et al. 2020). Potential adaptation strategies include planting at lower densities than would have been prescribed in the past, adapting densities to microclimate, and creating spatial discontinuity in fuels (North et al. 2019). Nevertheless, increased fire frequency and drought stress may result in transitions from forest to non-forest (e.g., at lower elevations), or from dense to sparse forests (at higher elevations) (Busby et al. 2020).

Fire and extensive mortality can provide opportunities to plant diverse species and genotypes, including genotypes adapted to drought, and to modify forest structure. Applications such as the Seedlot Selection Tool (seedlotselectiontool.org/sst/) or postfire reforestation index tools (treesarethebeesknees.users.earthengine.app/view/srme-reforestation-tool) may help to identify seedling stocks that are adapted to local present and projected future climate.

Because fires cross jurisdictions, adaptation efforts ideally will be collaborative (Spies et al. 2010, Stein et al. 2013), with budgets, action priorities, and maintenance of roads, trails, and other forms of access coordinated among agencies and landowners (Halofsky and Peterson 2016). Collaborative collection and sharing of monitoring data also will contribute to scientific understanding and evaluation of adaptation treatments (Joyce et al. 2009).

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Floods

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Anticipated Effects of Climate Change on Flood Magnitude

Several factors suggest that flood magnitudes in Oregon will increase in a warmer climate. One is that large precipitation events are expected to become more intense (Allen and Ingram 2002, Westra et al. 2014, Warner and Mass 2017). The primary reason for the increase in intensity is simply that warmer air can hold more water, so there may be more moisture in the air available to fall out as rain or snow in a warmer climate. Atmospheric rivers, in particular, often bring heavy precipitation and, consequently, flooding in Oregon (e.g., Konrad and Dettinger 2017). A statewide flood in April 2019 and a flood in northeast Oregon in February 2020 illustrate the manner in which strong atmospheric rivers can result in extensive flooding and damages (Box 1). Atmospheric rivers are projected to bring more water vapor to the Pacific Northwest in the future, again because warmer air can hold more water (*State of Climate Science*, this volume). In general, the intensity of heavy precipitation events over the twenty-first century in Oregon is projected to increase, although not uniformly across the state (e.g., Cooley and Chang 2020; *State of Climate Science*, this volume).

A second factor suggesting that flood magnitudes will increase is that rainfall-driven floods tend to have larger flood peaks than snowmelt-driven floods given the same amount of precipitation (Davenport et al. 2020). Therefore, as rising temperatures cause the proportion of precipitation falling as rain relative to snow to increase, flood magnitudes are projected to increase (Chegwidden et al. 2020).

A third factor is that total wet-season (November–April) precipitation is projected to increase in the Pacific Northwest (Dalton et al. 2017, Easterling et al. 2017, Rupp et al. 2017a, b). Greater precipitation, even after accounting for increases in evaporation (Seager et al. 2014), implies a higher likelihood of wetter soil and reduced depth to ground water—both of which are enabling conditions for flooding—prior to the arrival of heavy precipitation events. Chegwidden et al. (2020) also concluded that rainfall-driven floods are more sensitive to increases in precipitation than snowmelt-driven floods, so the projected increases in total precipitation, and in rain relative to snow, likely will increase flood magnitudes in the region.

Historical Trends in Precipitation Intensity and Extreme River Flows

Relatively small sample sizes and high variability in extreme streamflow events make it difficult to detect long-term trends. Therefore, only large changes in the observational record are detectable. Consistent with the challenges to such analyses, a study of annual maximum daily flows (peak flows) from 1941 through 2015, recorded at 58 gauges in Oregon, found no statistically significant ($p < 0.05$) trends at sites that have little to no reservoir storage upstream (Hodgkins et al. 2019). Statistically significant trends—all decreasing and in western Oregon—only were detected at sites with substantial upstream reservoir storage, suggesting that these decreases could be attributable to reservoir and dam operations since the 1940s.

Projected Changes in Naturalized Extreme Flows

It is standard practice to consider the impact of climate change on naturalized river flows (defined as observed flows that have been adjusted for human regulation and withdrawals). This practice allows for removal of the complicating factor of human activity when assessing effects of climate change on hydrology. Additionally, naturalized flows can be used as inputs when assessing management of the same river systems.

Queen et al. (2021) projected changes in the 10-year and 100-year annual maximum naturalized daily flows at multiple locations in the Columbia River Basin, comparing flows in the second half of the twentieth century (1951–2000) to those in second half of the twenty-first century (2050–2099). The 10-year flow had a 10% likelihood of being exceeded in a given year, whereas the 100-year flow had a 1% likelihood of being exceeded in a given year. They considered 40 hydroclimate scenarios, all assuming RCP 8.5 (a scenario that represents a continuation of current levels of greenhouse gas emissions throughout the twenty-first century, or a relatively high amount of warming), and statistically downscaled meteorological data from ten global climate models as inputs to four hydrological model configurations. The range in changes among the 40 individual scenarios was large, but the average of the 40 scenarios is considered the best estimate of the effect of climate change on these probabilistic flood magnitudes (Table 1). Similar to an earlier study (Maurer et al. 2018), increases of 5% or less in the average of the 10-year and 100-year peak flows were projected along the Columbia River upstream from Vancouver. Much larger increases were projected for other rivers within and adjacent to Oregon. Projected increases for the Willamette River and its tributaries from the Cascades were particularly high, ranging from 39% at Willamette Falls to 63% at Hills Creek Dam on the Middle Fork Willamette for 100-year flows. Changes in flows assuming RCP 4.5 (a scenario that represents moderate reductions in global greenhouse gas emissions, with a peak near the middle of the twenty-first century, or a relatively low amount of warming) were about two-thirds the magnitude of those that assumed RCP 8.5.

River	Location	Projected increase (%)	
		10-year	100-year
Willamette Basin rivers			
Willamette	Willamette Falls to Harrisburg	33–45	39–50
McKenzie	Walterville to Vida	54–56	55–58
Willamette	Eugene	50	54
Middle Fork Willamette	Jasper to Hills Creek Dam	50–57	57–63
Row	Cottage Grove	25	39
Other rivers			
Columbia	Vancouver to McNary Dam	2–3	5
Snake	Ice Harbor Dam to Anatone	19–24	25–29
Snake	Hells Canyon Dam to Nyssa	39–41	52–56
Grande Ronde	Troy	48	68

Table 1. Projected impact of climate change on the magnitude of 10-year and 100-year annual maximum daily flows from 1950–1999 to 2050–2099, assuming RCP 8.5 and averaging over 40 scenarios. Projected changes over a range of locations generally increase from downstream to upstream. Adapted from Queen et al. (2021).

Sampling from the same 40 hydrologic and climate scenarios as Queen et al. (2021), the River Management Joint Operating Committee (RMJOC) analyzed changes in peak 10-day naturalized runoff volumes from large drainage areas of the Columbia Basin, including the Willamette Basin. They considered 10-day runoff volumes because it takes approximately 10 days for water to travel through the Columbia River reservoir system. The RMJOC examined 10-day naturalized runoff volumes preceding the five greatest peak flows at the drainage area outlet in winter (November through March) in each of three 30-year periods: 1976–2005 (historical), 2020–2049 (the 2030s), and 2060–2089 (the 2070s) (RMJOC 2020). The median of 10-day runoff volumes preceding the peak flow events in the Willamette Basin was projected to increase by 11% and 43% by the 2030s and 2070s, respectively, under RCP 8.5. Under RCP 4.5, projected increases were 19% and 37% by the 2030s and 2070s, respectively. In winter, the increases in peak flows from the Willamette River, combined with the shift to more frequent and higher peak flows on the Columbia mainstem, caused projected 10-day runoff volumes at the confluence of the Columbia and Willamette River to increase 15% by the 2030s and 65% by the 2070s under RCP 8.5. Under RCP 4.5, 10-day runoff volumes increased by 22% by the 2030s and 37% by 2070s.

The RMJOC (2020) conducted a similar analysis for large, system-wide spring floods, identifying the five greatest total April–August naturalized runoff volumes in each 30-year period. At the confluence of the Columbia and Willamette Rivers, these runoff volumes were projected to change little under RCP 4.5. Under RCP 8.5, the median of the five greatest runoff volumes decreased by about 5% by the 2070s.

Projected Changes in Flood Risk in Managed River Systems

The heavy management of the Columbia River substantially can impact the magnitude and timing of peak flows and, consequently, flood risk. Two recent studies examined the consequences of climate change on flood risk under the current operations of the Federal Columbia River Power System. In one study, the 13 reservoirs in the Willamette Basin operated by the Willamette Project were characterized as "highly effective at reducing flood risk" under two RCP 8.5 scenarios. Simulated flow at Salem, Oregon, a key control point for the Willamette Project, reached flood stage only once by the year 2099 (Tullos et al. 2020) despite increases in reservoir inflows

Box 1. Two recent flood events in Oregon

Atmospheric rivers in April 2019 and February 2020 illustrated the effects of these storms on Oregon's climate, water supply, and flood risk. The Northwest receives about 25–30% of its total winter precipitation from atmospheric river events (Slinskey et al. 2020; *State of Climate Science*, this volume). The two atmospheric river events in April 2019 and February 2020 also had a significant rain-on-snow component, which contributed to downstream flooding and damage. Runoff from snowmelt during rain-on-snow events compounds runoff from precipitation, amplifying a storm's potential to cause high-impact flooding, landslides, and avalanches.
One study of the Santiam River Basin suggested that 74% of peak daily streamflows with a return interval greater than one year were associated with rain-on-snow events (Surfleet and Tullos 2013). This association was highest within the transient rain and snow elevational band, between 1150 feet (350 m) and 3600 feet (1100 m). Recent climate model simulations projected a decreased frequency of high peak flow rain-on-snow events at low to intermediate elevations and an increased frequency of such events at high elevations (e.g., Musselman et al. 2018). The decrease in low to mid-elevation rain-on-snow peak flows is due to projected decreases in snowfall at these elevations. These results were consistent with earlier studies that demonstrated an increased occurrence of rain-on-snow events at high elevations, and decreased occurrence at low elevations, over the last 35 years, which was attributable to the warming climate (McCabe et al. 2007, Ye et al. 2008).

The apparent importance of rain-on-snow to peak flows, however, can depend on how rain-on-snow-affected flows are defined. Although Surfleet and Tullos (2013) considered a peak flow event to be associated with rain-on-snow if any of the existing snowpack melted, Chegwidden et al. (2020) used hydrological modeling to isolate events with a substantial rain-on-snow contribution: more than ~2.5 inches (10 mm) of basin-average soil water equivalent in the existing snowpack and a snowmelt contribution greater than 20% of the total precipitation plus snowmelt. Chegwidden et al. (2020) found that for the North Santiam Basin, and other basins like it in the vicinity, rain-on-snow was an important factor in about 10% of peak daily streamflows with a return interval greater than one year, but may be important in less than 1% of such events by 2100.

April 2019 statewide flood

An unseasonably strong atmospheric river that made landfall in Oregon on 7 April 2019 produced one of the state's historically significant floods. Precipitation and runoff from this event exceeded a number of daily precipitation and streamflow records across Oregon. Due mainly to the rainfall from this event, April 2019 was Oregon's third wettest April on record. The timing of the atmospheric river coincided with the winter maximum snowpack, with snow water equivalent on 1 April at or well above normal for all Oregon mountain basins. Heavy rain and rain-on-snow conditions produced near-record runoff volume and streamflows throughout much of the state (e.g., Fig. B1a). The total April runoff volume set maximum monthly records at 58 streamflow stations across Oregon, and was second-highest at 10 other stations.

At the time of the storm, many reservoirs were drafting higher as operations were switching from flood control to spring and summer filling. The exceptionally high runoff filled many reservoirs, leading operators with no choice but to release water into already full river channels. Widespread flooding ensued across much of the state for the next week, and federal disaster declarations were approved in six

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implied by the projected increases in naturalized flows (Table 1). The resilience of the system was attributed to the current emphasis on flood-risk management in the operating rules and the relatively large volume of storage in the reservoirs compared to projected changes in streamflow (Tullos et al. 2020). However, the study's authors acknowledged that their hydrological model underpredicted peak daily runoff during winter, which could have led to an underestimation of flood risk.

The RMJOC (2020) examined the entire Columbia River reservoir system and determined that the greatest change in flood risk would result from an increase in regulated flows from the Columbia mainstem during winter. Current system operations for minimizing flood risk along the Columbia River largely are designed to manage spring runoff rather than winter runoff, and adaptive management of reservoir operating policies is not anticipated to fully offset potential increases in winter flood risk. As a result, the five largest regulated winter flood events on the lower Columbia River (below the confluence with the Willamette River) occurred when the contribution from the Columbia mainstem, averaged over the five events and relative to the 1976–2005 baseline period, was 44% and 151% larger by the 2030s and 2070s, respectively, under RCP 8.5. Under RCP 4.5, the Columbia contribution increased by 36% and 72% by the 2030s and 2070s, respectively. The substantial projected increase in peak flows from the Willamette River is especially challenging for flood management on the lower Columbia River, where flow from the Willamette River into the Columbia River further increases water levels on the Columbia above the confluence. For the same five largest winter flood events, the average contributions from the Willamette River were 29% and 39% larger by the 2030s and 2070s, respectively, under RCP 8.5. Under RCP 4.5, the increases in the Willamette contribution area were similar: 29% by the 2030s and 40% by the 2070s.

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counties as a result of damage associated with the storm. By the end of April, mountain snow water equivalent dwindled to well below average over all Cascade Range basins in Oregon and Washington. The early melt-out of the snowpack preceded below-average summer streamflows on several major rivers draining the Cascades, such as streamflows in May and June along the Willamette (Fig. B1a). Some impacts of this flood were documented in the Oregon Office of Emergency Management's 2019 April Flooding Spotlight: storymaps.arcgis.com/stories/2cfe3ce9706045c585b5f1f3d1c79bb0.

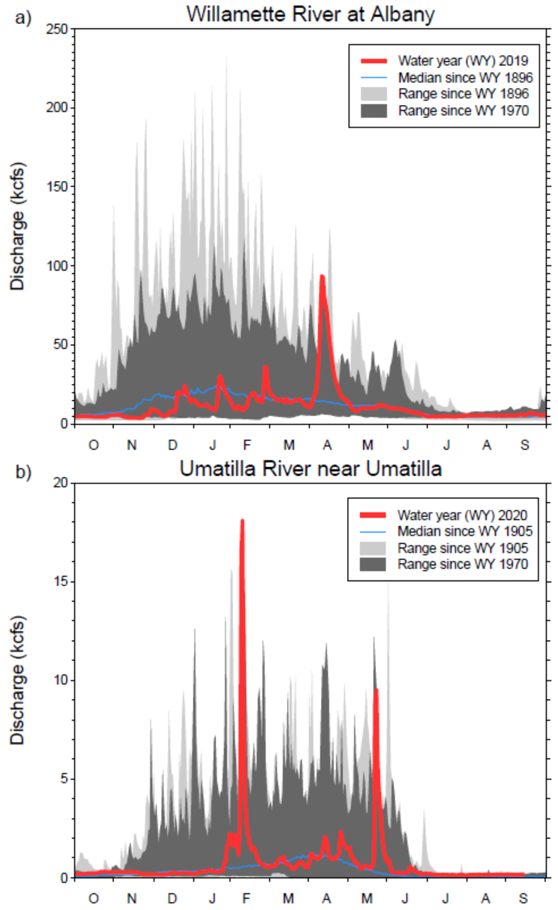

Figure B1. Daily flow (red line) during the water year (1 October–30 September) measured in (a) 2019 at the Willamette River at Albany (USGS gauge 14174000) and (b) 2020 at the Umatilla River near Umatilla (USGS gauge 14033500). The light blue line indicates the median daily flow over the period of record (1896–2020 for the Willamette River, 1905–2020 for the Umatilla River), and the gray shading indicates the full range of daily flows. The darker gray shading includes the water years since 1970, by which nearly all existing flood management infrastructure was completed. The lighter shading covers all years in the period of record.

February 2020 northeast Oregon flood

In early February 2020, while much of Oregon was in drought, a strong atmospheric river affected northeast Oregon. This atmospheric river was extremely unusual: its flow was not the

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typical southerly or westerly, but curved around an eastern Pacific high and streamed subtropical moisture from the northwest. Due to the unusual orientation of the upstream moisture transport, heavy precipitation began on the cold side of the atmospheric river as snow down to an elevation of 2000 feet (610 m), then transitioned to heavy rain to an elevation of about 5000 feet (1500 m) as the atmospheric river's warm front moved north. As a result, precipitation along the northern Blue and Wallowa Mountains was exceptionally heavy, and quickly drained into the Middle Columbia and Lower Snake River Basins. Similar to the April 2019 event, this atmospheric river featured a fairly significant rain-on-snow component that contributed to the observed high runoff volume.

The peak flow on the Umatilla River at Pendleton set a record high on 6 February at about 19,000 cubic feet per second, surpassing previous high flows from 1965 and 1996 (Fig. B1b). At a number of stations along the Umatilla River, recorded monthly runoff volumes were the second highest on record for February. Some impacts of this flood were documented in the Oregon Office of Emergency Management's 2020 February Flooding Spotlight: oregon-oem-geo.hub.arcgis.com/app/cb570e3df4e14e03a096b0b920534db9.

In the set of simulations conducted by the RMJOC (2020), no major floods (water level greater than 25 feet [7.6 m]) occurred along the Columbia River at Portland and Vancouver during the historical period (1976–2005). However, RMJOC (2020) projected that during 2060–2089, this location would reach major flood stage three times under RCP 4.5 and five times under RCP 8.5. At least one major flood was projected during the 2030s. Moderate flood stage (greater than 20 feet or 6.1 m) was projected to occur in nine and twelve years from 2060–2089 under RCP 4.5 and RCP 8.5, respectively, but only in one to three years (depending on hydrological model used) during 1976–2005. Flood stage (greater than 16 feet [4.9 m]) occurred in at least 20 of those 30 years under either RCP, compared to four to nine years from 1976–2005.

Given the potential for a substantial increase in flood risk on the lower Columbia River, two recent investigations used two-dimensional hydraulic modeling to simulate peak water levels from the mouth of the Columbia River upstream to Bonneville Dam on the Columbia River and Willamette Falls on the Willamette River during plausible future flood events. Helaire et al. (2020) projected flood hazards with the 1996 and 1923 floods (the largest and third largest Willamette River floods since 1900) as baseline events while adjusting runoff and sea level rise to be consistent with climate change projections. A 10% increase in runoff to both the Willamette River and Columbia mainstem was assumed. This change is small relative to the increases even by 2030s given in the RMJOC (2020) study, suggesting that potential changes of this magnitude already may be occurring. With this 10% increase in runoff, water levels in the Portland and Vancouver area increased by 2.56 and 2.69 feet (0.78 and 0.82 m) relative to the 1996 and 1923 floods, respectively. Sea level rise of 2 and 4.9 feet (0.6 and 1.5 m) added 0.3 and 1 feet (0.1 and 0.3 m), respectively, to these water levels. The upper end of the projected range of sea level rise (4.9 feet) is considered very large, with a 1.3% probability of being exceeded by 2100 under RCP 8.5 (*Coastal Hazards*, this volume). The effects of runoff and sea level rise on flood risk varied spatially. Areas near the confluence of the Columbia and Willamette Rivers were most sensitive to runoff changes, whereas coastal regions were most sensitive to sea level rise.

Wherry et al. (2019) also used the 1996 winter flood as a baseline. Roughly consistent with the changes by the 2030s reported in RMJOC (2020), they increased the Willamette River runoff by

20% and Columbia River runoff by 40%, assuming that extremely high water levels in the Portland and Vancouver areas are most likely under a scenario in which a major atmospheric river affects western Oregon when winter flows on the Columbia River are moderately high. With this increase in runoff, they modeled two scenarios of sea level rise: 0.8 and 3.3 feet (0.25 and 1.0 m) by 2040 and 2090, respectively. Sea level rise of 3.3 feet has a 17% probability of being exceeded by 2100 under RCP 8.5 (*Coastal Hazards*, this volume) Under such conditions, peak water level increased by 4.1 to 5.4 feet (1.3 to 1.7 m) above the 1996 flood. Wherry et al. (2019) concluded that while critical levees would not be overtopped with these scenarios, most levees along the Columbia Corridor Levee System at Portland (north Portland along the Columbia River) would be "subject to prolonged exposure from water levels that exceed the safe levee height, which is defined by the U.S. Army Corps of Engineers as the highest flood level for which reasonable flood protection is provided."

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Coastal Hazards

Peter Ruggiero and Meghan Dalton

Variability in water levels associated with El Niño Southern Oscillation events, tides, storm surges, and waves, especially in conjunction with relative sea level rise, can result in hazardous coastal flooding and erosion along the Oregon coast. Coastal communities and ecosystems face heightened, yet uncertain, risks associated with projected changes in these processes. Relative refers to the fact that sea level rise is calculated with respect to land elevations. Differences in the rate of vertical land motions along the Oregon coast can affect relative sea level rise strongly.

Observed and Projected Trends in Sea Level

Global mean sea level has risen by about 7–8 inches (16–21 cm) since 1900, and recent observations suggest that rates of sea level rise have accelerated over the last 25 years (Nerem et al. 2018). Global mean sea level is very likely to continue to rise by about 1–4 feet, relative to the year 2000, by the year 2100 (Sweet et al. 2017, Hayhoe et al. 2018). Instabilities in Antarctic ice sheets that are plausible, but have low probability, could result in much higher (~8 feet [2.4 m]) global sea level rise (Hayhoe et al. 2018) (Fig. 1, Table 1).

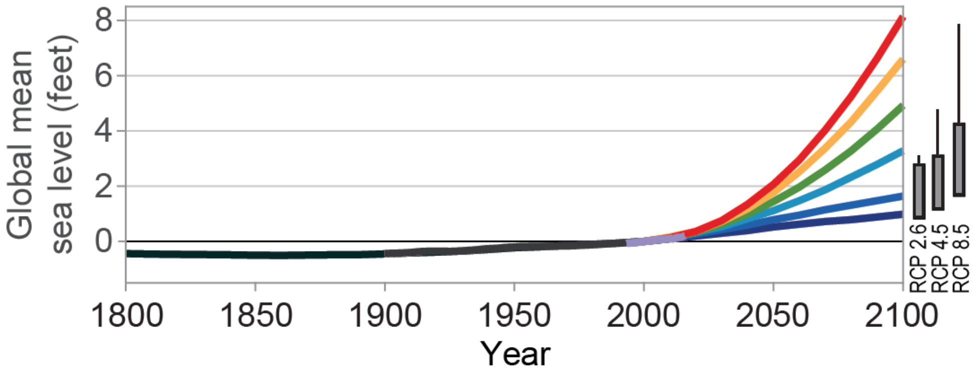

Figure 1. Global mean sea level rise from 1800 through 2100 on the basis of tide gauge-based reconstruction (black), satellite-based reconstruction (purple), and six future projected scenarios (navy blue, royal blue, cyan, green, orange, red) used in the Fourth National Climate Assessment. Gray boxes indicate very likely ranges for three RCPs in 2100 without accounting for melting of Antarctic ice, and lines augment the very likely ranges by accounting for melting of Antarctic ice. Source: Sweet et al. 2017, science2017.globalchange.gov/chapter/12/.

Scenario	RCP 2.6	RCP 4.5	RCP 8.5
Low (1 ft)	94	98	100
Intermediate-low (1.6 ft)	49	73	96
Intermediate (3.3 ft)	2	3	17
Intermediate-high (4.9 ft)	0.4	0.5	1.3
High (6.6 ft)	0.1	0.1	0.3
Extreme (8.2 ft)	0.05	0.05	0.1

Table 1. Probability (percentage) of exceeding each global mean sea level scenario in 2100 under three RCPs. Source: Sweet et al. 2017, science2017.globalchange.gov/chapter/12/.

Recent advances in sea level observations and modeling have led to greater understanding of the processes that contribute to global and regional changes in sea level, including changes in ice sheets and glaciers; water storage on land; thermal expansion of sea water; freshwater input; vertical land motion; and tides, storm surges, and waves (Hamlington et al. 2020). Sea level rise projections vary along the Oregon coast (Table 2), primarily due to variations in vertical land motions.

Anticipated Effects of Climate Change on Ocean Wave Climate

Wave climate refers to attributes of waves that are averaged over a given period of time in a given location. Wind waves can be dominant contributors to total water levels at the coastline via their influence on wave setup and swash (Melet et al. 2020). Although significant uncertainties remain, along the mainland west coast of the United States, mean wave height is projected to decrease by approximately 2–20% (Hemer et al. 2013, Wang et al. 2014, Erikson et al. 2015, Morim et al. 2019), and mean wave period is projected to increase by approximately 2–5% (Hemer et al. 2013, Erikson et al. 2015, Morim et al. 2019), by 2100. Mean wave direction is projected to shift anticlockwise (more waves from the south) by approximately 2–5% by 2100 (Erikson et al. 2015, Hemer et al. 2013, Morim et al. 2019), likely due to a shift in storm tracks toward the north along the west coast of the United States. Projection of future deep-water wave conditions has progressed considerably. However, downscaling of the deep-water wave conditions to the nearshore must be completed on a site-to-site basis to understand the local effects of these changes. Such local downscaling can be computationally demanding and time intensive. Because wave transformation across the shelf determines which storm events affect the coastline, a similar deep-water change to the wave climate could have different impacts at nearby locations (Serafin et al. 2019).

	Astoria		Newport		Charleston	
Scenario	**2050**	**2100**	**2050**	**2100**	**2050**	**2100**
Low	0.1	0.3 ft	0.6	1.2	0.4	0.7
Intermediate-low	0.3	0.8	0.8	1.7	0.5	1.2
Intermediate	0.7	2.5	1.2	3.5	1.0	3.1
Intermediate-high	1.3	4.8	1.8	5.7	1.5	5.3
High	2.0	7.4	2.5	8.4	2.3	8.0
Extreme	2.4	9.3	2.9	10.3	2.7	10.0

Table 2. Median local sea level projections, in feet above a 1992 baseline, for three coastal cities in Oregon under the scenarios used in the Fourth National Climate Assessment. Projections include vertical land motion trend estimates. Source: Climate Central Surging Seas Risk Finder, riskfinder.climatecentral.org/state/oregon.us?comparisonType=county&forecastName=Basic&forecastType=NOAA2017_extreme_p50&level=4&stationNum=1&unit=ft.

Littoral cell (south to north)	Long-term rate (feet/yr)	Short-term rate (feet/yr)
Brookings	1.3 ± 0.7	-0.16 ± 0.3
Pistol	0.7 ± 1.6	1.6 ± 0.3
Gold Beach	1.3 ± 2.3	2.0 ± 0.3
Nesika	0.0 ± 0.3	-1.3 ± 0.7
Humbug	-1.3 ± 1.3	-1,3 ± 0.3
Port Orford	0.0 ± 0.3	-1.0 ± 0.3
Bandon	0.0 ± 0.7	0.7 ± 0.3
Coos	1.6 ± 1.0	0.1 ± 0.3
Heceta	-1.3 ± 1.0	-0.3 ± 0.3
Newport	1.6 ± 0.7	-1.6 ± 0.3
Beverly	-0.7 ± 1.6	-3.6 ± 0.3
Lincoln	0.3 ± 1.6	-1.0 ± 0.3
Neskowin	-1.0 ± 1.6	-3.6 ± 0.3
Sand Lake	-0.3 ± 1.3	-1.6 ± 0.3
Netarts	-1.6 ± 1.0	-3.3 ± 0.3
Rockaway	1.0 ± 1.0	2.0 ± 0.3
Cannon Beach	0.7 ± 2.0	-1.6 ± 0.3
CRLC, Clatsop Plains	10.2 ± 3.6	6.2 ± 0.3
Oregon average	1.3 ± 0.03	0.1 ± 0.07

Table 3. Long-term (late 1800s–2002) and short-term (1967–2002) rates of erosion (mean ± uncertainty estimate) along the Oregon coast (after Ruggiero et al. 2013). Red values indicate that the rates are statistically significant. CRLC, Columbia River littoral cell.

A simultaneous increase in wave period and decrease in wave height may have contrasting effects on a location's wave energy flux. Global wave power, which is the transport of wave energy, increased globally since 1948, most likely due to increases in upper ocean warming (Reguero et al. 2019). However, average and extreme conditions may be modified by the future global climate in different ways. For example, although the annual average wave height may decrease across the west coast of the United States, annual maximum and winter wave heights may increase (Wang et al. 2014). Ongoing research will continue to advance understanding of the impacts of various alterations to the wave climate and will treat extreme and average conditions differently.

Coastal Erosion

Over the past 100 years (late 1800s through 2002), trends in beach erosion were statistically significant in only three of Oregon's 18 littoral cells (coastal compartments within which sediment movement is self-contained), Humbug, Heceta, and Netarts. Erosion in these cells ranged from 1.3–1.6 feet (0.4–0.5 m) per year (Table 3). However, in the shorter term (1967–2002), 10 of these littoral cells eroded at a statistically significant rate of 1–3.6 feet (0.3–1.1 m) per year. This increase in rates of erosion along much of Oregon's coastline may be related to the effects of sea-level rise and evolving patterns of storminess (Ruggiero et al. 2013).

The comprehensive, region-wide coastal change study (Table 3) revealed multidecadal, counterclockwise rotations of the shoreline in several littoral cells in central Oregon (Fig. 2, Ruggiero et al. 2013). The shoreline rotations were detected in analyses of shoreline change from 1967–2002, a period that encompassed two major El Niño events (1982–1983 and 1997–1998). Previous research identified the potential for extreme El Niño events to contribute to littoral cell rotations at seasonal to interannual extents. However, the dynamics resulting in persistent (multi-decadal) rotation were not understood until recently (Anderson et al. 2018). Contrary to previous understanding, climate variability over multiple decades (for example, the Pacific Decadal

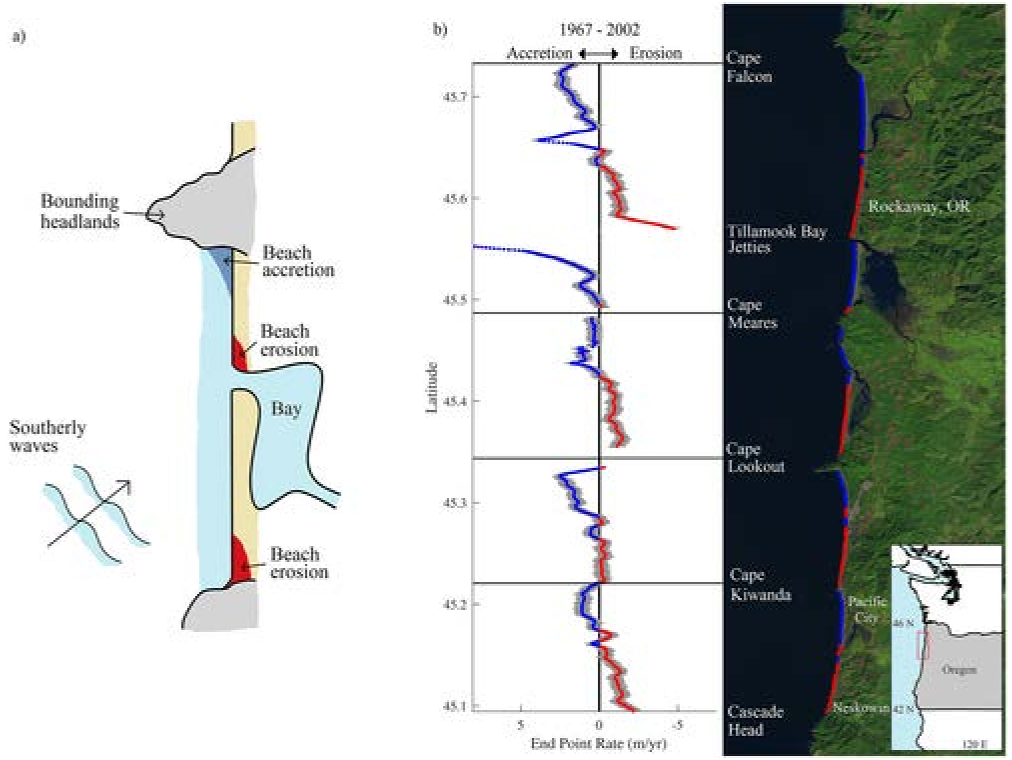

Figure 2. (a) Typical hot spot erosion during an El Niño year and (b) shoreline change from 1967 through 2002 across four littoral cells along the north-central Oregon coast (Tillamook County). Blue and red indicate shoreline accretion and erosion, respectively, and gray bands quantify uncertainty (after Anderson et al. 2018).

Oscillation) appears to affect the locations of persistent erosion in coastal Oregon. Substantial changes to the twenty-first century wave climate may play a major role in future shoreline evolution in Oregon (Anderson et al. 2018).

Coastal Flooding

	Astoria		Newport		Charleston	
Scenario	**RSLR by 2100 (feet)**	**Year**	**RSLR by 2100 (feet)**	**Year**	**RSLR by 2100 (feet)**	**Year**
Low	0.3	>2200	1.2	2070	0.7	2130
Intermediate-low	0.8	2110	1.7	2060	1.2	2090
Intermediate	2.5	2070	3.5	2050	3.1	2060
Intermediate-high	4.8	2050	5.7	2040	5.3	2050
High	7.4	2040	8.4	2040	8.0	2040
Extreme	9.3	2040	10.3	2030	10.0	2040

Table 4. Year by which at least one flood exceeding four feet above mean high tide is virtually certain (>99%) to occur. Estimates assumed median relative sea level rise (RSLR) projections for three coastal cities in Oregon under the scenarios used in the Fourth National Climate Assessment (see Table 2) and historic extreme flood levels for each location. (Source: Climate Central Surging Seas Risk Finder, https://riskfinder.climatecentral.org/state/oregon.us?comparisonType=county&forecastType=NOAA2017_int_p50&level=4&unit=ft)

The projected increase in relative sea levels along the Oregon coast raises the starting point (the still water level) for waves, storm surges, and high tides to impinge on beaches and backshore areas. Possible changes to each of these drivers has the potential to make coastal flooding in Oregon (associated with total water levels) more severe and more frequent in the future. A simple estimate of coastal flood risk by Climate Central combined relative sea level rise projections and historic flood frequencies to estimate the multiple-year risk of flooding above a certain threshold. For example, one can project the year by which at least one coastal flood exceeding four feet above mean high tide could occur in coastal Oregon locations (Table 4). Assuming the intermediate sea level rise scenario (Table 2), at least one flood exceeding four feet above mean high tide was projected to occur by 2050 in Newport, by 2060 in Charleston, and by 2070 in Astoria. These flood risk projections did not incorporate changes to wave dynamics or storm surges. When the latter were included, such coastal flood levels were likely to occur sooner.

Relative sea-level rise narrows the gap in elevations between commonly occurring high tides and the thresholds above which flooding begins. Coastal communities were developed with an understanding of this gap and the flooding that could occur under extreme conditions. When considering only long-term sea level trends (still water levels), the gap between high tide and flooding may be filled on the order of decades (e.g., Table 2). When considering high frequency sea-level variability associated with waves (total water levels), flooding and its effects on the built and natural environment may become frequent much sooner, on the order of years (Mills et al. 2018, Hamlington et al. 2020). Incremental increases in relative sea-level rise can produce exponential increases in coastal flood frequency (Taherkhani et al. 2020). For example, on the west coast of the United States, approximately 2.1 inches (5.3 cm) of sea level rise doubles the odds of exceeding the present-day, 50-year water-level event (that which has a 2% chance of occurring in a given year) (Taherkhani et al. 2020). Similarly, the odds of such extreme flooding double about every five years. These findings underscore the urgency of adapting Oregon's coastlines to increases in flooding and erosion (Taherkhani et al. 2020).

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Marine and Coastal Change

Charlotte Regula Whitefield, Caren Braby, John A. Barth, and Meghan Dalton

Oceans worldwide have absorbed 29% of all carbon dioxide (CO_2) emitted to the atmosphere since the beginning of the Industrial Revolution (Jewett and Romanou 2017). Increases in global atmospheric concentrations of CO_2 have caused fundamental shifts in the amounts and distribution of chemical (e.g., salinity, acidity, dissolved oxygen) and physical (e.g., temperature, currents, sea level, winds) properties of the ocean and atmosphere. These physical and chemical changes are affecting marine ecosystems and coastal human communities worldwide (Chavez et al. 2017, Pershing et al. 2018). The world's ocean, coasts, and estuaries are among the most species-rich ecosystems on Earth (Mora et al. 2011). Climate and ocean change are expected to impact a wide range of organisms at all trophic levels. Although some organisms may benefit from climate and ocean change, the majority are expected to be affected negatively (Mora et al. 2011). The ecosystem and species responses to change generally are complex, and result from multiple changes in ocean chemical and physical conditions. This complexity challenges the ability to forecast how ecosystems and fisheries will shift, or what actions will be most meaningful in managing the impacts of near- and mid-term changes. Research investments to understand how climate and oceans are changing and impacting Oregon's marine ecosystems and species, particularly species of economic and cultural interest, would facilitate adaptation to and mitigation of changes as they occur. Because Oregon's coastal human communities rely on a productive marine ecosystem for fisheries, tourism, and cultural identity, undesirable changes will have social and economic repercussions for the state (e.g., Kelly 2019, Magel et al. 2020).

Observed and Projected Chemical and Physical Changes in the Ocean

The most direct and well-documented effect of climate change on the oceans is warming (Pershing et al. 2018). Open-ocean, surface waters in the eastern North Pacific, offshore of the northwestern United States, warmed at a rate of 1.15 ± 0.54°F (0.64 ± 0.30°C) per century from 1900 through 2016, and are projected to warm by 5.0 ± 1.1°F (2.8 ± 0.6°C) by 2080 relative to the period 1976–2005 under RCP 8.5 (a scenario that represents a continuation of current levels of greenhouse gas emissions throughout the twenty-first century, or a relatively high amount of warming) (Jewett and Romanou 2017). In addition to gradual ocean warming as a result of climate change, episodic severe events, known as marine heat waves, are now being documented. One such event occurred from 2013 through 2017 in the waters of the eastern North Pacific (Harvey et al. 2020). This so-called warm blob first appeared in the upper ocean during the winter of 2013–2014 (Bond et al. 2015) as a warm water anomaly. The warm blob spread across the eastern North Pacific, then onto the Oregon shelf in autumn 2014 (Peterson et al. 2017). By mid-September 2014, sea surface temperatures off central Oregon had risen by 8.1°F (4.5°C) above regional averages, and the anomalously high temperature persisted within the region until early 2016 (Peterson et al. 2017). The temperature continued to be anomalously high in the deeper water column, ~492 feet (~150 m), until at least late 2017 (Barth et al. 2018, Fisher et al. 2020). A second marine heat wave that was similar in size and intensity to the 2013–2017 event reemerged in the North Pacific in mid-2019, but weakened by December 2019 (Jacox 2019, Oliver et al. 2020). It is not yet known what long-term effects, if any, will emerge from the second event (Oliver et al. 2020), but it is likely that marine heat waves will occur regularly as atmospheric and oceanic temperatures destabilize over the coming decades. Warming ocean temperatures affect marine ecosystems in a variety of ways, including but not limited to changing the metabolic rates of organisms, increasing the toxicity of harmful algal blooms, and causing species' ranges to shift (e.g., Somero et al. 2016, Harvey et al. 2020, Trainer et al. 2020).

Warming ocean temperatures have profound effects on other aspects of ocean physics, particularly water density and stratification in the upper part of the water column, which in turn reduces transfer of oxygen among surface and deeper layers (Pershing et al. 2018). Additionally, warm water holds less oxygen than cool water, so increasing water temperature directly decreases the concentration of dissolved oxygen. Trends in dissolved oxygen are more difficult to detect given that oxygen concentration varies considerably due to periodic circulation patterns and interdecadal oscillations (e.g., seasonal coastal upwelling, seasonal coastal storm mixing, El Niño-Southern Oscillation [ENSO], Pacific Decadal Osculation [PDO], and other patterns that also are disrupted by climate variability; Pierce et al. 2012). Local coastal processes of decomposition further can give rise to temporally and spatially variable low-oxygen or hypoxia events (oxygen concentration less than 1.4 ml per liter of ocean water). On the shelf and adjacent slope, changes are already noticeable; oxygen levels off Newport, Oregon, decreased 40% at 197–230 feet (60–70 m) from 1960–1971 and 1998–2009 (Pierce et al. 2012). These changes have led to an increasingly recognizable and severe annual hypoxia season in late summer in Oregon and throughout the Pacific Northwest (Chan et al. 2008, 2019), which results in massive die-offs and displacement of key marine species (Chan et al. 2019). The risk of an increasing number of hypoxia events is high given that oxygen levels were projected to decline on average by 17% by 2100 throughout the open ocean, assuming RCP 8.5 (Jewett and Romanou 2017, Pershing et al. 2018).

Globally, over the last 150 years, surface ocean waters absorbed large amounts of anthropogenic CO$_2$ from the atmosphere and became 30% more acidic than the ocean prior to the Industrial Revolution (Jewett and Romanou 2017, Osborne et al. 2020). This process, referred to as ocean acidification, is caused by the chemical reactions that result from atmospheric CO$_2$ entering the ocean, reacting with seawater to release H+ ions and altering the carbonate chemistry of the ocean. Multiple parameters are used to document and describe ocean acidification, including dissolved CO$_2$, pH, total alkalinity, and calcium carbonate (aragonite, Ω) concentrations (Doney et al. 2020). Over the next 100 years, surface ocean waters are projected to acidify by 100 to 150% (assuming RCP 8.5), resulting in a decline of open ocean pH from 8.1 (current average) to as low as 7.8 (Jewett and Romanou 2017). At current levels, negative impacts are already evident across many marine organisms worldwide, including toxicity of harmful algal blooms (Fig. 1), olfactory senses in fish, and shell formation in shellfish (Doney et al. 2020).

Figure 1. Nearshore algal bloom. Source: U.S. Geological Survey.

Along the West Coast, ocean acidification, and to some extent hypoxia, are correlated with seasonal and decadal changes in coastal upwelling (Chan et al. 2008, 2019; Osborne et al. 2020), which brings deep nutrient-rich, low-oxygen, and acidified waters up onto Oregon's coastal shelf (Jewett and Romanou 2017). By 2100, coastal upwelling along Oregon's coast is projected to intensify in spring but weaken in summer, and fewer (by about 23–40%) strong upwelling events are expected (Jewett and Romanou 2017). Seasonal upwelling is important not only in driving ocean circulation but to the ecology of the species that rely on upwelling for primary production, larval migration, and other ecological functions.

As the oceans continue to change, marine ecosystem function has been shifting, and organisms have been observed (in lab and field settings) to respond in a variety of ways to shifting conditions. Research currently is focused on examining the differences in responses among taxa and the capacity of different taxa to adapt to changing ocean conditions. Sessile species (e.g., macroalgae, eelgrasses, and some invertebrates, such as bivalves, barnacles, and sea anemones) and localized species (e.g., small phytoplankton and zooplankton, non-migratory fishes, and some invertebrates, such as crabs, shrimp, and sea stars [Fig. 2]) are the most affected by local or regional changes in oceanography (e.g., Grantham et al. 2004, Bednaršek et al. 2020, Harvey et al. 2020). In contrast, mobile species, such as migratory fishes, seabirds, and marine mammals, often can move away from localized stressors, and are more affected by extensive shifts in marine food webs (e.g., Cheung et al. 2015, 2020; Harvey et al 2020). Regardless of their mobility, many species' reproductive cycles are tied to oceanographic and environmental drivers (e.g., light, temperature, seasonality of spring and autumn ocean upwelling, freshwater inputs, and food or nutrients; Chavez et al. 2017, Harvey et al. 2020). Ocean change is likely to affect foraging during species' migrations, including the location and timing of feeding and the types of prey available or selected, potentially reducing growth and population viability. Changes in oceanographic patterns may exceed species tolerances and disrupt reproductive cycles (e.g., Bakun et al. 2015, Chavez et al. 2017). The following sections describe some of the fundamental observed and projected impacts of ocean and climate change on Oregon's coastal and estuarine organisms.

Figure 2. Sea Stars, Oregon Islands National Wildlife Refuge. Source: U.S. Fish and Wildlife Service.

Phytoplankton

Phytoplankton (single-celled photosynthesizing organisms) are at the base of most marine food webs and are essential for most life in the ocean. Like terrestrial plants, phytoplankton are sensitive to light, temperature, nutrients, and CO$_2$. Because phytoplankton include hundreds to thousands of species with diverse life histories, individual taxa are likely to respond differently to changes in climate and ocean acidification, possibly resulting in substantial changes in species composition and distributions in the coming decades and centuries (e.g., Dutkiewicz et al. 2015, Peña et al. 2019, Trainer et al. 2020). Shifts in the species composition, timing of blooms, and densities of phytoplankton will affect the foundation of the marine food web.

Nutrient-rich coastal upwelling supports the bloom of marine phytoplankton along Oregon's coast (Small and Menzies 1981, Xiu et al. 2018). Changes in the magnitude and duration of coastal upwelling will affect the timing, duration, and intensity of phytoplankton blooms (Bakun et al. 2015). In addition, changes in upwelling could increase or decrease coastal hypoxia, which occurs when a high biomass of phytoplankton sinks to the sea floor and decomposes. Decomposition is a microbial process that consumes benthic oxygen and releases carbon dioxide. Hypoxia can further alter nutrient cycles in the oceans, with cascading effects on the marine food web (Bakun et al. 2015, Xiu et al. 2018).


Figure 3. Tufted Puffin (*Fratercula cirrhata*), a seabird that occurs along the Oregon Coast. Source: U.S. Geological Survey.

Increases in ocean temperature likely will alter the metabolism of some phytoplankton (Toseland et al. 2013), changing not only their nutritional content and production of fatty acids (Hixson and Arts 2016), but their potential to produce biotoxins (Stillman and Paganini 2015, Wells et al. 2015, Trainer et al. 2020). The marine heatwave of 2013–2017 sparked the largest harmful algal bloom recorded in the Pacific Northwest (McCabe et al. 2016, Peterson et al. 2017). Along the Oregon coast, certain environmental conditions (e.g., increasing temperature, decreasing ocean acidity) can prompt some species of *Pseudo-nitzschia* and *Alexandrium* to produce domoic acid and saxitoxins, respectively. Once accumulated into the tissues of shellfishes and other filter feeding organisms, these toxins can amplify at higher trophic levels and cause amnesic shellfish poisoning or paralytic shellfish poisoning in humans, marine mammals, and seabirds (Fig. 3) (McKibben et al. 2015). In the future, such blooms are likely to increase in frequency, and potentially in toxicity. Harmful algal blooms also are influenced by other ocean changes. For example, increasing concentrations of dissolved CO_2 decrease ocean pH (the primary indicator of ocean acidification), which also has been linked to increasing intensity and duration of harmful algal blooms (McKibben et al. 2017).

Ocean acidification also is expected to affect species composition of phytoplankton. The effects of ocean acidification vary among species (Eggers et al. 2014, Dutkiewicz et al. 2015). Nevertheless, some calcifying phytoplankton species, including coccolithophores, are directly and negatively affected by ocean acidification (Hofmann et al. 2010). Coccolithophores' production of calcium carbonate plates, which create their outer cell coverings, sequesters dissolved CO_2 and then deposits CO_2 into deep ocean sediments when they die and their coccolith plates sink. Because decreasing ocean acidity reduces the availability of calcium carbonate, these processes may be impeded (Hofmann et al. 2010).

Zooplankton

Marine zooplankton, like phytoplankton, will be affected by ocean change in different ways depending on their morphology and physiology. Warming ocean temperatures, including marine heat wave anomalies (described above), increase rates of food consumption by zooplankton, and lead to northward range shifts in some species (Xin et al. 2018, Fisher et al 2020, Harvey et al. 2020). Observed dissolution of the shells of small zooplankton, including pteropods, copepods, and crab larvae, suggests that population-level productivity is declining as a direct result of ocean acidification (Doney et al. 2020). There is ample evidence that effects on several major taxonomic groups, including copepods and pteropods, may be substantial (Doney et al. 2020).

One particularly important group, copepods, are tiny pelagic crustaceans that at times comprise the majority of the biomass of zooplankton in marine ecosystems, and are major food sources for several species of juvenile fish and other prey at the base of the food web (Wang et al. 2018). The species composition of copepods, however, changes from relatively nutrient-rich species to nutrient-poor species with warm ocean conditions. As climate continues to change, this may result in a decline in the nutrient content of copepods that support commercially and recreationally important fishery species. Additionally, as ocean acidity increases, some species and life stages of copepods may respond disproportionately (Wang et al. 2018).

Pteropods, or sea butterflies, are small sea snails with carbonate-based aragonite shells. They can be a major food source for commercially important fishes along the Oregon coast, particularly salmon (*Oncorhynchus* spp.) (Somero et al. 2016). The amount of habitat for pteropods is declining off the West Coast due to increasing ocean temperatures and acidity, and decreasing levels of oxygen (Bednaršek et al. 2014, 2016, 2018, 2019). Here, ocean acidification is increasing the extent and severity of aragonite undersaturation states relative to pre-industrial conditions, resulting in pitting of pteropods' shells (Bednaršek et al. 2014, 2018, Feely et al. 2018). The incidence of dissolution was projected to triple by the middle of the twenty-first century (Bednaršek et al. 2014, 2019).

Invertebrates

The physiology and morphology of invertebrates in the oceans is extraordinarily diverse, and a wide range of ocean change impacts on these taxa has been observed (Mora et al 2011). Considerable work has focused on the sensitivity of early life stages of benthic invertebrates to warming, hypoxia, and acidification (e.g. Grantham et al 2004, Busch and McElhany 2016, Pandori and Sorte 2019, Bednaršek et al. 2020a, Doney et al. 2020) because early survival often dictates the productivity of adult populations.

Ocean acidification threatens the growth and survival of most classes of shell-forming invertebrates, including bivalves and crabs, although some species are more strongly affected than others (Busch and McElhany 2016, Bednaršek et al. 2020a, Doney et al. 2020). During their larval stage, as their initial shells are formed, bivalves (e.g., clams, mussels, oysters) are highly sensitive to reduced calcium carbonate saturation (Waldbusser et al. 2015, Hales et al. 2018). Changes in pH and dissolved CO_2 also can alter invertebrate physiology, reproductive success, and metabolic rates (Somero et al. 2016, Bednaršek et al. 2020a). Acidified coastal environments can be particularly detrimental for larval

Dungeness crabs (*Metacarcinus magister*) (Fig. 4), with severe shell dissolution observed in larvae along the West Coast (Bednaršek et al. 2020b). Shell dissolution in Dungeness crab larvae increased by an estimated 10% over the last two decades as atmospheric concentrations of CO_2 increased, reducing growth and demonstrating energetic trade-offs between shell growth and shell thickness (Bednaršek et al. 2020b). Studies in Oregon are examining the effects of ocean acidification (pH and calcium carbonate ions) and warming temperature on pink shrimp (*Pandalus borealis*), which are an economic resource for Oregon's coastal communities (G. Waldbusser, personal communication). The results of this study may inform management decisions related to ecology and economics.

Figure 4. The National Oceanic and Atmospheric Administration's Northwest Fisheries Science Center conducts research on the effects of ocean acidification on Dungeness crab along the West Coast. Credit: Austin Trigg / NOAA.

Episodic seasonal hypoxia events are having a considerable effect on benthic invertebrates off the coast of Oregon. Of particular concern to regional resource managers and coastal communities are shifts in the distributions of adult and juvenile Dungeness crabs corresponding with episodes of hypoxia (Froehlich et al 2014, Magel et al. 2020). Die-offs in crab pots were correlated with hypoxic regions (Grantham et al 2004). Catch per unit effort and the general condition of Dungeness crabs were significantly and positively related to oxygen concentration off the coast of west-central Oregon (Keller et al. 2010).

Extensive range shifts of pelagic invertebrates partially are attributable to unusually warm waters that brought tropical and subtropical species north to Oregon's shorelines. In 2016 and 2017 (correlated with the marine heat wave), extremely abundant pyrosomes (*Pyrosoma* spp.), tunicates that also are called gelatinous sea pickles, were observed off Oregon's shores (Brodeur et al. 2018). Pyrosomes consume high biomass of phytoplankton, but provide little nutrition for higher trophic levels. The ecological effects of pyrosome blooms are unknown (Brodeur et al. 2018). Additionally, although their abundance off the coast of Oregon usually is low, market squid (*Doryteuthis opalescens*) has become a profitable fishery in the past decade (Thompson et al. 2019). Normally concentrated along the central California coast, populations of this species have been moving north, possibly due to increases in water temperature (Thompson et al. 2019).

Warming ocean waters have been linked in some studies to increasingly intense disease outbreaks and mass mortality in the Pacific Northwest (Hewson et al. 2018, Byers 2021). For example, Sea Star Wasting Disease has been found in over 20 species of sea stars from Alaska to Baja California since 2013. Symptoms of this disease vary, but the most notable is a complete breakdown of sea star tissues (Hewson et al. 2018). Mortality of sea stars can have cascading ecosystem impacts given that they can be major predators in marine ecosystems (Rogers-Bennett and Catton 2019).

Fishes

As temperatures warm and oceanographic conditions change, the ranges of many marine fishes are projected to move poleward in the northeast Pacific, and an influx of warm-water species along the Oregon coast is expected (Cheung et al. 2015). The geographic ranges of mobile and migratory fishes shift substantially during short-term events such as El Niño and marine heat waves. Such shifts can affect physiology, foraging by other species, and the viability of fisheries, especially if the range shifts persist as climate changes (e.g., Peiro-Alcantar et al. 2019). These poleward range shifts in fish populations may generate new recreational and commercial fishing opportunities (Weatherdon et al. 2016). The effects on individual species, species with which they interact, and fisheries may be either negative or positive. Declines in some northeast Pacific fisheries (e.g., salmon and steelhead [*Oncorhynchus mykiss*]) also are projected (e.g., Crozier et al 2019). Warmer ocean waters could alter the ranges and migrations of salmon and steelhead, lead to thermal stress, increase susceptibility to disease and predation during spawning, and increase stratification of the water column, which would change habitat structure and reduce the food supply for adult and larval fishes (Wainwright and Weitkamp 2013, Crozier et al 2019).

Ocean acidification and hypoxia can affect the metabolism of many fishes. Slow-swimming and larval stages are particularly vulnerable because they have less ability to move away from adverse conditions (Somero et al. 2016). A series of bottom trawls suggested that catch per unit effort, species richness, and the general condition of five fish species was significantly and positively related to oxygen concentration off central Oregon (Keller et al. 2010). Hypoxia off the Oregon and Washington coasts appears to reduce the abundance of Pacific halibut (*Hippoglossus stenolepis*) due to short-term geographic displacement; hypoxia in 2016 coincided with absence of halibut, and led to changes in the annual regional fishing quota across the sampled region (Sadorus et al. 2016). Increases in ocean acidification also could disrupt food availability for many fish species by altering conditions for the growth of some prey (e.g., pteropods), whereas changes in coastal upwelling could shift the timing of nutrient availability for other prey, such as phytoplankton. Therefore, over time, there may be desynchronization of prey availability at certain life stages (e.g., reproductive maturation, larval fish development; Wainwright and Weitkamp 2013). The growth and development of eggs and larvae of some North Pacific commercial flatfish species (particularly northern rock sole [*Lepidopsetta polyxystra*]) are negatively affected by elevated CO_2 levels, the direct cause of ocean acidification (Hurst et al. 2017).

Mammals and Sea Birds

Because they are homeotherms and breath air, marine mammals and sea birds are thought to respond indirectly to the effects of ocean change, primarily via changes in regional food webs (e.g., Harvey et al. 2020). Changes in the quantity and nutritional content of phytoplankton and zooplankton will continue to cascade through trophic levels and among generations in marine ecosystems. Prey availability on foraging grounds may have the greatest impact on reproduction and sustainability of these populations and species in the coming decades (e.g., Harvey et al 2020).

Ocean change has led to changes in interactions between marine mammals and human activities. For example, the number of entanglements of humpback whales (*Megaptera novaeangliae*) in commercial Dungeness crab fishing gear increased sharply in recent years (Okey et al. 2014, Lebon and Kelly 2019). It has been hypothesized that ocean changes (e.g., increases in temperature, changes in the timing and magnitude of upwelling), combined with an increase in humpback whale abundance as the species recovers from historic harvest, are causing the increase in entanglements. As a result of ocean change, the distributions of species on which humpback whales prey are shifting. Humpback whales are generalists that forage on both krill and schooling fishes. As humpback whales migrate to and from their breeding grounds along the West Coast, they follow their prey on and off the continental shelf. In 2016, high concentrations of domoic acid from a regional harmful algal bloom prompted an unprecedented delay in the opening of the West Coast's Dungeness crab fishery, inadvertently intensifying the spatial overlap between whales and crab fishery gear. Whales that are entangled can become injured, ill, or otherwise impaired in their ability to feed or swim (Santora et al. 2020). The current rate of entanglements could lead to fisheries restrictions under the Marine Mammal Protection Act and Endangered Species Act. Regional resource managers and fishing communities actively are working together on management solutions (Lebon and Kelly 2019).

Globally, seabird deaths due to biotoxins from harmful algal blooms and other ocean changes (e.g., prey shifts) are increasing in magnitude and frequency (Fey et al. 2015). Among the seabirds that have been impacted by harmful algal blooms are cormorants, terns, waterfowl, alcids, shearwaters, and pelicans (Fey et al. 2015). The mechanisms by which harmful algal blooms affect seabirds are diverse. For example, surfactant-like proteins produced by the dinoflagellate *Akashiwo sanguinea* coat feathers and prevent flight (Jones et al. 2017). Toxins produced by the diatoms *Pseudo-nitzschia* spp. cause paralytic shellfish poisoning, and accumulate in birds that consume the shellfish (Ekstrom et al. 2020). Although the magnitude of many of these events has been relatively small (hundreds of birds), several events have affected large breeding colonies (hundreds of thousands of birds) (Jones et al. 2017, Ekstrom et al. 2020). Harmful algal bloom-induced seabird mortality may become more prevalent in the California Current System given the documented increase in occurrence and intensity of harmful algal blooms and changes in ocean temperatures, acidity, and other attributes (Ekstrom et al. 2020).

Macroalgae (Eelgrass and Kelp)

The effects of climate and ocean change on macroalgae are relatively unclear, and likely will vary among regions, ecosystems, and species. Increases in sea level will reduce the ability of eelgrass and kelp to photosynthesize, whereas ocean acidification may increase growth over the short term. Climate and ocean change are expected to alter eelgrass and kelp habitats through changes in sea level, ocean acidification (e.g., dissolved CO_2), water temperature, upwelling, freshwater runoff, and sedimentation. Dissolved oxygen and pH can vary across small spatial extents and with proximity to macroalgae. As macroalgae photosynthesize, dissolved oxygen increases and dissolved CO_2 and pH decrease (e.g., Frieder et al. 2012, Ratliff et al. 2015, Chan et al. 2017). Because kelp and eelgrass are primary producers with high biomass that contribute to ecosystem structure (Fig. 5), kelp and eelgrass beds could buffer some types of ocean change in the short term through the uptake of CO_2 and release of oxygen during photosynthesis (Koweek et al. 2018). Ocean upwelling strongly affects kelp and eelgrass abundance (Hayduk et al. 2019). There is increased interest in whether kelp and eelgrass beds could provide refugia for other marine organisms in the near future (Ratliff et al. 2015, Chan et al. 2017).

Eelgrass beds acts as nursery grounds for hundreds of marine species, including commercially important taxa such as Dungeness crabs and Pacific herring (*Clupea pallasii*). Eelgrass beds provide protection against coastal erosion through wave attenuation, sediment stabilization and accretion, and prevention of sediment resuspension (Sherman and DeBruyckere 2018). Additionally, eelgrass beds improve water quality by trapping and storing particles and nutrients, including toxicants.

Eelgrass systems also hold considerable stocks of organic carbon and many continue to accumulate and sequester carbon. Carbon that is stored in these shallow coastal systems may substantially reduce the magnitude and speed of climate change (Röhr et al. 2018, Prentice et al. 2020).

Figure 5. Kelp beds, Oregon Islands National Wildlife Refuge. Source: U.S. Fish and Wildlife Service, https://creativecommons.org/licenses/by/2.0/legalcode.

Kelp biomass is decreasing rapidly along most of the Oregon and Washington coastline. Climate change and thermal tolerances likely are among the causes. Because the annual biomass of kelp beds is highly variable, understanding how kelp populations are responding to climate change requires long-term data. Much research on kelp responses to climate change has focused on a few relatively long-lived, perennial, canopy-forming species, such as those in the genus *Macrocystis*. Canopy-forming kelps appear to be more sensitive to warming than other kelps throughout their ranges (Beas-Luna et al. 2020). In at least some cases, populations of *Nereocystis*, an annual canopy-forming species, were negatively correlated with nitrate concentrations in ocean water and positively correlated with winter wave height; upwelling and wave height have been increasing in Oregon (Hamilton et al. 2020). There also is evidence that increases in abundance of sea urchins, which are driven by decreases in predation as sea stars are affected by Sea Star Wasting Disease (Byers 2021), is increasing grazing on kelp (Rogers-Bennett and Catton 2019).

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Natural Systems

Erica Fleishman

Natural systems, a term used in Oregon's 2021 Climate Change Adaptation Framework to encapsulate terrestrial, aquatic, coastal, and marine ecosystems, encompass the structure, composition, and function of life at all levels, from genes to biomes (Franklin 1981, Noss 1990). Structure often refers to the complexity of vegetation strata, such as grasses and herbaceous flowering plants, shrubs, and trees. Composition usually means the identities of species. Function generally includes ecological and evolutionary processes that sustain life. This chapter explores the extent to which scientific evidence suggests that species in Oregon and the Northwest may be able to adapt to projected changes in climate, and examines the potential responses of several species of concern across the state to anticipated climate change. The chapter also introduces some of the ways in which climate science can be applied to facilitate adaptation and persistence of Oregon's natural systems. Natural systems or species that already are stressed by land-use changes generally may be less resilient to climate change.

Species Distributions

At virtually all spatial and temporal extents and resolutions, climate is correlated strongly with many species' distributional limits (Rehfeldt et al. 2006), abundances (Fogarty et al. 2020), and survival (Hansen et al. 2015). Species can persist as climate changes by migrating or by adapting in place (Thurman et al. 2020). Changes in climate over the past 40 years have been associated with shifts in where certain plants and animals occur (e.g., Kelly and Goulden 2008, Moritz et al. 2008, Forister et al. 2010) and in phenology, or seasonal events in the life cycle of plants and animals (Bradley and Mustard 2008, Hodgson et al. 2011, Helm et al. 2013, Renaud et al. 2019). For example, both plastic and evolutionary changes in phenology have been documented in response to changes in seasonal temperature (Bradshaw and Holzapfel 2008, Canale and Henry 2010, Chown et al. 2010), and are projected in response to diverse changes in climate in the Northwest (Kooyers et al. 2019, Reed et al. 2019, Prevéy et al. 2020). To illustrate, by 2085 and assuming RCP 8.5 (a scenario that represents a continuation of current levels of greenhouse gas emissions throughout the twenty-first century, or a relatively high amount of warming), flowering and ripening of beaked hazelnut (*Corylus cornuta*), Oregon grape (*Mahonia aquifolium*), and salal (*Gaultheria shallon*) are projected to advance by roughly one month relative to 1981–2010 (Prevéy et al. 2020).

Projections of current or future distributions of species that are based on their current associations with climate variables (e.g., Parra and Monahan 2008, Franklin et al. 2009, Case et al. 2020), especially average temperature (Pearson and Dawson 2003), can be misleading. These projections sometimes result in unduly dire inferences (Razgour et al. 2018), such as that two-thirds of the bird species that inhabit the United States may be at risk of extinction from climate change (Wilsey et al. 2019) (Fig. 1). However, organisms generally respond to extremes, not means (although some respond to cumulative phenomena, such as growing degree days [a measure of heat accumulation]), and the effects of a given climate attribute can differ among species, populations, and life stages (McDermott Long et al. 2017). Similarly, species vary in physiological tolerances to temperature (Boyles et al. 2011) and other climate variables. Distributions or other species-level metrics may be linked more closely to interactions among climate variables—and among species—than to single climate variables (Harsch and HilleRisLambers 2016). Additionally, although temperature is measured and modeled readily, it may not be the variable to which species are most responsive.

Figure 1. The status of Sagebrush Sparrows (*Artemisiospiza nevadensis*) may be affected by changes in climate, land use, and fire dynamics in Oregon's high deserts. Photograph by Frank Fogarty.

For instance, insects can be affected strongly not only by winter temperature but by reductions in snow cover and by drought (Minckley et al. 2013, Johansson et al. 2020, Wagner 2020).

Methods for estimating some climate extremes affect inferences about the effects of those extremes. For example, methods for estimating evaporative demand affect assessments of drought severity (Dewes et al. 2017). To illustrate, drought can be estimated on the basis of the evaporative demand drought index, which in turn is a function of temperature, humidity, wind speed, and incoming solar radiation (Hobbins et al. 2016, McEvoy et al. 2016). Different species are more or less sensitive to those four components, and therefore may not have consistent or predictable responses to an aggregated drought index.

Local Adaptive Responses of Species

Species-environment relations are not static (MacDonald 2010, Walsworth et al. 2019). Therefore, even when the current ecology of a species is well understood, it often is difficult to predict with confidence how the species will respond to projected changes in climate, especially when climate change interacts with land-use change or other environmental changes. Species adapt in response to climate change, land-use change, and other environmental changes (Thomas et al. 1996, Skelly et al. 2007, Winter et al. 2016). Contemporary field data and paleoecological data (MacDonald et al. 2008, Willis and MacDonald 2011) on terrestrial and aquatic vertebrates, invertebrates, and plants demonstrate that these responses may be rapid, on the order of years or decades (Boughton 1999, Singer 2017). Nevertheless, the anticipated rate of widespread climate change from 2010–2100 generally exceeds that documented in paleoenvironmental records from the recent geologic past (~2 million years), or even over the past 65 million years (Diffenbaugh and Field 2013). As a result, some evolutionary processes may not be able to keep pace with climate change. Open-source software for estimating the speed of climate change in a given region recently was released (Molinos et al. 2019).

Adaptive responses may reflect phenotypic plasticity, or modifications of behavior, appearance, or physiology of individuals in response to environmental change (Fig. 2). Such adjustments are a common means of persisting through climate variability or land-cover change. Alternatively, adaptive responses may result from adaptive evolution: heritable genetic changes that affect individuals' phenotypes (observable traits) and increase probabilities of persistence of populations or species (Reed et al. 2011). Plasticity also is heritable and therefore can evolve. Analysis of field data on levels of phenotypic plasticity, and the extent to which such plasticity is adaptive, is rare (Merilä and Hendry 2014, Hall and Chalfoun 2018), although advances in genomics may improve understanding and assessment of adaptive capacity (Oyler-McCance et al. 2016). Nevertheless, it is feasible to incorporate estimates of phenotypic plasticity and local adaptation in models of species' responses to climate change (Chown et al. 2010, Crozier et al. 2011, Garzón et al. 2011). Doing so typically yields estimates of survival and area occupied that are higher than if evolutionary processes were not modeled (Garzón et al. 2011). Realistic ways to collect data that allow description and prediction of evolutionary responses to climate change range from sampling the fossil record (Willis and MacDonald 2011), to long-term genetic studies, to selection experiments (Hoffman and Sgrò 2011).

Figure 2. Caterpillars of the butterfly *Limenitis weidemeyerii* are able to feed on different species of trees and shrubs that grow in riparian areas or drier areas. Photograph by Erica Fleishman.

On the one hand, species distribution–climate projections may overestimate the extent of geographic ranges and, by extension, probabilities of persistence of species with populations that are locally adapted to a comparatively narrow range of resources or climatic conditions (Reed et al. 2011). On the other hand, the projections may underestimate ranges and probabilities of persistence of species with abiotic and biotic tolerances that change through plasticity or evolution (Visser 2008, Chevin et al. 2010, Nicotra et al. 2010, Razgour et al. 2019). Not only natural environmental change but management actions, even if intended to mimic natural processes, can trigger evolutionary responses. Adaptive capacity also is affected by whether individuals can move freely or whether habitat fragmentation and other barriers impede movement (Thorne et al. 2008, Willis and MacDonald 2011, Fleishman and Murphy 2012).

It often is suggested that contemporary interactions among species will be disrupted because of differences in the speed at which species respond phenologically to climate change (Renner and Zohner 2018). For example, some articles posit that many mutualistic interactions among species, or dependencies in which both species benefit, will be affected negatively (Knell and Thackeray 2016). This concept usually is referenced as phenological or trophic mismatch. However, evidence suggests that mismatch is rare, and primarily limited to antagonistic interactions at high latitudes in the northern hemisphere (Renner and Zohner 2018). Whether changes in phenology among interacting species will be problematic depends on the taxon and the location within the species' ranges (Both et al. 2006, McKinney et al. 2012).

New Insights on Species of Concern

Climate projections and management plans often are structured on the basis of land-cover or land-use types. Doing so assumes, explicitly or implicitly, that species usually associated with a given land-cover or land-use type have comparable responses to environmental change (NDOW 2012, CDFW 2015). However, in part because habitat is different for every species, this assumption rarely is correct except at a rather coarse level (e.g., extensive loss of wetlands is unlikely to benefit most species that are restricted to wetlands or benefit from occasional to frequent use of wetlands). For example, associations of climate variables with relative abundances of breeding bird species in southern California from 1968–2013 varied within groups of species with similar land-cover associations, nesting locations, and migratory patterns (Fogarty et al. 2020). Habitat is not synonymous with land-cover type or vegetation type, but encompasses the space within which a species lives or can live, and the abiotic and biotic elements in that space that generally are required for survival and persistence (Hall et al. 1997, Morrison and Hall 2002). Furthermore, changes in land use can complicate interpretation of observed range shifts or projected future shifts due to climate change (Fleishman and Murphy 2012, Beschta et al. 2014). Strategic acquisition of open space, especially when such areas have diverse topography and geology (Anderson and Ferree 2010), may contribute to conservation as climate changes despite the difficulty of predicting where different species may persist.

Because effects of any environmental change vary substantially among species, this section does not make generalizations about how sets of species in various ecosystems across Oregon are likely to respond to particular changes in climate. Instead, the section focuses on selected individual species in major ecological regions that play dominant roles in the natural, economic, or social systems of Oregon, whether native or non-native and whether desirable or undesirable.

Aquatic ecosystems. Dalton et al. (2017) indicated that the amount and quality of habitat for fishes in Oregon, especially cold-water fishes, likely will decrease in response to increasing peak flows, earlier runoff, reduced summer low flows, and increases in summer stream temperatures. A systematic review of responses of juvenile salmonids, including sockeye, Chinook, chum, coho, and pink salmon (*Oncorhynchus nerka*, *O. tshawytscha*, *O. keta*, *O. kisutch*, and *O. gorbuscha*) in the Pacific Northwest, to human activities in estuaries and nearshore waters similarly suggested with moderate to high confidence that decreases in flows and connectivity, and moderate to low confidence that increases in temperature in relatively warm locations, might decrease body condition, movement, survival, and growth (Hodgson et al. 2020). These direct and indirect effects of climate change are projected within Oregon in the coming decades.

Chinook and steelhead (*O. mykiss*) salmon runs, all listed as threatened under the U.S. Endangered Species Act, migrate through the Columbia and Snake Rivers in Oregon and Washington, including a corridor that has warmed about 4.5°F (2.5°C) in recent decades, to spawning grounds in Idaho, Oregon, and Washington (Keefer et al. 2018). Spring- and most summer-run Chinook salmon migrated before river temperatures peaked. Their body temperatures were similar to ambient temperatures, and rarely reached thresholds associated with physiological stress and behavioral change (Keefer et al. 2018). Natural selection may shift migration dates earlier or later in the future to reduce exposure to high temperatures. By contrast, the maximum body temperatures of most steelhead were near thermal tolerance limits (68–72°F, or 20–22°C) in the lower Columbia River. When stream temperatures are high, Chinook and steelhead can reduce their body temperatures to some extent by moving into relatively cool waters near tributary confluences. Whether this strategy will be effective in the future may depend in part on the extent to which stream temperatures increase, and whether increases are spatially variable. Additionally, food availability for salmon generally decreases, and juvenile mortality increases, when the nearshore ocean is unusually warm, and both long-term and episodic warming of these areas is likely.

Much research on how freshwater and anadromous species may respond to climate change has focused on direct physiological responses, but changes in the frequency of flooding or the seasonal pattern of high flows also affect species interactions (Wenger et al. 2011), phenology (Peckarsky et al. 2011), survival of juveniles, and colonization by non-native species (Warren et al. 2009) (also see *Floods* and *Marine and Coastal Change*, this volume).

Coast Range. Two of the most iconic species in the Coast Range are Marbled Murrelets (*Brachyramphus marmoratus*) and Northern Spotted Owls (*Strix occidentalis caurina*). Because reductions in habitat area and connectivity for both taxa have been considerable, climate change may pose a greater threat to their continued persistence than if relatively little of their historical habitat was lost. Marbled Murrelets, which are listed as threatened under the U.S. Endangered Species Act, nest in old-growth and late-successional forests and forage in nearshore oceans in the Pacific Northwest. From 1999–2018, the species was less likely to colonize locations with little old growth during years in which ocean temperatures were relatively high and prey abundance was low (Betts et al. 2020). Ocean temperatures are likely to continue increasing over the next 80 years, and marine heat waves may become more common (*Marine and Coastal Change*, this volume) If consistent declines in the status of the species prompt a change in its designation from threatened to endangered, commercial and recreational activity in its habitat likely will be restricted further.

Northern Spotted Owls, also listed as threatened, are declining throughout their range, which extends beyond the Coast Range to western British Columbia, Washington, Oregon, and northern California. At present, a primary driver of their decline is competition with native Barred Owls (*Strix varia*), but changes in the amount or quality of the species' habitat, or in the species' survival and reproduction, also are possible as climate changes. Observed relations between annual survival of the species and seasonal temperature, precipitation, and precipitation extremes at local and regional levels varies geographically. Generalizations state that wet winters and hot, dry summers—both of which are projected to become more common in Oregon—are associated with decreases in survival and reproduction (Wan et al. 2018), yet local survival also can be associated positively with warm summers and wet growing seasons (Glenn et al. 2011). Across the species' range, survival was higher in the year following a shift in the Pacific Decadal Oscillation from the cool to warm phase (Glenn et al. 2011). In Mount Rainier National Park, Washington, which is cool and wet relative to much of the range of Northern Spotted Owls, territory occupancy was related positively to mean minimum temperatures during the early nesting period (March and April) (Mangan et al. 2019) Accordingly, at that local extent, projected increases in spring temperatures may benefit the species.

East Cascades. Mountain pine beetle (*Dendroctonus ponderosae*) is a native insect that tunnels into conifers, including but not limited to ponderosa pine (*Pinus ponderosa*), lodgepole pine (*P. contorta*), limber pine (*P. flexilis*), and whitebark pine (*P. albicaulis*). Whitebark pine is a candidate for listing under the U.S. Endangered Species Act. The severity of outbreaks of mountain pine beetles may be greater, and less predictable, in relatively dense stands of trees (Nelson et al. 2018). In Oregon, mountain pine beetles are most common on the east slope of the Cascade Range. Larval feeding on the inner bark inhibits the flow of nutrients throughout the tree, and the beetles carry a fungus that inhibits the flow of water throughout the plant. The insects are eruptive and may cause greater damage to trees that already are stressed by drought, the incidence of which is projected to increase. In some cases, species that are drought-stressed may be more susceptible to cumulative effects of multiple diseases, For instance, whitebark pine affected by blister rust (*Cronartium ribicola*), which can be more prevalent when water availability is limited, may be more susceptible to colonization by mountain pine beetles (Jackson et al. 2019). Mortality of whitebark pine from mountain pine beetles also may increase as autumn temperatures increase to 32°F (0°C), but not above that temperature (Buotte et al. 2017).

Historically, freezing temperatures each winter resulted in considerable mortality of mountain pine beetles in a given area. Similarly, cold extremes increase mortality of western spruce budworm (*Choristoneura freemani*), which defoliates Douglas-fir (*Pseudotsuga menziesii*) (Senf et al. 2017). However, as Dalton et al. (2017) noted, as the number of days above freezing increases, winter survival and generation times of mountain pine beetles are projected to increase and decrease, respectively. Facultative diapause (a period of dormancy during development) may be a mechanism for changes in generation times. Although mountain pine beetles were not thought to enter diapause, it appears that facultative diapause and developmental delays can occur when late-instar larvae are exposed to cool temperatures, and that diapause is more common in northern than southern populations (Bentz and Hansen 2018). Survival and the likelihood of eruptions also appears to increase during a series of relatively warm winters (Bone and Nelson 2019). Consequently, mountain pine beetles may pose greater threats to native trees in the future.

Northern Basin and Range and Blue Mountains. As noted in *Wildfire* (this volume), rapid expansion of cheatgrass (*Bromus tectorum*) (Fig. 3), a non-native invasive grass, has increased the extent and frequency of fire in sagebrush shrubsteppe across the Intermountain West, including eastern Oregon, and is associated with reductions in habitat amount and quality for numerous native species of plants and animals. Within its range in the western United States, cheatgrass currently is most abundant in areas where precipitation is greatest during autumn and spring, which facilitates the species' germination and growth (Bradley et al. 2016), and with hot, dry summers. Percent cover and biomass of cheatgrass also tends to increase in years with heavy winter and spring precipitation (Knapp 1998, Garton et al. 2011), and may remain high during the following year (Bradley et al. 2016). Both hot, dry summers and wet winters are projected to become more common in Oregon during the twenty-first century (*State of Climate Science*, this volume).

Figure 3. Sampling cheatgrass (*Bromus tectorum*) in the high desert. Photograph by Erica Fleishman.

The likelihood of presence or the abundance of cheatgrass often decreases as elevation increases (Compagnoni and Adler 2014, Chambers et al. 2016). Germination, growth, and reproduction of cheatgrass generally are highest at intermediate elevations with moderate temperatures and water availability. At low elevations, cheatgrass is limited by relatively high temperatures and low precipitation, and at high elevations, the species is limited by low soil temperatures (Meyer et al. 2001; Chambers et al. 2007, 2017; Compagnoni and Adler 2014). Projected increases in temperature at high elevations (as at all elevations) may reduce that constraint on cheatgrass expansion in the future. Furthermore, soil moisture and nutrient levels commonly increase as elevation increases, supporting higher primary productivity and competition between cheatgrass and other species (Chambers et al. 2007, Compagnoni and Adler 2014), especially perennial grasses, which can reduce the cover and density of cheatgrass (Reisner et al. 2013, Bradley et al. 2016, Larson et al. 2017).

Statewide, especially western Oregon. Swiss needle cast (*Nothophaeocryptopus gaeumannii*), a native fungus, reduces the photosynthetic capacity, growth, and competitive ability of Douglas-fir. Two genetic lineages of Swiss needle cast occur in Oregon. The first occurs nearly everywhere that Douglas-fir grows in its native or introduced range, whereas the second largely occurs within several miles of the ocean west of the Coast Ranges in Oregon and Washington, and may be more virulent (Bennett and Stone 2019). Cold winter temperatures and warm summer temperatures are associated with lower prevalence and severity of Swiss needle cast, whereas spring and early summer moisture are associated with higher prevalence and severity (Bennett and Stone 2019). The interaction of May and August land surface temperature (the temperature of the highest-altitude surface in a given location, such as the tree canopy) explained more variation in incidence of Swiss needle cast in the Coast Range of Oregon than other measures of spring and summer land surface temperature and water balance, especially on private lands (Mildrexler et al. 2019). These results suggested that cool, moist conditions in spring and warm, dry conditions in late summer coincide with expansion of the fungus, and that relatively young, even-aged stands of Douglas-fir are more vulnerable than stands with greater diversity of ages and species (Mildrexler et al. 2019). Tolerance to Swiss needle cast in coastal Douglas-fir populations appears to reflect local adaptation to climate and pathogen pressure (Wilhelmi et al. 2017).

Dendrological reconstruction of Swiss needle cast in western Oregon from 1985–2011 suggested that outbreaks are synchronous and episodic, with primary periodicities of 20–40 years, and generally are associated with relatively warm winters and cool, wet summers (Lee et al. 2017). Effects of Swiss needle cast may increase disproportionately at higher elevations and latitudes if future winter temperatures in those locations consistently exceed 39°F (4°C) (Lee et al. 2017), which is plausible by the late twenty-first century given the range of projected temperatures under RCP 8.5.

Applications of Climate Science to Adaptation of Natural Systems

Recent science can inform spatially explicit prioritization of mitigation efforts, such as carbon sequestration, in natural systems (Buotte et al. 2020). New research also can inform implementation of recommendations in Oregon's 2021 Climate Change Adaptation Framework for increasing the resilience of the state's natural systems to climate change. For example, the recommendations include expansion and restoration of riparian buffers and stream channel wetlands with the aim of protecting water quality, increasing stream flow, reducing flood damage, and providing habitat for aquatic and terrestrial animals. Riparian systems serve these roles not only in relatively wet ecosystems in western Oregon but in the high deserts of eastern Oregon, where they are small and have high species richness. For example, about 80% of the terrestrial animal species in the Great Basin (Thomas et al. 1979), including 66–75% of the breeding bird species, are associated with riparian areas for breeding, feeding, or shelter (Dobkin and Wilcox 1986, Earnst et al. 2012). Riparian systems can be threatened by intensive livestock grazing, diversion of surface water and groundwater, expansion of non-native invasive species, and land-use change. To illustrate, recruitment of aspen (*Populus tremuloides*) (Fig. 4) at Hart Mountain National Antelope Refuge from 1850–2009 was much more strongly associated with grazing by domestic livestock than with drought, annual precipitation, and annual temperature (Beschta et al. 2014). The riparian area in the Intermountain West likely will decrease due to increased aridity over the next century (Melack et al. 1997, Cayan et al. 2013), but it is unclear how the configuration of riparian systems or vegetation may change. In northeastern Oregon, decreases in summer precipitation, increases in temperature, and increases in drought are likely to decrease minimum flows, which may make some streams intermittent rather than perennial (Reynolds et al. 2015). Riparian plants and animals also may be affected by changes in competitive interactions. For example, non-native invasive species of tamarisk (*Tamarix* spp.) shrubs and trees, which can displace native riparian vegetation, are widespread east of the Cascade Range, especially in relatively warm and dry areas (Kerns et al. 2009). Expansion of tamarisk is projected as climate continues to change (Kerns et al. 2009).

Figure 4. Aspen (*Populus tremuloides*) along a perennial stream in the high desert. Photograph by Erica Fleishman.

Responses of terrestrial, riparian-associated species to climate change are difficult to project in part because the effects of changes in the structure and composition of riparian vegetation differ among species (Strong and Bock 1990, Dickson et al. 2009). For example, some species respond strongly to extent of riparian areas, whereas others respond more strongly to fragmentation of riparian areas (Fahrig 2013). Abundance and recruitment likely are more sensitive than species presence to changes in the amount or fragmentation of riparian cover (Fleishman et al. 2014). Moreover, many riparian areas in the Intermountain West are naturally fragmented. Species that evolved in naturally fragmented systems may have different responses to habitat area and fragmentation than species in human-fragmented systems (Haig et al. 2000, Pavlacky and Anderson 2007, Habel and Zachos 2012). As climate changes, the microclimate in some riparian areas may provide a movement corridor and biological buffer from some effects of climate change. For instance, cool, wet, low-elevation ravines may provide refugia for limber pine in the Great Basin (Millar et al. 2018).

The Climate Change Adaptation Framework also recommends identifying and protecting areas of high connectivity of land cover and species' habitats, and potential climatic refugia. Such areas could include both extensive areas with little fragmentation of natural land cover and corridors that connect patches or refugia for particular taxa (Heller and Zavaleta 2009). The quality and configuration of a species' habitat affect its population dynamics and relations with other species

(Pulliam 1988, Dunning et al. 1992, Watkinson and Sutherland 1995) and its connectivity, usually defined as the probability that genes or individuals move among patches of the species' habitat (McRae 2006, McRae et al. 2012). By maintaining genetic diversity, which generally is correlated positively with evolutionary potential, gene flow contributes to adaptive capacity (Sgro et al. 2011), and movement of individuals allows for recolonization or population growth (McRae 2006, McRae et al. 2008, Loss et al. 2011). Estimation of connectivity with genetic data can indicate relatively recent levels of breeding among populations or plausible responses to changes in climate and land use in species that are the focus of conservation efforts or are considered pests (Wood et al. 2015, Wittische et al. 2019, Byer et al. 2020).

Efforts to conserve species are more likely to be effective when populations or areas that function as habitat are connected rather than isolated (Harris 1984, Hanski 1999, Haddad et al. 2015). The reverse is true for attempts to control or eradicate species (Glen et al. 2013). Connectivity is affected by climate; topography; the built environment; vegetation composition, structure, and configuration; and ecological processes, such as fire or flows of water and nutrients. Interactions among species, whether mutualistic or antagonistic, also can affect connectivity (Glen et al. 2013). In some cases connectivity of multiple species can be modeled simultaneously (Koen et al. 2014, Fleishman et al. 2017, Brennan et al. 2020). However, just as habitat is species-specific, corridors designed with the goal of facilitating movement of multiple species (such as a corridor of a given land-cover type) may not be effective for individual species.

Novel applications of connectivity analysis are facilitating projection of how species may respond to climate change. For example, Creech et al. (2020) estimated vulnerability of desert bighorn sheep (*Ovis canadensis nelsoni*) to climate change on the basis of genetic diversity, genetic and geographic isolation, the rate of movement necessary for a species to remain within its current climate envelope, and maximum elevation within a given patch of habitat (assumed to be a surrogate for temperature and precipitation). Modeling changes in wind patterns is challenging. Nevertheless, strong winds that flow from relatively warm to cool locations may increase adaptive capacity of diverse taxa that largely are dispersed by wind, whereas weak winds or winds that flow from cool to warm locations may decrease adaptive capacity (Kling and Ackerly 2020). The former are more common on the west side of mountain ranges in Oregon, whereas the latter are more common on the east side.

Climate change is one of multiple, often interacting types of environmental change that will affect the distributions and effects of species that are invasive, pests, or pathogens. The Climate Change Adaptation Framework recommends designing and implementing an early detection and rapid response program to detect and control such species. Environmental DNA (eDNA), for instance, is becoming an effective means of establishing presence of undesirable or desirable terrestrial or aquatic species that are difficult to sample or cryptic, especially in aquatic ecosystems (Bálint et al. 2018, Schumer et al. 2019). Ongoing advances in remote surveillance and networks of trained citizen observers also may facilitate detection, especially in rural areas and wildlands.

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Built Environment

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The built environment encompasses the buildings in which people live and work, the industrial and agricultural infrastructure used to create essential goods and services, and the lifeline infrastructure systems that provide water, electricity, natural gas, transportation, and communications. On the whole, the built environment is both the dominant contributor to Oregon's greenhouse gas emissions, accounting for over 90% of the total (59 million metric tons of carbon dioxide equivalent in 2017; ODEQ 2020), and an essential bulwark protecting people against the worst effects of climate change (Chester et al. 2020). Buildings and infrastructure also are increasingly vulnerable to climate-related risks as the intensities of storms, droughts, heat waves, and wildfires grow (Shortridge and Camp 2019).

The multiple physical and social components of the built environment form interdependent networks (Clarke et al. 2018, Maxwell et al. 2018). Therefore, direct climate-related risks to any one component can act as indirect risks to the others. For example, wildfires simultaneously and directly threaten buildings, electricity transmission systems, water resources and water treatment infrastructure, and road accessibility. Wildfires pose indirect or secondary threats to other systems in the network, such as the communication systems that rely on electricity and the water distribution systems that rely on water resources and treatment infrastructure. Additionally, climate-related natural hazards can create ripple effects in the built environment, such as landslides in recently burned areas that can disrupt the physical integrity of natural gas lines and drinking-water pipes and wells. Accordingly, improving resilience of any infrastructure component has potential to improve the resilience of other systems and resources in the network that supports the built environment.

Reinforcing infrastructure systems, and making them durable and redundant, therefore is urgent (Shakou et al. 2019), as is the adaptation of buildings, towns, and cities to reduce the risk of illness and death when these systems are overwhelmed (Baniassadi et al. 2019). This chapter reviews the state of climate risks to water infrastructure, electricity generation and distribution systems, buildings and cities, transportation networks, and communication systems. The review notes the most cost-effective and energy-efficient strategies for addressing these risks, highlighting the ways in which Oregon's climate, natural resources, and local expertise offer distinct opportunities to make many of the necessary adaptations for minimizing future greenhouse gas emissions and becoming resilient to multiple stressors and hazards.

Water Infrastructure

Infrastructure for water in Oregon encompasses a wide variety of assets (ACSE 2019). For example, Oregon's 882 dams (USACE 2018a) provide hydroelectric power, flood control, water for drinking and irrigation, and recreation. Eighty percent of Oregonians obtain their drinking water from nearly 3400 public water treatment and distribution systems that are supplied by surface water, groundwater, or both. These systems also provide water for fire suppression. Over 250,000 wells in Oregon supply water for drinking and irrigation, and more than 230 levees (USACE 2018b) across 360 miles (580 km) provide flood protection to about 100,000 Oregonians and 22,000 buildings in 27 of Oregon's counties. The state's wastewater systems include 198 publicly owned treatment works regulated via the National Pollutant Discharge Elimination System permit program, almost 50 facilities with Water Pollution Control Facility permits for discharging wastewater effluent to land, and more than 400,000 on-site septic systems. Oregon's stormwater systems are regulated by approximately 2450 general and 12 individual National Pollutant Discharge Elimination System permits and 45 individual Water Pollution Control Facility permits.

Climate change-induced shifts in precipitation and rising temperatures are affecting the quantity and quality of Oregon's surface water and groundwater (*State of Climate Science*, this volume), and threaten the ability of water infrastructure systems to provide expected and timely services.

Flood Management

Flood protection and mitigation infrastructure in Oregon is vulnerable to current and projected sea level rise and storm surges and to increases in the intensity of winter precipitation (*State of Climate Science*, this volume). This infrastructure also faces risks from increased incidence of landslides and debris flows following relatively high precipitation (LaHusen et al. 2020). Problems from landslides triggered by precipitation are expected to exacerbate over time as the intensity of some precipitation events increases. Much of Oregon's flood protection and mitigation infrastructure was designed on the basis of historic trends and variability in tidewater levels and precipitation intensities.

In coastal communities, projected increases in sea level of up to 4.7 feet (1.4 m) by 2100 (Sepanik et al. 2017; *Coastal Hazards*, this volume) are expected to increase pressure on many levees, tide gates, and urban sewer and stormwater pipes. These increases in tidewater levels can make tide gates ineffective and levees unsafe, increasing flood hazard when stormwater is not efficiently conveyed away from those communities.

Inland communities, such as those along the Columbia and Willamette Rivers and their tributaries (Wherry et al. 2019), similarly are threatened by flooding because their stormwater and stormwater sewage infrastructures do not have sufficient capacity to convey projected increases in runoff. These communities likely will benefit from more-detailed evaluation of infrastructure limits and from examination and implementation of gray infrastructure—pipes, tunnels, pumps, and other means of conveying and storing stormwater in urban areas—and green infrastructure enhancements (McPhillips et al. 2020, O'Donnell et al. 2020).

Moreover, policies and financial tools will be needed to support investments in flood infrastructure. For example, as of 2020, less than 6% of Oregon's levees were certified by the Federal Emergency Management Agency (FEMA) (ASCE 2019). Policy and financial tools are needed to support applications for costly FEMA certification of levees that protect community infrastructure, such as hospitals, schools, airports, water treatment plants, law enforcement services, and chemical storage.

Water Supply

Projected drier summers and reduced snow-to-rain ratios (*State of Climate Science*, this volume), exacerbated by groundwater depletion in some regions, threaten the ability of existing water supply infrastructure to meet the growing demand for multiple uses of water (e.g., domestic, industrial, irrigation, recreation) (Clifton et al. 2018). The shift in seasonal flows may require adjustments to existing irrigation infrastructure, such as canals, pipes, storage reservoirs, ponds, and wells. Seasonal changes also may warrant adjustments to water rights, ideally allowing reused and other sources of water to be leveraged or existing resources to be conserved (Jaeger et al. 2017, ASCE 2019) to ensure that the water supply is reliable, water quality regulations are met, costs are managed, and systems are maintained. Adjustments by water utilities may include improving the efficiency of the distribution system to minimize losses (CPMC 2014a, b), promoting conservation behaviors and technologies (e.g., changes to building and plumbing codes; conversion of treated wastewater to potable water [ASCE 2019]), and identifying alternate sources and opportunities for enhancing storage capacity.

Wildfires

Projected increases in the frequency and extent of wildfires (*Wildfire*, this volume) may increase susceptibility of watersheds to flooding, erosion, and landslides, with both short-term and long-term effects on downstream waters and water infrastructure (Smith et al. 2011, Loiselle et al. 2020, Niemeyer et al. 2020, Proctor et al. 2020, Robinne et al. 2020, Schulze and Fischer 2020). Post-wildfire rainfall may increase downstream loadings of suspended and dissolved contaminants such as ash, suspended sediments, nutrients (nitrogen and phosphorus), metals, salts, organic carbon, cyanides, polycyclic aromatic hydrocarbons, polychlorinated dibenzo-q-dioxins and dibenzofurans, and polychlorinated biphenyls (Chong et al. 2019). Many of these contaminants trigger further water infrastructure and public health problems. For example, high levels of turbidity and total suspended solids can reduce the rate of water treatment, making it difficult to maintain a continuous supply of potable water. If sufficient or alternate treatment facilities are not available, the ensuing disruptions can be prolonged. Similarly, high flux of sediments triggered by wildfire-associated erosion can enter and decrease the storage capacity of reservoirs. High levels of turbidity in water contaminated by wildfire residues also may require increased disinfection and oxidation of metals and organics, leading to further increase in formation of disinfection byproducts. High concentrations of metals (e.g., iron, zinc, and manganese) can stain pipes, make the taste or color of water unpleasant, and cause health problems. For example, humans can suffer from poisoning from regular consumption of water with high levels of barium and copper, gastrointestinal problems when copper concentrations are 3–5 mg per liter, and elevated cancer risk from exposure to carcinogens such as arsenic and hexavalent chromium. High levels of trace metals in water bodies can lead to fish kills and die-offs of other aquatic organisms. High concentrations of sodium and chloride also can corrode pipes and pipe fittings and make water taste unpleasant. Furthermore, contamination of groundwater aquifers by chemicals such as polycyclic aromatic hydrocarbons (Mansilha et al. 2014) may degrade the water quality of wells that provide drinking water in many communities.

Non-Climate Stressors

In addition to climate change-related stresses, the long-term stability of water infrastructure systems is being reduced by aging infrastructure, human population dynamics, market forces, technology shifts, urbanization, and the potential for large Cascadia Subduction Zone earthquakes. For example, despite a legacy of investments and innovations, many of the water infrastructure systems in Oregon are at the end of their service life (ASCE 2019). Numerous dams and pipelines are 50 to 100 years old and need significant upgrades or replacements. Cracks, separated pipe joints, and root intrusions in sewer pipes can lead to inflow and infiltration of stormwater and groundwater during wet seasons, resulting in loadings as high as five to seven times their dry-season flows and reducing the efficiency and capacity of wastewater treatment before discharge. As the intensity of storms increases, vulnerabilities in the sewer pipes can exacerbate concentrations of environmental toxicants and human health risks (*Public Health*, this volume).

Adaptation

Adaptation of current water infrastructure is likely to be most effective in the context of interacting systems and stresses (Clarke et al. 2018). For example, improving efficiency of water distribution systems and water supplies to prepare for the aftermath of earthquakes and other disasters can limit distribution losses from pipe leaks and identify sources for augmenting supply, thereby also increasing resilience to climate change. Such integrated approaches can help identify new opportunities for infrastructure investments and technologies, and identify previously unanticipated trade-offs among costs, benefits, and risks. Integration requires extensive stakeholder engagement and coordination among city, county, state, and federal organizations.

Energy Infrastructure

In Oregon, electricity is generated primarily by hydroelectric dams (55%), thermoelectric natural gas power plants (28%), wind farms (12%), and solar installations (1%), each with distinct vulnerabilities to climate change (ODOE 2020). Oregon also imports electricity from other states as needed. Power then is delivered to customers by thousands of miles of above-ground transmission lines that are exposed not only to wildfires (Box 1) but also to storms and high summer temperatures. Liquid fuels, including natural gas, jet fuel, and gasoline, by contrast, primarily enter Oregon through Portland's Critical Energy Infrastructure hub on the Willamette River. Road and rail systems then carry these products throughout the state, compounding energy infrastructure and transportation risks (see *Transportation Infrastructure*, below) (Oregon Solutions 2019, ODOE 2020). The following section focuses on electricity infrastructure because of its vulnerability to climate-related risks (ODOE 2020) and its central role in decreasing reliance on fossil fuels.

Box 1. September 2020 Wildfire Ignitions

On the evening of 7 September, 2020, Portland General Electric interrupted power to 5000 Mount Hood-area homes during a period of extreme fire danger (Withycombe 2020). The utility hoped to avoid a catastrophic event similar to the deadly Camp Fire in northern California two years earlier, which was sparked by electrical transmission lines (Penn and Eavis 2020). Other Oregon utilities kept their lines energized that night, however, and some were downed in high winds. Resulting sparks ignited 13 fires that coalesced into the deadly Beachie Creek fire. Transformer sparks also were implicated in the Holiday Farm fire, which destroyed hundreds of structures in Blue River and Vida (Kavanaugh 2020). Ten months earlier, the Governor's Council on Wildfire Response had given highest priority to legislation requiring utilities to prepare risk-based wildfire procedures that would include criteria for initiating preemptive power outages (GCWR 2019); however, that legislation had not yet been passed.

Electricity Supply

Infrastructure. Oregon's electrical distribution system is part of the Western Interconnection, a major grid that extends from the Rocky Mountain states to California and includes the Canadian provinces of British Columbia and Alberta. This grid is divided into eight regions: Northwest, Northern California, Southern California, Great Basin, Rocky Mountains, Desert Southwest, Canada, and Mexico. The Western Interconnection is managed by the Western Electricity Coordinating Council (www.wecc.org), which is responsible for ensuring a reliable supply of electricity throughout the region. Many balancing authorities direct electricity from generation sites to consumption sites, using continuously varying prices to balance supply and demand. Regional supplies first serve regional demands, minimizing transmission losses, and over- and under-supplies are resolved by exports and imports. Within this system, the Northwest is a net electricity exporter, particularly to Northern California and Southern California (Voisin et al. 2020) (Fig. 1).

Regional risks. The Western Interconnection is sensitive to three climate-related changes that affect electricity production: increasing duration and frequency of drought; increasing percentage of precipitation that falls as rain rather than snow, and extreme precipitation events; and increasing air and water temperatures (*State of Climate Science*, this volume). Droughts diminish streamflows, lowering hydropower generation (Gleick 2016), and low snowpacks similarly decrease summer hydropower production, although shifts in precipitation may cause higher than normal winter streamflows (Glabau et al. 2020). Thermoelectric (for example, natural gas) plants also require cooling water, usually taken from nearby rivers. When streamflows decline or water temperatures rise, as is projected for the Columbia and Willamette Rivers (*State of Climate Science*, this volume), thermoelectric plant generation capacities typically also decline. Under recent ranges of interannual variability, for example, individual plants are expected to lose up to 30% of their capacities on occasion (Voisin et al. 2016).

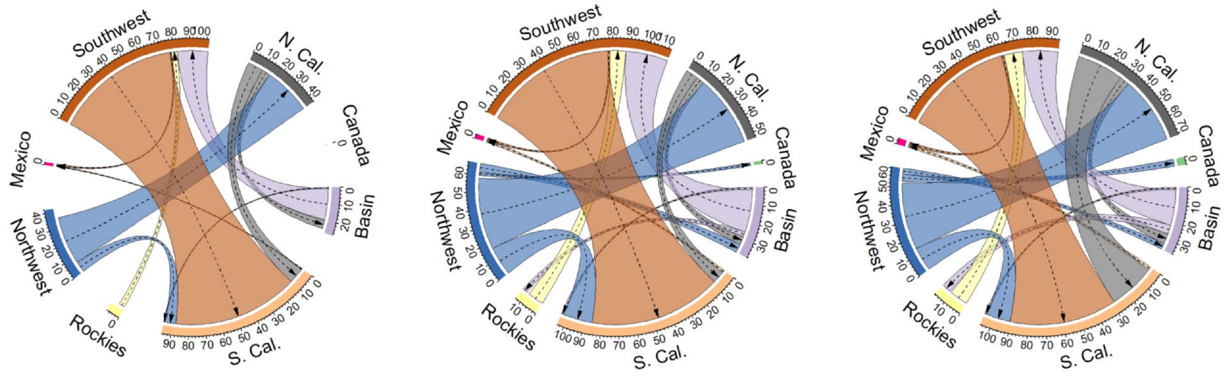

Figure 1. Effects of Northwest water abundance on power flows in the Western Interconnection grid in a dry year (left), normal year (middle), and wet year (right). Source: Voisin et al. 2020; reprinted with permission.

Grid-scale responses. Within the Western Interconnection, each region's power generation and distribution systems continuously trade electricity with the others. At the same time, these linked regions are likely to experience different climate-related stresses at any given time. Therefore, the responses of individual power plants to specific climate stressors cannot represent the response of the grid as a whole, and considerable effort has been devoted to understanding the integrated effects of drought and warmer temperatures on hydroelectric and thermoelectric plant operation at the grid level. These studies suggest that considerable resilience to anticipated climate-related stresses exists in the Western Interconnection as the result of the size of the generation system, its transmission capabilities, and recent improvements in water use and thermal efficiencies.

In particular, Miara et al. (2017) found that thermoelectric plants in the Western Interconnection were far less sensitive to diminished water supplies and increased water temperatures than those in the eastern United States grid because they increasingly have been equipped with either water-free cooling or evaporative cooling systems, which perform well in arid western climates, rather than the once-through cooling water systems typical of plants in the eastern grid. This feature is expected to allow the Northwest region of the Western Interconnection to maintain available capacity and reserve margins within about 2% of contemporary values from 2035–2064 even under RCP 8.5 (a scenario that represents a continuation of current levels of greenhouse gas emissions throughout the twenty-first century, or a relatively high amount of warming).

Additionally, Voisin et al. (2020) found that the effects of climate-related water shortages in the Northwest on hydroelectric and thermoelectric power production would propagate through the Western Interconnection, and that the grid largely would compensate (up to the RCP 8.5 scenario in 2050) by raising both production and electricity prices. In relatively wet years in the Northwest, that region is expected to export power to Northern California and, to a lesser extent, Southern California. Because Northern California also would tend to have high precipitation in these years, its hydropower generation similarly would be high, allowing it to export significant power to Southern California. Southern California then would become less dependent on the Desert Southwest, which would lower its own fossil-fueled power production in response. In normal water years, the Northwest would remain a net exporter of electricity to Northern California, but Northern California would generate less of its own hydropower and therefore export less to Southern California. As a result, Southern California would require more power from the Desert Southwest, which would increase production. In the driest years, these patterns would intensify: the Northwest would export less (but remained a net exporter), Northern California would export slightly less, and the Desert Southwest would expand production further to make up the difference (Fig. 1).

This reliance on electricity generation in the Desert Southwest during drought years would, however, amplify any production limitations in that region, and any volatility in natural gas prices (O'Connell et al. 2019), raising prices across the grid. Still, these studies indicated that the grid is adaptable to near-term hydrologic changes and suggested that ongoing efforts to maintain regional cooperation will be valuable in preserving this adaptability. They also clarified the long-term adaptive value of diversifying and spatially separating electricity generation technologies, and of adopting wind and solar technologies that are less sensitive to hydrologic and thermal changes.

Wind power. Onshore wind power has expanded rapidly in Oregon over the past decade (ODOE 2020, Research and Technology Reviews, Wind), and levelized costs are now competitive with natural gas generation at approximately three to five cents per kilowatt hour (Lazard 2019). Additionally, the continental shelf adjacent to the Oregon-California border is one of the United States' most promising sites for offshore wind generation, with an estimated technical capacity of 62 megawatts (MW) (Musial et al. 2016). Such an installation would require considerable investment (ODOE 2020, Research and Technology Reviews, Wind), but to illustrate the magnitude of the resource, the corresponding annual output of ~230,000 GWh (785 trillion Btu) would exceed Oregon's current electricity generation (ODOE 2020, Energy by the Numbers; Musial et al. 2019).

The effects of climate change on Pacific Northwest wind patterns themselves are uncertain (Pryor and Barthelmie 2010) but could become significant: wind power increases with the cube of wind speed, such that a doubling of wind speed results in an eight-fold increase in power, causing wind power generation to be highly sensitive to wind speed. The current understanding is that Oregon's onshore summer wind speeds over the next several decades may decline slightly from recent averages (Sailor et al. 2008), remaining within the bounds of historical variation, but that wind speeds during winter, when the state's highest peak loads occur, will be relatively consistent (Pryor and Barthelmie 2011). Offshore, however, near- and mid-term future climate scenarios projected that wind speeds throughout the year will increase over current levels (Costoya et al. 2020).

Wave power. Wave power continues to show significant potential for renewable electricity generation in the Pacific Northwest. However, wave energy converter technologies for harnessing the renewable energy in ocean waves are not yet commercially viable. The lack of pre-permitted technology testing infrastructure historically created significant hurdles for the commercial development of the sector. In response, the U.S. Department of Energy funded the PacWave project at Oregon State University, which is developing a 20-megawatt, grid-connected, pre-permitted test facility for wave and marine energy technology testing. PacWave will be available for commercial testing during 2022, and will allow technology developers to test technology concepts at scale, assess environmental impacts, and generate electricity for the utility grid.

As one of the most active wave climates in the world, the Oregon coastline has an annual average wave energy transport of 40,000 watts per meter. The most active winter conditions average ~90,000 watts per meter. Wave energy resources are dependent on both wave height and energy period. The energy flux increases linearly with wave energy period, and with the square of the wave height ($P \sim 0.5*\text{Wave Height}^2*\text{Wave Period}$). The development of wave energy will provide valuable coastal renewable electricity generation (complementary to the solar and wind resources on the east side of the Cascade Range), and features much greater forecasting potential than other renewable resources. The impacts of climate change on wave conditions off the Oregon coast continue to be actively investigated (*Coastal Hazards*, this volume). Annual average conditions appear to remain relatively consistent, whereas local storm patterns and waves are consistent with predicted changes in offshore wind conditions. However, long-distance swell events and associated extreme conditions have the potential to increase off the coast of Oregon (Morim et al. 2019).

Solar power. Like wind power, solar photovoltaic power has expanded rapidly in Oregon: installation rates have increased from approximately 15 megawatts per year in 2010, dominated by building-scale projects, to nearly 140 megawatts in 2019, dominated by utility-scale projects (SEIA 2020). Oregon now has 880 megawatts of installed photovoltaic capacity (SEIA 2020), nearly doubling the 477-megawatt capacity reported in the second quarter of 2018 (ODOE 2018). Most residential and commercial systems are located in the Willamette Valley, whereas most utility-scale projects are sited east of the Cascade Range and in southern Oregon (ODOE 2020, Research and Technology Reviews, Solar).

Photovoltaic generation is highly sensitive to changes in cloud cover, timing, and atmospheric aerosol density, and cloud cover variability normally causes the solar resource (i.e., solar radiation incident upon a surface) to vary from year to year. Additionally, global and regional climate models do not project future cloud cover patterns well. As a result, model-based projections of future climate-related effects on surface solar radiation, and therefore on solar photovoltaic generation, are inconsistent (Craig et al. 2018). Photovoltaic generation also becomes less efficient as panel temperatures rise. Solar panels are primarily heated by direct solar radiation, but because warm panels lose excess heat more readily to cooler air, increasing air temperatures pose a secondary climate-related risk (Peters and Buonassisi 2019). Nevertheless, the current expectation is that climate-related effects on photovoltaic generation across the United States will be small, with declines of less than 1% per decade in the Pacific Northwest (Wild et al. 2015).

Electricity Demand

On 14 August, 2020, a severe heat wave began that extended from Arizona to Washington and covered nearly the entire Western Interconnection. The heat had been forecast, and the grid's capacity and resilience were believed to be sufficient, but as air-conditioning use drove demand higher, the California Independent System Operator (CAISO) found itself short of power (Penn 2020a). Demand also was high in the Desert Southwest and Northwest regions, limiting their ability to sell power, and electricity prices rose past $1000 per megawatt-hour (Kasler 2020). That evening, for the first time since 2001, CAISO ordered rolling blackouts (Phipps 2020), affecting an estimated two million people over four hours (Chediak and Baker 2020). Unexpectedly, the same situation occurred the next day (Penn 2020a). Criticism quickly focused on the relatively high wind and solar proportions of California's electricity resources, and then on residential customers for overconsumption (Uhler 2020). Ultimately it was found that neither were to blame: both had behaved exactly as models predicted. Instead, this event revealed a combination of planning errors and misfortune, in which plants retired for age and environmental reasons still were listed as available, whereas numerous usable plants temporarily had been taken out of service. As a result, CAISO was closer to full capacity than it realized, illustrating the way in which heat waves quickly expose weaknesses in any part of grid operation (Penn 2020b).

Oregon's electricity supply is also vulnerable to heat waves (*Extreme Heat*, this volume), primarily in the form of price spikes that must be absorbed by utilities and their customers. During the August 2020 heat wave, and again in early September, daily electricity prices in the Pacific Northwest rose to eight times the 2020 average (USEIA 2020a). Oregon's most rapidly growing loads—air-conditioning, refrigeration, and chiller operation—also occur during summer. Pacific Northwest residents have resisted home air-conditioning longer than those in other parts of the United States, where home air-conditioning is nearly universal, in response to relatively mild summers, the effectiveness of natural ventilation and shading (see *Urban Heat Islands*, below), and environmental concerns. Nevertheless, the percentage of Oregon homes with air conditioning is rising. Statewide adoption increased from 42% to 57% from 2012–2017 (ODOE 2020, Energy by the Numbers, Where our Transportation Fuels Come From), and in Portland, adoption increased from 66% to 79% from 2011–2019 (AHS 2019, AHS 2011). These trends are attributed to warmer summers, declining air-conditioner costs, stable electricity prices, and wider cultural acceptance (ODOE 2018). The impact of this development is debated: heat-related illness and death are growing risks that fall disproportionately on society's most vulnerable members, and affordable air conditioning effectively mitigates that risk. At the same time, the rapid rise of air-conditioning globally is intensifying the problem of summer heat that it addresses, causing its use to be counterproductive when it is not needed for health purposes (Davis and Gertler 2015; see also *Passive Survivability*, below).

Electric vehicle demand. Electricity demand for transportation also is growing, motivated by the desire to reduce vehicular greenhouse gas emissions. The mix of electricity types used during charging strongly influences the extent to which these emissions can be reduced. Life-cycle analyses indicated that battery-equipped (plug-in) electric vehicles reduce emissions by about 10% compared to conventional gasoline vehicles when powered by electricity from natural gas (Hawkins et al. 2013), with progressively lower emissions as the proportion of hydropower, wind, solar, or nuclear power increases (Faria et al. 2013, Peng et al. 2018). Electricity generated from coal, by contrast, increases emissions above conventional gasoline vehicle levels. As a result, promotion of electric vehicles in areas with high shares of coal power in the electricity mix is counterproductive (Bauer et al. 2015). At the same time, the extraction and processing of metals such as nickel, copper, lithium, and aluminum for electric vehicle batteries and motors is energy-intensive, causing electric vehicles to consume substantially more energy in production than conventional analogs (Bauer et al. 2015). These processes also create mine-scale wastes that acidify surface waters, leach toxins, and release photochemical oxidants, giving electric vehicles greater human-toxicity and terrestrial acidification potential than conventional vehicles (Hawkins et al. 2013, Bauer et al. 2015). Trade-off among these effects depend on both the power resource mix, with renewable power favoring electric vehicles, and on the electric vehicles' lifetime. The greater the number of miles driven, the greater the impacts of operational energy become relative to production impacts. Together, these considerations illustrate the information provided to development of electric transportation policies by conducting life-cycle analyses that incorporate vehicle manufacturing (Hawkins et al. 2013, Bauer et al. 2015).

In light of Oregon's high existing proportions of hydropower and wind power, and commitments to expand renewable electricity supplies further, Governor Kate Brown recently issued Executive Order 17-21, "Accelerating zero emission vehicle adoption in Oregon to reduce greenhouse gas emissions and address climate change," currently implemented by the Zero Emission Vehicle Interagency Working Group (ODOE 2018) (see *Transportation Infrastructure*, below). Similarly, in California, the sale of gasoline-powered cars will be banned in 2035 (State of California 2020), and analogous efforts are underway in Arizona and Washington (U.S. Department of Energy 2020a,b, State of Washington 2020). Transportation accounts for about one-third of all energy demand in these states (USEIA 2020b), and public media have expressed ongoing concerns about grid reliability if conversion to electric vehicles proceeds (e.g., Gold 2020). To be sure, the typical unmanaged practice, in which drivers connect their vehicles to home charging stations after their evening commutes, would add further demand during peak load hours. With this approach, even low levels of electric vehicle adoption likely would increase peak demand, raise prices, and require upgrades to electricity distribution systems (Muratori 2018). However, the widespread adoption of electric vehicles has the potential to assist the balancing of electricity production and consumption across the grid, greatly reducing problems posed by intermittent wind and solar power, if charging is managed (Richardson 2013).

As wind and solar power provide increasing proportions of a region's electricity, fossil-fuel plant generation must be increased quickly, with loss of efficiency, to accommodate the hours when wind and solar resources subside. The reverse occurs, again with loss of efficiency, when wind and solar power return. Additionally, renewable power in excess of demand requires curtailment, or a reduction of output below the current potential, effectively wasting the renewable energy. Smart charging, in which a third party remotely controls the time over which a plugged-in vehicle is charged to maximize the benefit to the grid, could allow the existing grid in California to accommodate up to five million vehicles (a twenty-fold increase over current capacity) while avoiding up to 10% of operating costs and 40% of current curtailment (Szinai et al. 2020).

This work has two implications for Oregon. First, increasing numbers of electric vehicles are likely to raise peak loads and electricity costs in the Northwest regional grid if charging remains unmanaged. However, these effects are avoidable with effective charging management. Second, as the number of electric vehicles grows, smart grid technology has excellent potential to diminish or eliminate electricity price increases and the need for new peak-demand electricity purchases, and to improve the integration of wind and solar power into the state's electricity resource mix.

Demand response. To limit peak electricity demands, and to integrate wind and solar power into the supply with minimal need for curtailment, utilities and grid operators can use a strategy in which the demand is encouraged to respond to the supply. This is accomplished by demand-response pricing, in which usage during times of high demand or low supply is more expensive, allowing the reduction to be voluntary. In contrast to time-of-use pricing, the time of day during which rates are higher is a function of grid conditions. Because the Northwest region historically had greater regional supply than demand, it only is beginning to develop demand-response capacity as coal plants are retired and renewable power capacity increases (ODOE 2018). In the Seventh Northwest Conservation and Electric Power Plan, however, the Northwest Power and Conservation Council strongly recommended the development of significant demand response capacity by 2021 as the most cost-effective way to meet growing summer and winter peak demands under critical water and extreme weather conditions (NPCC 2016).

Policy Applications

Oregon's electricity infrastructure is increasingly vulnerable to climate-related changes and shocks from wildfire, drought, and heat wave-induced demand. At the same time, the Western Interconnection is responsive and resilient, with good capacity to respond to droughts and supply interruptions in the Northwest through production increases in the Desert Southwest, albeit with price increases. Through this network, the Pacific Northwest's power exchanges and prices are highly connected with those of California, the dominant power importer in the system, and the activities of CAISO. As a result, California's heat waves, electric vehicle mandates, building code changes, and other relevant policies will affect Oregon's electricity prices, whereas Oregon's droughts will affect prices in California. To meet regional goals of maximizing wind and solar power while avoiding price spikes, greater intervention in consumer use patterns will be necessary to minimize peak loads and to redirect consumption to periods of high renewable power supply. This will be especially important as the number of electric vehicles increases, with after-work plug-ins adding substantially to early evening peak loads if charging times are not delayed. Still, rapid expansion of electric vehicles has the potential to ease the integration of intermittent wind and solar power into the grid supply if charging times are managed by demand-response or smart systems, giving Oregon incentive to develop these in parallel with California.

Buildings and Cities

People experience the effects of climate change most immediately in their dwellings, workplaces, and communities, and the resilience of these elements has immediate and potentially long-lasting effects on human health and well-being. The exposure of Oregonians' shelters and livelihoods to climate risks varies dramatically across the state and, as a result, some populations are more vulnerable to wildfires, droughts, heat waves, storms, and the secondary effects of power outages, electricity prices, and building thermal performance. At the same time, Oregon has substantial climatic, cultural, and information resources with which to address these problems, and progress is underway. The primary challenge will be to accomplish the necessary adaptations as rapidly as they are needed.

Urban Heat Islands

Portland has one of the most intense urban heat island effects in the United States (*Public Health*, this volume), as defined by the average difference between the temperatures of a city and its rural surroundings (Climate Central 2014) (Fig. 2). Eugene, Medford, and Albany also experience considerable urban heat island effects. In Salem, Bend, and Ashland, these effects are less severe but still pronounced (Chakraborty et al. 2020).

Urban heat islands are created by the concentration of heavy, dense materials in cities that absorb heat well and become warmer themselves in response, primarily the asphalt and concrete of roadways and rooftops (Mohajerani et al. 2017) and the brick, stone, and concrete of buildings (Santamouris 2013a). Solar radiation accounts for much of the energy these materials absorb, but the heat emitted by vehicles, air conditioners, refrigeration equipment, and industrial machinery also contributes substantially. Once warm, buildings and roadways slowly re-emit this energy, causing densely built and paved areas to remain many degrees warmer than their surroundings, even during cool nights.

Urban heat effects tend to be concentrated in certain areas. In Portland, these include interstate corridors, industrial zones, and neighborhoods east of Interstate 205, where temperatures can be as much as 15–20°F (~8.3–11.1°C) warmer than Forest Park on the western side of the city (Hart and Sailor 2009). Such areas are typically are occupied by communities in which education is limited, income is low, and the proportion of children and elderly residents is high (Waldroupe 2016). Urban heat island effects therefore are greatest in neighborhoods where people are most susceptible to heat stress (Voelkel et al. 2018) (Fig. 3) (also see *Public Health*, this volume). Compounding urban heat island effects, homes in low-income neighborhoods often are less able to manage excessive heat, with less-insulated roofs, limited access to cross-ventilation, and inability to afford air conditioning (Sakka et al. 2012).

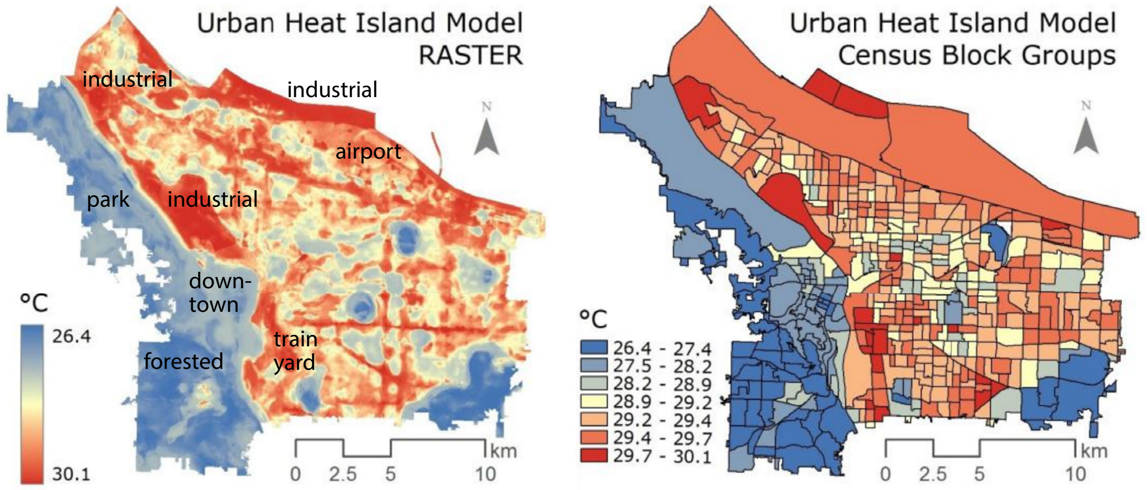

Figure 2. Urban heat island effects as measured (left) and defined by census block (right) in Portland, Oregon. Reprinted with permission from Voelkel et al. 2018.

Urban heat island effects can be addressed through strategies that focus on materials, vegetation, transportation, or buildings. If multiple strategies are used, the effects are cumulative. Among the materials-based approaches, the uses of light-colored pavements and light-colored or reflective coatings on existing pavements widely have been successful (Santamouris 2013b), although their use should be restricted to parking lots to avoid creating glare on roadways (Mohajerani et al. 2017). Porous and permeable pavements have been similarly successful due to their diminished heat retention ability and their ability to absorb moisture from rain or humid air, allowing them to remain cooler through subsequent evaporation (Qin 2015). The use of white and reflective roofs also has been explored, but these increase winter heating loads, and as a result they are not recommended in relatively cool climates such as Oregon's (Testa and Krarti 2017).

Additionally, vegetation-based approaches have been investigated widely in Portland, with excellent success (USEPA 2017). Trees planted along streets intercept, absorb, and reflect solar radiation that otherwise would warm roadways and sidewalks, and their evapotranspiration has high cooling effectiveness in dry summer climates like those across Oregon, although they may require summer irrigation. Shrubs, vegetated swales, and lawns also typically remain many degrees cooler than adjacent streets (Makido et al. 2019).

The third set of strategies involves transportation: replacing gasoline-powered cars with cooler electric vehicles is predicted to diminish urban heat island effects considerably. Reducing the number of automobiles through mass transit, and reducing the area of paved roadway accordingly, is expected to be comparably effective (Kolbe 2019).

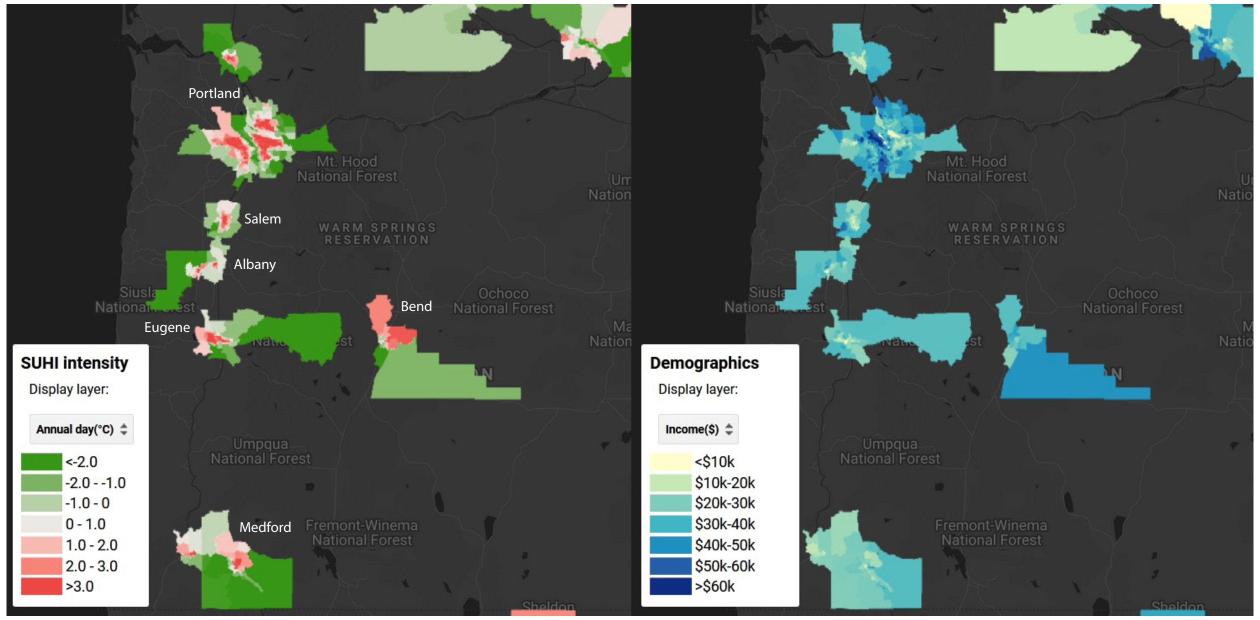

Figure 3. Summer urban heat island intensities in Oregon cities (left) and annual income (right). Source: US Summer Urban Heat Island Disparity Explorer, https://datadrivenlab.users.earthengine.app/view/usuhiapp (Chakraborty et al. 2020).

The most effective approaches involve the design of both office (Kolokotroni et al. 2012) and residential buildings, particularly including affordable housing, to reduce cooling needs through roof insulation, night ventilation, and shading (Oikonomou et al. 2012), which reduces use of air conditioning. The heat emitted by air conditioners is too extensive, in cities with near-universal air conditioning, to overcome urban heat island effects otherwise (Santamouris et al. 2015). Oregon has extraordinary climatic cooling resources. Even on the hottest days in the hottest cities, air temperatures drop by 25°F (~13.9°C) or more on the vast majority of nights (NWS 2020), and dry summer climates across the state facilitate evaporative cooling. Current evidence strongly suggests that the widespread adoption of such passive (non-mechanical) cooling strategies across Oregon would substantially slow the pace of air-conditioning adoption, simultaneously improving thermal comfort and lowering greenhouse gas emissions while mitigating urban heat island effects (Kolokotroni et al. 2012, Oikonomou et al. 2012, Santamouris et al. 2015).

Urban Wildfire Resilience

In 2019, the Governor's Council on Wildfire Response found that the cumulative economic losses from wildfires were 11 times greater than the immediate costs of firefighting, causing the cost of a single high-fire season in Oregon to total several billion dollars (GCWR 2019).

During the 2020 wildfires, dense smoke spread through the Willamette Valley to the coast, raising airborne fine particulate-matter ($PM_{2.5}$) concentrations to hazardous levels for ten days in many areas (AirNow 2020; *Public Health*, this volume). Although the short- and long-term health effects of smoke exposure in Oregon have not been quantified, evidence from recent fires in Australia and California suggests that they will add substantially to wildfire costs (Richardson et al. 2012, Jones and Berrens 2017, Johnston et al. 2020) (*Public Health*, this volume).

Over 1.2 million Oregonians were estimated to live in areas of high wildfire risk in 2010 (Fig. 4). Oregon's population since has grown by 10% (U.S. Census 2019), primarily due to in-migration from other states (State of Oregon 2019a). Although this growth rate is expected to decline slightly over the next decade (State of Oregon 2019b), western Oregon is likely to have considerable climate-related in-migration that is not yet incorporated into population growth projections (Wicks 2011).

In response to this anticipated population growth, particularly in the wildland-urban interface, Oregon Governor Kate Brown convened the Council on Wildfire Response in 2019 to develop specific recommendations for action regarding electricity infrastructure, cities and buildings, communication networks, and public health measures to mitigate fire risks (GCWR 2019). For buildings, the council strongly recommended the establishment of consistent policies requiring defensible space, or areas cleared of trees and other combustible elements. In Oregon, unlike other fire-prone states, such policies do not currently exist. Until recently, the presence of defensible space has been viewed as the dominant contributor to structure survival in wildfires, although the extent of clearing needed is debated (Penman et al. 2019). Among homes burned from 2001 through 2010 in San Diego County, California, vegetation touching or overhanging a structure was correlated with fire loss, but the useful land clearance was less than expected, with no significant advantage provided by clearance of over 40% of the woody vegetation in the land around a home (Syphard et al. 2014).

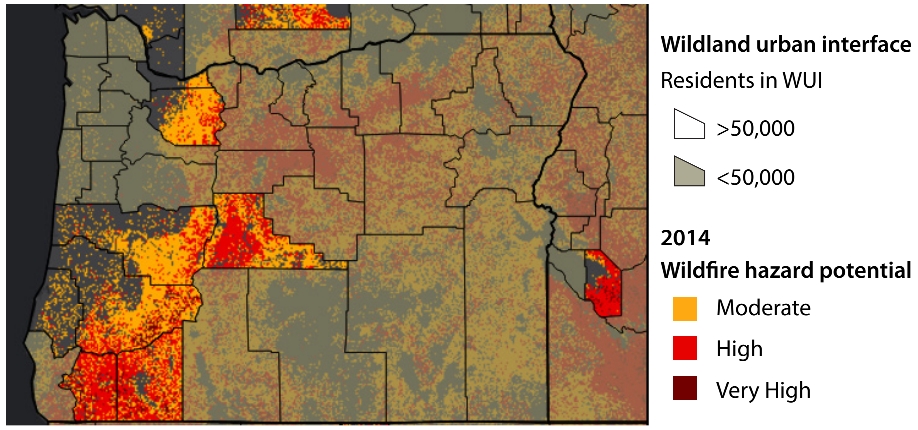

Figure 4. Oregon population living in the wildland-urban interface (2010) and accompanying wildfire hazard evaluated in 2014. Counties shown in bright colors have more than 50,000 residents living in the wildland-urban interface, including Multnomah, Clackamas, Deschutes, Lane, Douglas, Coos, Josephine, and Jackson counties. Source: Alvarez 2020.

Another investigation of 40,000 homes throughout California that were exposed to wildfires from 2013 through 2018 indicated that the distance between buildings and surrounding vegetation explained less than 1% of the variation in building survival (Syphard and Keeley 2019). Buildings lost in these wildfires generally were not ignited by the fire itself, but by wind-driven embers traveling up to a mile ahead of the fire front that landed on combustible materials on or inside the house. Of greater importance was the ignitability of the building itself, as predicted by the status of eaves, vents, and windows, followed by siding, deck, and roof materials. These results strongly support the Oregon Council's recommendation of updating building code requirements for wildfire overlay zones. Because the fire resistance of individual materials was less important than the access of the structure to flying embers, the most protective measures were found to be the enclosing of eaves; screening of roof vents; replacement of single-pane windows with double-pane windows, which improves their resistance to radiation and cracking; replacement of asphalt roofs with metal, tile, or other materials; and replacement of wood decks and porches with composite materials.

The strongest finding of recent studies is that buildings in low-density, fire-prone areas—rural areas and the wildland-urban interface—are at far greater risk of fire loss than those in urban areas (Syphard et al. 2019). This highlights the importance of investment in small-community fire response plans, as recommended by the Governor's Council on Wildfire Response, and in strategies to maintain compact growth in the Portland, Salem, and Eugene-Springfield areas.

Passive Survivability

Air conditioning adoption is increasing across the Pacific Northwest, with approximately 58% of homes in the region now equipped with mechanical cooling, compared to 28% in 2001 (RECS 2001, AHS 2019, 2020). Building code requirements for insulation and airtightness have increased over the same time period (State of Oregon 2020a), lowering heating loads as predicted by building energy models, but they have not included requirements for shading or natural ventilation. As a result, new codes inadvertently have led to the creation of enclosed spaces that no longer cool as effectively as traditional homes did. Instead, when mechanical air-conditioning stops, these buildings tend to become much warmer than outside air because they have no diversions for solar gain and no outlets for internal heat gain (Sailor et al. 2019). Oregonians therefore are becoming increasingly dependent on air conditioning, relinquishing passive cooling methods that are highly effective in Oregon's climates (Rempel and Remington 2015), and potentially exacerbating urban heat island effects and health risks in the process (Kolokotroni et al. 2012, Oikonomou et al. 2012).

As a result, Oregon dwellings increasingly lack passive survivability, or the ability to maintain conditions within survivable limits. Therefore, increasing numbers of people are at risk of heat-related illness during air-conditioning failures, which are particularly likely to occur during heat waves as the result of power outages or unit failures. In the United States, the combination of air-conditioning dependence and air-conditioning failure is the dominant cause of heat stress, a burden that falls disproportionately on low-income populations. Extensive improvement of passive survivability in residential buildings, through top-down interventions if necessary, appears to be the most effective and inexpensive solution to excessive air-conditioning dependence in affordable housing (Baniassadi et al. 2019). In Oregon, winter survivability is also crucial, since multiple-day power outages can occur even in cities during heavy snowstorms (Hernandez 2017, Rodriguez 2018, Guevarra 2019, AP 2020). Recent changes in building codes are aligned with this goal.

Passive survivability is difficult to accomplish in extreme climates, but this is not the case in Oregon. Although Oregon's summers are becoming warmer, air temperatures still typically fall by tens of degrees F for several hours overnight (NOAA 2020). As a result, night ventilation is highly effective if sufficient air can pass through a building, which requires operable windows on multiple walls or at high and low positions on a single wall (Rempel and Remington 2015, Rempel and Lim 2019). These requirements are not included in current energy codes, but if they were added, they easily could be met at the design stage without increasing costs beyond adding security grilles to ground-level windows. Exterior shading also is highly effective, if it can be retracted in winter to allow solar heat gain, and low relative humidities in summer give direct evaporative cooling high potential (Yang et al. 2019). The primary challenge in passive cooling performance is the well-timed operation of operable elements, so that windows are opened at night and closed before the hottest hours of the next day; shades are deployed in the morning to intercept solar radiation before the space starts to warm; and evaporative cooling is operated primarily during the hottest, driest hours (late afternoon and early evening) (Rempel and Lim 2019). Collectively, these measures are expected to maintain peak indoor temperatures 10–16°F (5.6–8.9°C) below peak outdoor temperatures, or as much as 25°F (13.9°C) cooler than the indoor temperatures would have been otherwise (Rempel and Remington 2015).

Policy Applications

Oregon's buildings and cities, and especially frontline communities within them, face growing and, in some cases, severe risks from wildfires and heat waves. With respect to fire, recent research strongly supports the creation of overlay codes for buildings at high risk of fire damage that would require the enclosing of open eaves, screening of roof vents, and upgrading of single to double-pane windows for protection from the flying embers that first reach buildings in high winds. Removal of trees and woody plants that touch buildings and overhang roofs is also critical, whereas other clearing can be moderate.

With respect to heat waves, research supports extensive planting of street trees and other vegetation, which has excellent potential to cool Oregon cities through shade and evapotranspiration, particularly in neighborhoods with abundant asphalt but few trees. Light-colored pavements also are promising. However, white roofs should be avoided in Oregon's cool climates. In addition, electrification of transportation is expected to diminish urban heat island effects by lowering the number of heat-emitting cars. Improving the passive survivability of buildings is a high priority as well, particularly in communities most vulnerable to heat-related illness. This approach would take advantage of Oregon's dry and relatively mild summers to reduce cooling loads through natural ventilation, shading, and evaporative cooling, measures that are not currently required by building energy codes. The resulting reduction in cooling loads also has the potential to delay air-conditioning dependence, further slowing the intensification of urban heat island effects.

Transportation Infrastructure

Transportation infrastructure in Oregon (ASCE 2019) includes 2782 route miles (4477 km) of rail track that are operated by Union Pacific Railroad Company, BNSF Railway Company, and regional, local, and switching and terminal railroads; 74,000 miles (119,000 km) of roads operated by federal agencies (27%), Oregon Department of Transportation (11%), and county, tribal, and city jurisdictions; and 7615 bridges and 546 culverts.

Much of the railroad infrastructure is aging. Many of the short line timber bridges were built between 1930 and 1950, and 23 of the 24 tunnels on the short line system were excavated between 1883 and 1915. Oregon's bridges also are aging, and many are vulnerable to tsunamis, earthquakes, and flooding. The average age of all surveyed bridges in Oregon is 46 years old, and is expected to exceed a typical design life of 75 years by 2051 if five to ten bridges per year are replaced. Roadways, although regularly maintained and updated, are stressed by the growing population and by natural hazards. An assessment conducted by the Oregon Department of Transportation, Federal Highway Administration, and local governmental authorities in 2014 identified multiple vulnerabilities in Oregon's transportation infrastructure due to climate change and extreme weather (ODOT 2014). The study reported vulnerabilities in highways on the Coast Range, roads that have large cuts or fill slopes, low-elevation areas that are prone to flooding, and in the transportation infrastructure in coastal areas that are exposed to storm surges and inundation. Seismic Lifeline Routes in Oregon, intended to facilitate emergency response and recovery after an earthquake, also were found to be vulnerable to the effects of climate change. The study recommended that adaptation to climate change be site-specific, and reflect cost-benefit analysis of multiple options such as construction of buttresses, slope protection, grade change, construction of soldier pile walls or ocean debris barriers, widening and reinforcement of channels, and increasing the elevation or width of bridges.

Digital Infrastructure

Increasing the climate resilience of current and new physical infrastructure will require a commitment to data-driven capital planning. Digital infrastructure is necessary to anticipate future needs, identify information gaps (e.g., projected climate conditions, coastal erosion rates), coordinate agency collaboration, deliver projects that meet budget and calendar targets, and engage stakeholders and residents in the decision-making process. Improvements in digital infrastructure will require investments in communications infrastructure, such as high-speed broadband; internet-connected devices; and other technologies that are available to and cost-effective for urban and rural communities. These improvements then, for example, can increase climate-resilience of asset operations (e.g., leakage control in distribution systems via smart connected water meters, smart grids for recovery after extreme events, smart irrigation in agriculture) and interface with the public and customers by communicating consumption behaviors, responding to emergencies, and engaging residents in infrastructure projects.

Multiple smart technologies and data-driven analytics and visualization tools have been developed (or are being developed) by communities, researchers, and governmental organizations in Oregon. These technologies and tools can be useful digital resources for managing threats from climate change and other natural hazards. For example, WaterWorks (www.portlandoregon.gov/water/waterworks/?ref=home-sidebar), an interactive online tool developed by Portland Water Bureau, allows customers to obtain real time updates on water infrastructure repairs in their neighborhood. Portland Urban Data Lake (www.portlandoregon.gov/transportation/article/681572), a pilot program led by multiple organizations in Portland, acquires, integrates, stores, and analyzes data from multiple sources to advance Portland's Smart Cities initiative. Similar efforts developed by researchers include the O-HELP portal (http://ohelp.oregonstate.edu/), which provides data on vulnerability of lifeline infrastructure to earthquakes, landslides, and tsunamis; Envision, (http://envision.bioe.orst.edu/) an integrated modeling platform for simulating landscape change processes; and the InterACTWEL Portal (https://interactwel.org/), which supports coordination of community-wide and long-term adaptation planning of agriculture, water, and energy resources and infrastructure vulnerable to climate change. Oregon's state agencies have developed multiple web platforms for data sharing and visualization, including the following.

- Oregon Water Resources Department's mapping tools—Water Right (https://apps.wrd.state.or.us/apps/gis/wr/Default.aspx), Peak Discharge Estimation (https://apps.wrd.state.or.us/apps/sw/peak_discharge_map/), Groundwater Use Recording (https://apps.wrd.state.or.us/apps/gw/exempt_use_map/), Groundwater Information System (https://apps.wrd.state.or.us/apps/gw/gw_info/gw_map/Default.aspx)
- Oregon Department of Geology and Mineral Industries' mapping tools—HazVu (https://www.oregongeology.org/hazvu/index.htm)
- Oregon Office of Emergency Operations' emergency response systems—RAPTOR (https://www.oregon.gov/oem/emops/Pages/RAPTOR.aspx).
- Oregon Department of Transportation's mapping tool TransGIS (https://gis.odot.state.or.us/transgis/) and TripCheck (https://www.tripcheck.com/) for real-time road conditions.

Equitable participation in data-driven management of climate risks by urban and rural communities across the state will require investment in state-wide data infrastructure. The latter will facilitate integration of diverse digital products and improvement in economies of scale for infrastructure projects. Backing such infrastructure investments with governance frameworks for digital infrastructure will allow for integration of legal, privacy, and cybersecurity considerations in the design of tools, platforms, and services.

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Public Health

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Ecosystems and other aspects of the environment are affected by human actions, and in turn affect human health and well-being. Climate change thereby affects people's access to clean air and water, livable temperatures, and fertile land for food production. Actions that mitigate climate change can lead to many additional benefits for human health and well-being, such as cleaner air, safer and more-secure social and economic infrastructure, and the potential for less pollution.

This chapter summarizes the current state of knowledge of how climate change is affecting public health in Oregon, and will continue to do so in the future. Public health is affected directly through exposure to climate extremes or hazards, such as heat, wildfire, or storms; indirectly through changes to natural systems, such as via water pollution; or both, through damage to infrastructure. This chapter also addresses complex stressors and inequities in social, cultural, and economic systems that can mitigate or exacerbate the health impacts of climate change (Fig. 1). Further analysis and discussion is in York et al. (2020).

Climate-related drivers of health: environmental hazards	Stress factors: inequities in social, physical environment, cultural, and economic supports
Heat	Systemic inequities in policies
Infectious disease vectors	
Wildfire	Inequities and unequal investment in social determinants of health (e.g., housing, education, income, wealth, transportation access, food security, income security, access to health care)
Air quality (e.g., pollen, wildfire smoke, smog, ozone)	
Storms, floods, landslides	
Sea level rise	Capacity and adaptive capacity of infrastructure, institutions, and systems to support human health (e.g., culturally specific services, surge capacity of hospitals)
Drought, water insecurity	

Effects on human health
Hazard-related acute conditions (e.g., heat stroke, asthma attack)
Hazard-related chronic conditions (e.g., heart disease, diabetes, respiratory illness)
Infectious diseases (e.g., Lyme disease)
Mental health conditions
Adverse pregnancy outcomes

Figure 1. Drivers and effects of climate change on health outcomes.

Oregonians already are experiencing climate hazards that affect health and the social, physical, cultural, and economic infrastructure that supports health. In 2020, the area burned in Oregon, more than 1.2 million acres (486,000 ha), was among the greatest on record (ODF 2020a). The fires destroyed individual homes and institutional buildings that support daily life in many areas, including the towns of Phoenix and Talent. Wildfire smoke is a respiratory irritant, and smoky days can lead to increases in hospital admissions for people with asthma, while making people more susceptible to respiratory viruses (Borchers et al. 2019, Gan et al. 2020, Henderson 2020). This issue intersects with the global COVID-19 pandemic that caused 1433 deaths in Oregon (OHA 2020; govstatus.egov.com/OR-OHA-COVID-19) and more than 234,000 deaths nationwide (covid.cdc.gov/covid-data-tracker/#cases_casesper100klast7days) as of 28 December 2020. Social, physical environment, cultural, and economic systems are sources of both supports and stressors in relation to environmental hazards of climate change. For example, if the hospital system is stretched beyond capacity, what normally functions as a support in access to healthcare becomes a stressor for those who cannot be treated. Similarly, loss to wildfire of infrastructure such as housing or community buildings reduces support for affected communities, adding stress to the trauma of wildfire-related loss. The wildfires and pandemic also revealed substantial pre-existing inequities in access to social, physical environmental, cultural, and economic system supports.

Pre-existing inequities are a critical factor of climate change and associated health effects. For example, Oregon has disparities in COVID-19 morbidity and mortality, with some Black and Brown communities disproportionately affected (OHA 2020; public.tableau.com/profile/oregon.health.authority.covid.19#!/vizhome/OregonCOVID-19CaseDemographicsandDiseaseSeverityStatewide/DemographicData). An ongoing history of disinvestment has led to lower rates of home ownership and less accumulated wealth in frontline communities, which include those experiencing economic disadvantage; Black, Brown, and Indigenous communities; and people who depend on natural resources for their livelihoods. These kinds of inequities influence a community's ability to recover from climate-change related events, such as floods, or other significant events, such as the economic losses of a pandemic (May et al. 2018, OHA 2018a, Rudolph et al. 2018, Amadeo 2019, Sifuentes et al. 2020). The communities that are experiencing disproportionate health and economic effects of the pandemic are those that also are likely to be most affected by climate-related exposures.

Racially marginalized Black (including African Americans and recent migrants from various African, South American, and island countries), Brown (including Latinx from Central and South American countries and Spain, Pacific Islanders, and Asian Americans from countries in the Middle East and Asia); and Indigenous (including Native Americans from federally recognized tribal nations, those affiliated with tribes not yet federally recognized, and recent migrants from other continents) communities, including refugees and immigrants, people experiencing low incomes or poverty, underinvested rural communities, young and old populations, pregnant people, individuals with pre-existing conditions, and people with disabilities, are more likely to be exposed to climate extremes and associated health impacts (Rudolph et al. 2018). Low-income and racially marginalized populations already experience health inequities related to inadequate physical, social, economic, and service environments (Rudolph et al. 2018). Because climate change disproportionately affects those who historically have lived in communities with little public and private investment, climate change mitigation or adaptation strategies designed and implemented in partnership with these communities can help to prevent exacerbation of existing inequities, and in some cases even improve health and social equity. The Portland Clean Energy Community Benefits Fund is an example of climate policy that explicitly focuses on racial and social justice components of climate change. The fund was created under local ballot measure #26-201, is led by communities of color, and is expected to contribute $44-61 million in annual revenue to address climate change (PCEF 2020; www.portland.gov/bps/cleanenergy). A mix of community-specific approaches and state-wide planning and policy efforts can help to address the distinct climate, community, and health circumstances of the communities most at risk of climate-related and other health impacts in Oregon.

Environmental Hazards

Heat

Mean average temperature in Oregon increased from 1895 through 2019, and 2015 was the warmest year on record (Mote et al. 2019; *State of Climate Science*, this volume). Mean average temperature and the number of hot days in Oregon is projected to increase throughout the twenty-first century (Dalton et al. 2017, Mote et al. 2019; *State of Climate Science* and *Extreme Heat*, this volume).

Extreme heat can have direct physiological effects on health, such as heat rash, heat cramps, heat exhaustion, fainting, and heat stroke. In urban areas, people experiencing economic hardship and Black, Brown, and Indigenous communities are more likely to live in urban heat islands, areas with fewer trees, more buildings, higher energy use, and more heat-absorbing asphalt. Maximum daytime temperature in urban heat islands can be as much as 13°F (7°C) warmer than surrounding areas (Jesdale et al. 2013, Hoffman et al. 2020). People who are socially isolated, those with physical or cognitive impairments, people with chronic illnesses, the very young and those of older ages, people working outdoors (e.g., farmworkers, construction laborers), those with less access to health care or transportation services, and people without air conditioning are at greater risk of extreme heat (Nerbass et al. 2017, Rudolph et al. 2018). Heat also contributes to adverse birth outcomes, including preterm birth and low birth weight (Bekkar et al. 2020). People with asthma; Black, Brown, and Indigenous people; and pregnant individuals are the most negatively impacted in relation to birth outcomes (Bekkar et al. 2020). Additionally, heat events can have negative effects on mental health (Thompson et al. 2018) and can increase rates of violent crimes (Jacob et al. 2007, Ranson 2014).

Many people living in Oregon, especially those experiencing economic hardship, whether low income or at poverty levels, do not have air conditioning. From 1986 through 1993, Black households in four major cities had 5.3% higher heat-related mortality than White households, and half the access to central air conditioning (O'Neill et al. 2005). In 2016 and 2017, 68% of single-family homes and manufactured homes in Oregon had cooling systems, whereas about a quarter of multi-family residences had cooling systems (NEEA 2019; *Extreme Heat*, this volume). Manufactured homes are one of the most common sources of unsubsidized, low-income housing, particularly in rural areas, and among older adults in those areas (MacTavish et al. 2006). Communities of color that are experiencing economic hardship are more likely to live in multi-family housing, especially in suburban and urban areas (Rose 2016). Oregon has some capacity to provide shelter from heat to community members through libraries, schools, and other public venues, but the number and geographical distribution of cooling centers is limited. Heat-related deaths and illness are preventable, yet many Oregonians are not familiar with the risks or how they can protect themselves.

Engaging various communities and occupational settings in Oregon on prevention and response activities can help develop resilience to heat exposures. The National Weather Service coordinates with state (Office of Emergency Management, Oregon Health Authority), county, and city agencies to broadcast heat-risk alerts that include meteorological data and health warnings (www.wrh.noaa.gov/wrh/heatrisk/). The manner in which public health agencies and organizational partners communicate risks to the public varies among jurisdictions. Every region and Tribal nation in Oregon has an emergency preparedness manager and coordinator who contributes to this process. Informational graphics that are color-coded and distributed in multiple languages are part of good public health practice (Rudolph et al 2018). Making more air-conditioned spaces available, advertising the availability of cooling centers, sharing the signs of heat illness, and providing information on how to cool down safely also contributes to preparation. Heat can arrive rapidly, and if communities are unprepared, opportunities to prevent illness and death will be missed. Partnerships among agencies, culturally specific organizations, and organizations that already serve vulnerable populations, such as schools, child care providers, nursing homes, and service providers to seniors, can ensure protocols are established to reach those who are isolated socially or by language, or have limited access to technology (Rudolph et al. 2018). *Built Environment* (this volume) discusses tree canopy and passive survivability as strategies to increase resilience to extreme heat.

Infectious Disease

Rising temperatures, changing precipitation patterns (Hines et al. 2017, CDC n.d.), and extreme weather and climate events are expected to change the geographic and seasonal distributions of some vectors and vector-borne diseases. Drier conditions will increase the risk of human exposure to pathogens such as *Borrelia burgdorferi*, the bacterium that causes Lyme disease, and West Nile Virus (OPHD 2008). The fungus that causes Valley Fever, *Coccidioides* spp., recently was detected in south-central Washington and central Oregon, and may expand if aridity increases. Warming coastal waters can lead to increases in density of *Vibrio* species, which can cause cholera, infections, and gastroenteritis (Froelich and Daines 2020). Losses of species and land development also can be linked to changing patterns of infectious diseases as humans come in contact with more vectors of infectious diseases (Gottdenker et al. 2014, Aguirre 2017).

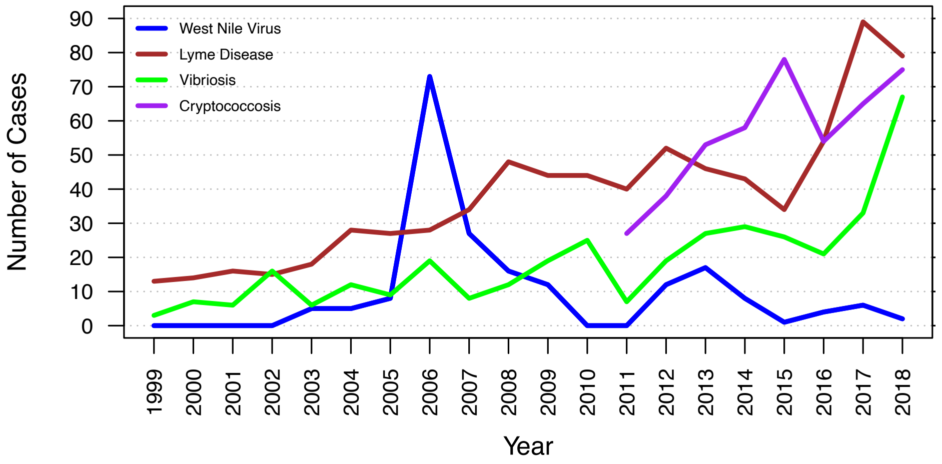

Figure 2. Occurrences of infectious climate-related diseases in Oregon from 1999 through 2018. Figure source: M. Dalton; data source: Oregon Heath Authority, public.tableau.com/profile/oregon.public.health.division.acute.and.communicable.disease.pre#!/vizhome/2018SelectedReportableCommunicableDiseaseSummary/TableofContents.

Previous Oregon Climate Assessments summarized how climate change is expected to affect vector-borne and water-borne diseases such as West Nile Virus, Lyme disease, vibriosis, and the fungal disease cryptococcosis, which often is caused by *Cryptococcus gattii* (e.g., Dalton et al. 2017; also see Skaff et al. 2020) (Fig. 2).

Wildfire Smoke

The number of large wildfires has been increasing in Oregon. Prior to 2020, the largest fire on record was the 350,000 acre (141,640 ha) Tillamook fire of 1933 (ODF 2020b). Warmer and drier conditions that accompany climate change likely contributed to the wildfires of 2020 (e.g., Abatzoglou and Williams 2016; *Wildfire*, this volume), which resulted in nine confirmed fatalities, nine people missing, and the destruction of more than 4000 residences and 1400 other structures (OEM 2020a, b). The mental health effects associated with these wildfires will be substantial, and the social fabric of many communities has been strained.

Nearly all of Oregon can be exposed to wildfire smoke. The risk varies widely as a function of local topography, weather, and fuels. Across Oregon, wildfire smoke is increasing the number of days per year of unhealthy air, defined as an air quality index that is considered unhealthy for sensitivity groups (Barnack 2020). The risk of exposure is expected to increase across the state as the frequency, size, and intensity of wildfires increases. In 2020, for example, almost all Oregonians were impacted by smoke. The air quality index across Oregon reached levels higher than those in any other major city worldwide (IQAir 2020). The index in Portland was considered hazardous for three consecutive days, and unhealthy for seven consecutive days (IQAir 2020) (Fig. 3).

The effects of exposure to this level of smoke on health of Oregonians have yet to be determined. In Washington State, each week of exposure to fine particulate matter under 2.5 micrometers ($PM_{2.5}$) concentrations that occurred during wildfires in summer 2020 was estimated to cause 88 deaths, 20 deaths from cardiovascular disease, and 9 deaths from respiratory disease (Liu et al. 2020). An estimated 16 excess daily pediatric respiratory visits to one emergency department and associated clinics occurred during the December 2017 Lilac Fire in San Diego County, California, and children ages 5 and under had the highest absolute excess visits (Leibel et al. 2020).

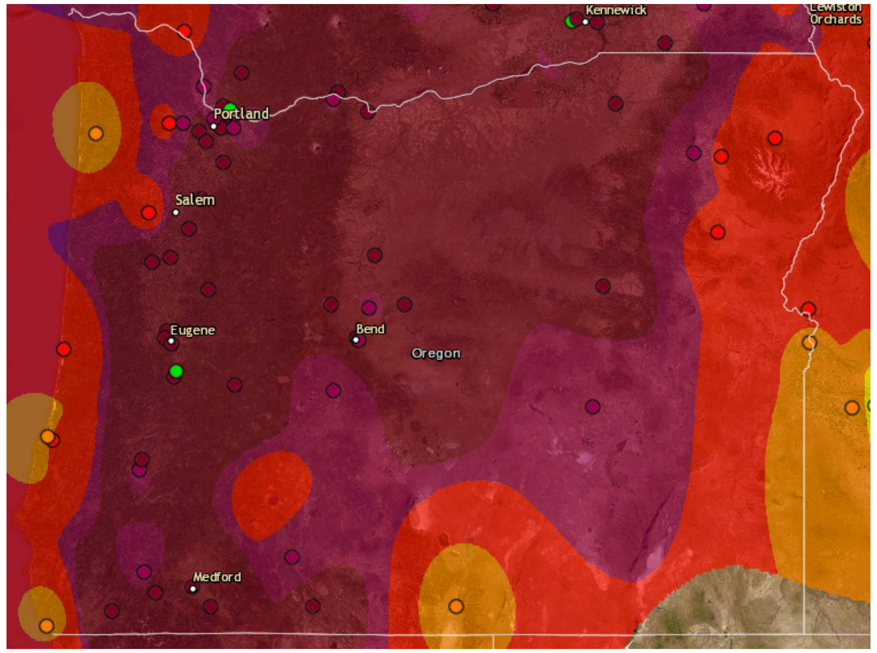

Figure 3. The air quality index (ozone, $PM_{2.5}$, and PM_{10}) on 12 September 2020 as indicated by the U.S. Environmental Protection Agency's AirNOW (airnow.gov). Maroon, hazardous; purple, very unhealthy; red, unhealthy; orange, unhealthy for sensitivity groups; yellow, moderate; green, good

Wildfire smoke contains a complex mix of pollutants with known health effects. $PM_{2.5}$ is of greatest concern; these small particles can be inhaled deep into the lungs, where they penetrate into the blood vessels and cause systemic inflammation (Xing et al. 2016, Fiordelisi et al. 2017, Hamanka and Mutlu 2018). $PM_{2.5}$ drives the air quality index for wildfire smoke, although other pollutants of health concern, such as black carbon, volatile organic compounds, and polycyclic aromatic hydrocarbons, are released when vegetation burns (Ward and Hardy 1991, Reid et al. 2016).

Although evidence of cardiovascular effects of exposure to wildfire smoke is inconsistent (Reid et al. 2016), the short-term respiratory impacts of exposure to wildfire smoke are well-documented. There is consistent and strong evidence of associations between short-term wildfire smoke exposure and respiratory health, such as exacerbation of asthma and chronic obstructive pulmonary disease (Reid et al. 2016). There is strong evidence of respiratory effects, including effects on children, of ambient $PM_{2.5}$ exposures not only from wildfires (Leibel et al. 2020) but from all sources (Brook et al. 2010). For example, in British Columbia, Canada, ambulance dispatches for respiratory and cardiovascular causes increased one hour after communities were exposed to wildfire smoke (Yao et al. 2020). In Portland, Oregon, similar acute responses to wildfire smoke exposure were observed during the 2017 wildfire season; emergency department visits for asthma-like symptoms spiked coincident with an increase in wildfire smoke concentrations (Fig. 4). This impact of poor air quality on health is associated with substantial healthcare and other costs. In 2018, there were 1163 asthma-related hospitalizations in Oregon, with an estimated cost of $9.2 million (OHA 2019b).

The effects of exposure to wildfire smoke over years to decades on the development and progression of disease are not well understood. Wildfire smoke can have more oxidative and proinflammatory components than air pollution from combustion of fossil fuels (Xu et al. 2020). Long-term exposure to ambient $PM_{2.5}$ from all sources has been linked to respiratory and cardiovascular disease and premature mortality (Brook et al. 2010, Arden Pope III et al. 2020). Few

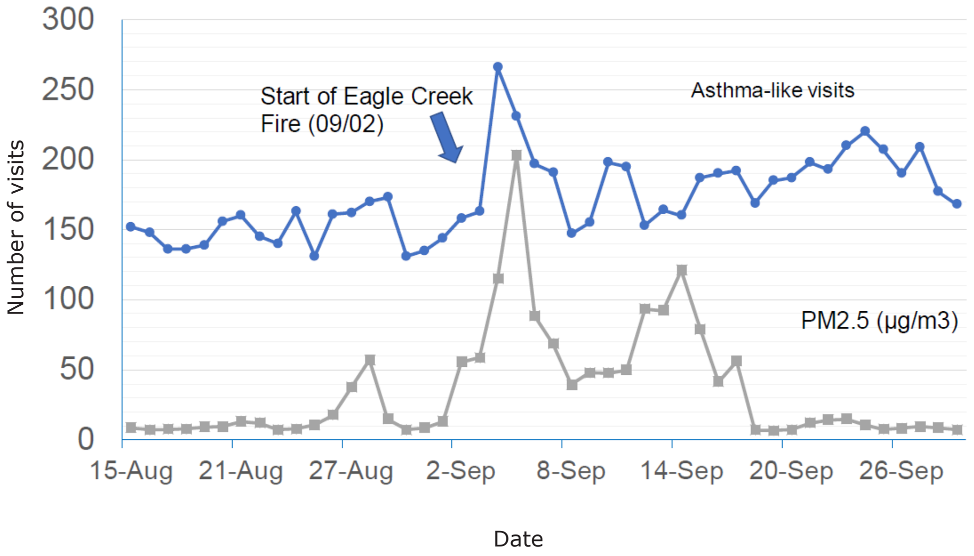

Figure 4. Emergency department visits for asthma-like symptoms and $PM_{2.5}$ maximum daily concentrations in affected Oregon counties (Multnomah, Washington, Clackamas, Yamhill, Wasco, Hood River, and Columbia) before and during the Eagle Creek Fire, 2017 (OHA 2019a).

studies have been able to isolate the impact of wildfire smoke from those of other sources of air pollution, and until recently wildfire smoke was treated as a short-term exposure source with only acute impacts on health. However, wildfire smoke now appears to contribute substantially to long-term exposure levels (McClure et al. 2018). A study in Seeley Lake, Montana examined how a two-week period of high exposure to wildfire smoke (daily average $PM_{2.5}$ greater than 220 ug/m^3) affected lung function of community members (Orr et al. 2020). Two years after the fire, lung function measures were significantly lower than predicted, suggesting that even short-term smoke exposures may have long-lasting effects on respiratory health. Ten years after the 1997 Indonesian forest fires, people exposed to wildfire smoke had lower lung capacity, self-reported general health, and physical functioning than those not exposed (Kim et al. 2017). Ongoing research may indicate how short-term exposures to extremely high levels of wildfire smoke affect future health outcomes.

People experience the impacts of wildfire smoke differently (Liu et al. 2017, Hutchinson et al. 2018). The health effects of climate change are strongly affected by the baseline status of individuals and communities, especially people's living conditions and pre-existing health conditions. These factors differ significantly by race, historical levels of economic investment, and level of pollution exposure. Among the individuals most susceptible are those with existing chronic conditions, older adults, pregnant women, and children (Liu et al. 2017, Hutchinson et al. 2018). People of color, people with low incomes, unhoused populations, agricultural workers, first responders, and rescue workers are those most susceptible to wildfire smoke exposure (Rudolph et al. 2018). Asthma hospitalizations in Oregon disproportionately affect Black, Pacific Islander, and Indigenous people as compared to other racial or ethnic groups (OHA 2018a). Exposure to smoke compounds this existing disparity.

There are few if any community shelters from poor air quality in most of Oregon. To reduce exposure to wildfire smoke, households rely on the integrity of buildings' heating, venting, and cooling (HVAC) air filters, such as high efficiency particulate air (HEPA) filters; portable air filters; or do-it-yourself air filtration systems (Rudolph et al. 2018; *Built Environment*, this volume). Low-income families may not be able to afford an adequate filtration system, and the number of people in Oregon who have no protection is unknown.

Statewide coordination to identify and address susceptible population during periods of poor air quality, including those from wildfire smoke, can reduce exposure to air pollution in communities most at risk. For example, the Oregon Health Authority has distributed KN95 masks to outdoor agricultural workers during periods with extremely unhealthy air quality.

Other Air Quality Issues

Ozone

Ozone is a highly reactive oxidative gas. Projected increases in ground-level ozone in the Northwest are relatively small compared to those in other parts of the United States (Dalton et al. 2013, 2017). However, if future increases in temperature cause ozone to increase to hazardous levels around the Portland metropolitan area, negative human health outcomes would be expected. Ozone is affected strongly by temperature and other aspects of climate (Jacob and Winner 2009). Near-surface ozone is a secondary pollutant formed when sunlight interacts with precursor compounds, such as nitrogen oxides, and the rate of formation is temperature-dependent (Jacob and Winner 2009). Future warming is expected to lead to increased ozone concentrations; the ozone season also will be extended, and ozone formation accelerated (Jacob and Winner 2009). Wildfires may produce ozone and lead to local exceedances of ozone air quality standards (Jaffe and Wigder 2012).

Exposure to high concentrations of ozone is associated with both acute and chronic health effects. The strongest links between acute ozone exposure and health are for respiratory disease (Chen et al. 2007). However, a meta-analysis of 196 articles found that short term (hours to days) increases in ozone concentrations were associated with increases in all-cause mortality (Orellano et al. 2020). The elderly are particularly sensitive to the short-term impacts of ozone exposure (Bell et al. 2014). Long-term ozone exposure also is a concern with respect to the development of disease. For example, the risk of death from respiratory causes may increase by 3% for each 10 ppb increase in ozone concentrations (Jerrett et al. 2009).

Pollen

Pollen also is projected to increase as climate changes and growing seasons lengthen (Ziska et al. 2011, Zhang et al. 2014). Oregon has only one pollen monitoring station that reports regularly to the public, and it is privately managed (Oregon Allergy Associates, n.d.). A greater number of stations across the state would facilitate better characterization of pollen counts and types, enabling government health agencies to issue public alerts and recommendations and enabling health care providers to better treat and inform patients whose asthma and allergies are exacerbated by pollen.

Allergic diseases have been increasing over the last decades, which may continue due in part to climate change. Climate change indirectly affects allergies by altering pollen concentrations, allergenic potential, composition, and species migration. Longer and more intense exposure to pollen can increase sensitization rates, and increased allergenicity of pollen may cause more severe health effects in allergic individuals (Damialis et al. 2019). The severity of allergic reactions also can increase when sensitive individuals are exposed simultaneously to pollen, $PM_{2.5}$, and ozone (Bédard et al. 2019), and the concentrations of all are projected to increase in the coming decades.

Storms, Floods, and Landslides

Storms, floods, and landslides can increase the risk of serious injuries and damage homes and community infrastructure, leading to long-term effects on health and quality of life. Flooding in Oregon often results from heavy precipitation driven by atmospheric rivers (*State of Climate Science* and *Floods*, this volume). Direct impacts of storms and flooding may include loss of life due to drowning, electrocution, or trauma from debris. In response to housing damage from storms and floods, people may use charcoal stoves, gas generators, or gas-powered cleaning equipment indoors, creating dangerously high concentrations of carbon monoxide. Storms and floods also can increase exposure to mold. Furthermore, storms often disrupt access to electricity, which can threaten the lives of people who rely on electricity-powered medical devices. Lack of refrigeration can contribute to food spoilage and loss of temperature-controlled medications, such as insulin.

Storms and flooding also affect the built environment (*Built Environment*, this volume). Transportation infrastructure, such as roads, bridges and public transit, may be inaccessible due to debris or other storm damage. Drinking water can become contaminated by storms and floods, and extreme rainfall can increase the incidence of water-borne diseases.

Additionally, flooding can contaminate waterways and private wells with sewage and toxic substances. Contamination of coastal waters by runoff is expected to increase as atmospheric river-driven precipitation extremes increase (Aguilera et al. 2019) and as the length of dry periods during which toxins collect on the surface increases (Gershunov et al. 2019). People living in low-lying areas and coastal communities and those that rely on private wells are at greatest risk of flooding or infrastructure damage, whether from lack of investment or from extreme weather events. People experiencing economic hardship, including those who spend more than 30% of their income on housing, are less likely to recover quickly if their homes are damaged or destroyed. People with low incomes, poor mental health, disabilities, or chronic medical conditions are among those at greatest risk of increased health inequities during and in the aftermath of flooding.

Heavy precipitation combined with saturated soils increases the risk of landslides. Coastal bluffs along the Pacific Ocean are prone to landslides after powerful storms, especially when precipitation is intense. Areas within a wildfire burn scar are particularly susceptible to landslides due to loss of vegetation and physical changes in the soil. As wildfires increase in frequency and intensity, Oregon may become more susceptible to runoff-initiated debris flows (Wall et al. 2020). Landslides can damage, block, or disrupt transportation infrastructure, drinking water, and sewer services, and reduce access to critical resources such as health care.

Flooding also can lead to outbreaks of infectious diseases, such as typhoid fever, cholera, leptospirosis, and hepatitis A. Pooled water can support breeding mosquitos, and may lead to increases in the incidence of West Nile virus (Rudolph et al. 2018). In coastal areas and inland lakes and rivers, high concentrations of cyanobacteria (*Marine and Coastal Change*, this volume) can be absorbed through skin, swallowing, inhalation, or consumption of shellfish harvested from affected areas (Berdalet et al. 2016). The toxins can lead to nausea, skin or heart conditions, liver damage, respiratory distress, headache, neurological complications, and even death (Berdalet et al. 2016). Monitoring biotoxins in seafood is an effective way to protect human health and prevent contaminated shellfish from reaching the market (Berdalet et al. 2016). Cyanobacteria also can be present in drinking and irrigation water. When producers use contaminated water for irrigation, farm workers can be at risk of inhalation and direct contact, and the contaminants can remain on crops (Brooks et al. 2016). Coastal communities that rely on shellfish for food and use waterways for fishing or other food gathering are at greatest risk of health complications from cyanobacteria.

Drought and Water Insecurity

People experience water insecurity when they do not have access to sufficient quantities of safe and affordable water for drinking, cooking, sanitation, and hygiene. Water insecurity results in poor health, especially among frontline populations. Preventable health outcomes of water insecurity include water-borne illnesses, exposure to contaminants, dehydration, malnutrition, the spread of communicable diseases, respiratory and skin infections, and indirect outcomes such as emotional distress, depression, and anxiety (Rudolph 2018). Drought contributes to food insecurity and to lower crop yields and increases in concentration of industrial and groundwater contaminants (Rudolph et al. 2018). Moreover, drought can impact social and economic stability, increase the risk of infectious diseases, and diminish mental health (Vins et al. 2015, Rudolph et al. 2018).

People face water insecurity in areas that are prone to drought, such as those in southern and eastern Oregon, and areas prone to flooding; both drought and flooding are likely to increase as climate changes (Gershunov et al. 2019). Communities with a history of public and private underinvestment or disinvestment may confront deteriorating drinking water infrastructure and limited resources to fund improvement. For example, the Confederated Tribes of Warm Springs is challenged with water insecurity from underinvestment, deferred repairs, and damaged infrastructure that is exacerbated by climate change. Coastal communities are vulnerable to sea level rise or saltwater intrusion. Water insecurity also impacts tenants or low-income owners of residences with plumbing in poor condition. People in populations experiencing economic hardship may be reliant on markets for relatively safe, but relatively expensive, bottled water. Characterization of communities experiencing water insecurity, assessment of community needs, private and public sector collaboration, and tracking of regional water scarcity might inform policies to protect and support community needs related to water.

Climate Stressors: Inequities in Supports

The supportive conditions where people live, work, learn, and play influence a wide range of health risks, vulnerabilities, opportunities, and protective factors. These conditions that affect people's health, called health determinants, are unevenly distributed in Oregon. According to the World Health Organization (2008), "the social determinants of health are mostly responsible for health inequities—the unfair and avoidable differences in health status seen within and between countries." The uneven distribution of social, environmental and economic health determinants can be prevented through tailored approaches to address distinct community needs for better health outcomes (WHO 2008, CDC 2013).

Health equity means that everyone has a fair and just opportunity to be as healthy as possible (WHO 2008, CDC 2013). Health inequities exist when these differences in health outcomes can be prevented by access to opportunities and prevention of risks (Table 1) (WHO 2008, CDC 2013). For example, systematic racism in government policies prevented most Black people from living in Oregon until the mid 1900s. They were denied access to business and home loans with favorable terms through redlining practices, kept out of specific neighborhoods through restrictive covenants only removed in the 1980s, and displaced through urban renewal practices in Oregon's largest cities (Smith 2018, Milner 2020, Nokes 2020). Black veterans also did not consistently receive the educational, home ownership, or related promised benefits of the GI Bill that White veterans received after World War II (Turner and Bound 2003, Humes 2006, Katznelson 2006). This inequitable reduction in opportunity for gaining and retaining wealth—effectively enforcing vulnerability—is reflected in current proportions of home ownership by Black families and median incomes (McIntosh et al. 2020). When segregation is combined with a history of government and private sector disinvestment in neighborhoods where Black communities live, it can result in inequitable risks or burdens that contribute to health outcomes. For example, the history of

Climate effects	Health risks	Priority populations	Example action
Storms, floods, landslides and sea-level rise	Injuries	People dependent on medical equipment that requires electricity	The Oregon Health Authority (OHA) partnered with the Oregon Department of Transportation (ODOT) to conduct a case study on creation of climate resilience on Oregon's North Coast (www.oregon.gov/ODOT/Programs/TDD Documents/Case-Study-Tillamook.pdf). The project interviewed state and local transportation and health leaders and documented lessons learned.
	Toxic exposures	Socially isolated people	
	Displacement	Older adults	
	Disruptions in medical care	Coastal communities	
	Mental health effects	Children	
		Pregnant individuals	
Wildfire	Respiratory diseases	People with pre-existing conditions	The 2019 OHA report *More days with haze: how Oregon is adapting to the public health risks of increasing wildfires* (www.oregon.gov/oha/PH/HEALTHYENVIRONMENTS/CLIMATECHANGE/Documents/2020/oha2688_0.2.pdf%22 %5Ct %22_blank) identified ways in which the public health system is adapting to increasingly severe wildfires and opportunities for climate adaptation.
	Cardiovascular diseases	Outdoor workers	
	Cancer	Children	
	Injuries	Pregnant individuals	
	Displacement	Older adults	
	Toxic exposures	Rural communities	
	Mental health effects	Tribal communities	
Infectious disease	Lyme disease	Outdoor workers	In 2016, OHA developed a guidance document for use of weather and environmental data with syndromic surveillance data (www.youtube.com/watch?v= BvTVSNZ2LuI&list=PLd4xfJU3qzMWQlcfWZDGEj1rMncXTUeWV&index=6) for rapid assessment of the correlation between weather factors or air quality measures and health outcomes, including infectious disease.
	West Nile disease	Outdoor recreationalists	
	Fungal diseases	People experiencing homelessness	
	Shigellosis	Tribal communities	
		Rural communities	
Drought and water quality hazards	Mental health effects	Low-income communities	In 2017, OHA partnered with members of the Confederated Tribes of Warm Springs on a digital storytelling project (www.oregon.gov/oha/PH/HEALTHYENVIRONMENTS/CLIMATECHANGE/Pages/perspectives.aspx) that documented climate-driven changes in water quality in rivers and water shortages on the reservation. OHA also has assessed water insecurity in Oregon (Schimpf and Cude 2020).
	Dehydration	Tribal communities	
	Toxic exposures	Rural communities	
	Diminished living conditions	Farming and farmworker communities	
		Coastal communities	
Extreme heat	Heat-related illness & death	People with pre-existing conditions	OHA contributed to the State of Oregon's 2020 Natural Hazard Mitigation Plan (www.oregon.gov/lcd/NH/Pages/Mitigation-Planning.aspx). For the first time, the plan includes a chapter on extreme heat. Inclusion makes the state eligible for Federal Emergency Management Agency funding for mitigation actions that reduce identified risks.
	Violence	Outdoor workers	
		Outdoor athletes	
		People without air conditioning or housing	
		Residents of urban heat islands	
		Children	
		Pregnant individuals	
		Low-income communities	
		Communities of color	
Air quality and allergens	Ozone and smog	Low-income communities	In 2018, at the request of the governor's Carbon Policy Office, OHA prepared a policy paper on climate change and public health (www.oregon.gov/oha/PH/HEALTHYENVIRONMENTS/CLIMATECHANGE/Documents/2018/2018-OHA-Climate-and-Health-Policy-Paper.pdf) that identifies communities most affected by health risks of climate hazards and pollutants from greenhouse gas emissions.
	Airborne pollen	Communities of color	
	Airborne molds	Communities near highways and industrial facilities	
		Outdoor workers	
		People with pre-existing conditions	
		Farmworker communities	

Table 1. Climate effects, health risks, priority populations, and example actions by the Oregon Health Authority. Source: York et al. 2020.

redlining resulted in communities that are measurably hotter than those that were not redlined (Hoffman et al. 2020). Parallel barriers exist within Native American; Latinx; Asian American; Pacific Islander; immigrant; refugee; lesbian, gay, bisexual, transgender, queer or gender non-conforming, and two-spirit (LGBTQ2S+); people with disabilities; and some rural communities, the details of which are beyond the scope of this report.

Climate vulnerability is closely connected to existing health inequities. Although no one is immune to climate change, the health risks associated with climate change disproportionately affect some people, communities, and regions. In this way, climate change exacerbates, and can compound, Oregon's existing health inequities. Over time, the accumulation of multiple, complex stressors among some populations is expected to become more evident as the effects of climate change interact with other social, economic, and demographic factors (Crimmins et al. 2016). Consistent with a national assessment and other analysis in the northwestern United States, Oregon-specific assessments point to social determinants as the primary driver of climate vulnerability (Crimmins et al. 2016). Access to housing, transportation, education, livable-wage jobs, childcare, health care, safe and toxicant-free neighborhoods, and social supports are all determinants of health (OHA 2018b).

Many communities in Oregon already experience challenges with access to basic needs, have pre-existing health conditions, and live in areas that have a history of public disinvestment or failing infrastructure. For example, 24% of adults and 30% of youth in Oregon have a disability (OHA 2018a). Individuals with disabilities may face barriers in safely responding to and recovering from extreme weather events, relocating, and receiving care. One in two households in Oregon spend 30% or more of their income on rent or a mortgage (OHA 2018a). These households generally are less likely to rebuild in the event of home loss or severe damage from an extreme weather event. Black, Indigenous, and Pacific Islander communities are more than twice as likely to die from diabetes as non-Latinx White communities (OHA 2018a). Individuals who have existing health conditions can be dependent on costly medications, such as insulin, and are less likely to have savings that may be needed to adapt to climate change. People living in rural areas have higher rates of chronic conditions, such as heart disease and asthma, that can be exacerbated by fine particulate matter (e.g., smoke, pollen, dust) than people living in urban areas (OHA 2018a). Many risks and barriers intersect. For example, LGBTQ2S+ young adults, some of whom may be socially marginalized, are more than 120 times more likely to report homelessness than their heterosexual and cisgender peers, putting them at greater risk of climate-related heat illness, injuries, and displacement (Morton et al. 2017), and LGBTQ2S+ seniors are more likely to be socially isolated.

People, populations, locations, and occupations with certain attributes may be affected disproportionately by climate change and associated health inequities (Haggerty et al. 2014, OHA 2018a, Rudolph et al. 2018) (Table 2). The examples do not reflect changes in vulnerability status following extreme events or other changes in conditions. For example, people with opioid addictions may not fall neatly into any of these groups, yet a climate extreme might have a greater impact on people with opioid dependencies than people without such dependencies.

Supporting these communities requires approaches that take into account health disparities and inequities, distinct needs, and existing strengths. Approaches that consider the historical economic and government decisions that have contributed to modern health inequities are part of an emerging trend of trauma-informed approaches that may help prevent population level inequities from becoming worse (NASEM 2017, Kraemer Tebes et al. 2019, Chandanabhumma and Narasimhan 2020). The multi-generational trauma of genocide, the Indian Removal Act of 1830, and enforced

Social, physical or demographic attributes that may be marginalized by dominant society	**Residential attributes**	**Occupations**
Existing chronic physical or mental illness, including addictions such as opioids	Urban heat islands	Wildland firefighters
Cognitive or physical impairments	Wildland-urban interface	Outdoor workers
Disabilities	Agricultural and coastal areas	Farmworkers, growers, ranchers, and fishermen
Racially marginalized (e.g., Black, Brown, Indigenous)	Reliant on wells	First responders
Low income and poverty	Steep slopes	Health care workers
Unhoused	Rural areas	
Immigrants, refugees	Built environment green space, or lack thereof	
Linguistically or socially isolated communities	Lack of transportation access	
People ages 65 and older		
Pregnant people		
Infants and children		
Lesbian, gay, bisexual, transgender, queer or gender non-conforming, two-spirit		

Table 2. Example attributes of people, populations, locations, and occupations that may be affected disproportionately by climate change (Haggerty et al. 2014, OHA 2018a, Rudolph et al. 2018).

assimilation of Native American children with the intended destruction of cultural and social connections contributed to current social, economic, and health inequities faced by Indigenous communities, including higher rates of poverty, asthma, and diabetes (Yellow Horse Brave Heart et al. 2011, Nutton and Fast 2015, Warne et al. 2017). Acknowledging and addressing this history is part of ensuring that communities receive culturally relevant, trauma-sensitive services and supports when government agencies partner with Native American, frontline, and marginalized communities.

Climate change also may increase food safety risks, as temperature and precipitation are key drivers of pathogen introduction and foodborne disease. For example, the occurrence of some pathogens, such as *Salmonella*, *Escherichia coli*, *Vibrio parahaemolyticus*, and *Campylobacter*, is likely to increase as climate changes in Oregon (Bancroft and Byster 2017). In some cases, climate change may reduce access of Indigenous peoples in Oregon to foods they traditionally harvested and hunted (*Tribal Cultural Resources,* this volume), affecting physical, social, and spiritual health.

Adaptation and Coordination

Adaptation is the primary way that people respond to inherent uncertainties. Communities are most at risk when their capacity to anticipate, address, adapt to, and recover from natural disasters and other stressors is low because they have little access to, for example, technology, information, wealth, resilient social networks among groups with different backgrounds, connections between people and organizations with power and resources, and community structures (Adger 1999, Dolan and Walker 2003, Sifuentes et al. 2020).

The current uncertainties of climate change, a pandemic, and inequities suggest that a collective, collaborative adaptive effort to strengthen social supports and infrastructure may reduce vulnerability. For example, a 1995 heat wave in Chicago revealed the role that social relationships, addressing inequities, community infrastructure, and culturally specific outreach can play in saving lives (Klinenberg 2002). More than 700 people died during a week-long heat wave (Klinenberg 2002). Those who died disproportionately were those who lived alone, did not leave home daily, lacked access to transportation, were sick or bedridden, did not have social contacts nearby, did not have an air conditioner, were male, or were Black (Klinenberg 2002). Members of the Latinx community were less likely to die because they lived in neighborhoods where social support was strong, with high population density, busy commercial life in the streets, and vibrant public spaces (Klinenberg 2002). Most of the Black neighborhoods with a high number of deaths historically had low levels of economic investment: many employers, stores, and residents had relocated in prior decades, weakening the social networks that otherwise might have addressed the heat wave (Klinenberg 2002). Notably, had social cohesion been stronger between groups of different backgrounds, more people would have been helped. In 2019, the Oregon Climate and Health Program and the Oregon Community Health Workers Association held a series of listening sessions with different frontline communities on the topic of climate change and social resilience. The process identified themes and actions that governmental agencies can take to strengthen social relationships in communities to increase climate resilience (Sifuentes et al. 2020).

Social isolation is relevant to counties where communities are isolated by distance or by language. About one in five people in Washington County, Multnomah County, and Marion County speak a language other than English in the home (OLTF 2015). Oregon Health Authority data indicate that more than one in every ten people in 12 rural counties (Baker, Columbia, Coos, Crook, Douglas, Grant, Jefferson, Kalmath, Lake, Morrow, Umatilla, and Yamhill) have diabetes, which will require access to life-maintaining medication in the event of an emergency. In these counties, emergency response personnel will have greater ability to plan a targeted response if their planning process includes consultation with people who, for example, speak multiple languages; live in isolated locations; are marginalized based on gender or sexual identities; have low incomes, chronic illnesses or impairments, or a disability; or are over the age of 65.

Research on disaster recovery in other states in the United States indicates that renters and people with the lowest incomes face the most challenging recovery process after their belongings are destroyed (Ma and Smith 2020). For example, because they did not have homeowners' insurance, renters in New Orleans faced more housing instability and increased risk of displacement after Hurricane Katrina than homeowners (Fussell and Harris 2014). The Federal Emergency Management Agency's public assistance program is designed to provide the areas with the greatest losses with the most funding. However, decades of little or no investment can lead to less infrastructure loss and therefore less aid. As a result, communities that started with less before a wildfire, flood, or other major hazard will fare even worse in the rebuilding process (Domingue and Emrich 2019, Flores et al. 2020), effectively being made vulnerable (Sifuentes et al. 2020). Reducing isolation, poverty, stress, and poor mental health on an ongoing basis can reduce losses from any climate change hazard.

Because climate change can amplify existing health inequities in Oregon, adaptation strategies could reduce health risks for those who historically have lived in underinvested communities. Many adaptation strategies, such as investments in active transportation and sustainable community design, can result in considerable public health benefits, especially when those improvements occur in collaboration with historically underserved communities. A coordinated state-wide effort would help to ensure equitable adaptation to climate change. For example, it may be possible to use a realistic scenario to explore adaptation alternatives while identifying groups that might be affected and their compounded risks, such as having a chronic respiratory condition while experiencing poverty and a disability. Risk assessment will be most effective when state-wide efforts are combined with initiatives that are tailored to each community's distinct population, health challenges, existing environmental hazards from climate change, and social determinants of health.

Given that climate change-related risks vary across Oregon, local community organizations are best suited to prioritize local, hazard-specific interventions. State-level public health organizations then can provide technical assistance and decision-support tools that local partners can use to address those priorities. In 2016, local public health authorities addressed climate issues such as drought, wildfire, air quality, flooding, storms, and heat through locally developed interventions. For example, one local public health authority developed a new system for sharing water contamination results with local water resource planners, and another integrated new air quality information into a home visit program and Women, Infants, and Children program to increase climate change awareness and literacy among the public.

Given increasing variability and the emergence of new threats, public health systems will need to modernize in ways that increase organizational readiness and resilience. Oregon's public health system is not currently equipped to handle the complex and emerging environmental risks that climate change will exacerbate (Berk 2016). Only one of Oregon's 33 local public health authorities reported that they have full ability to identify and prevent environmental health hazards.

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Tribal Cultural Resources

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For millennia, Indigenous peoples in Oregon have managed lands, inland waters, and coastal areas through processes that include Traditional Ecological Knowledge (TEK), a term created by western science to label Indigenous groups' science practices, environmental management, cultural and belief systems, and enactment of policy as sovereign nations. Understanding the concept of TEK is requisite to recognize the comprehensive effects of climate change, including the distinct effects of climate change on Tribes, and to identify mitigation and adaptation actions over multiple generations that will ensure Tribal resilience to climate change. TEK differs widely among Tribes and ecosystems but some characteristics are shared: Indigenous knowledge holders are the primary resource of information; knowledge is transmitted from one generation to the next, usually over three or more generations and among multiple family units (Chisholm Hatfield et al. 2018); understandings are place- or species-based; knowledges are based on longstanding observations and experiences; and information accrues over multiple lifetimes (Stevenson 1996, Johannes et al. 2000). Because TEK is distinct to each Tribe and its local landscape and ecosystems, definitions of TEK vary, encompassing the breadth and depth of the concept and the diversity of its practice and cultural foundations. TEK includes but is not limited to environmental management practices; cultural understanding; long-term observation and documentation of environmental conditions, interactions, and effects (Kimmerer 2002, Huntington et al. 2004); and sustainability efforts by Tribes.

Climate change affects not only Tribal resources and capital but social, ceremonial, and spiritual relationships. Oregon Tribes (Fig. 1) are working to identify, prepare for, and mitigate climate change (May et al. 2018, Sowerwine 2019). Nevertheless, Tribes sometimes face institutional barriers to adaptation. This chapter describes TEK as a lens to understand the unique impacts of climate change on Tribes, and discusses historical and current factors that contribute to these impacts or facilitate opportunities for adaptation.

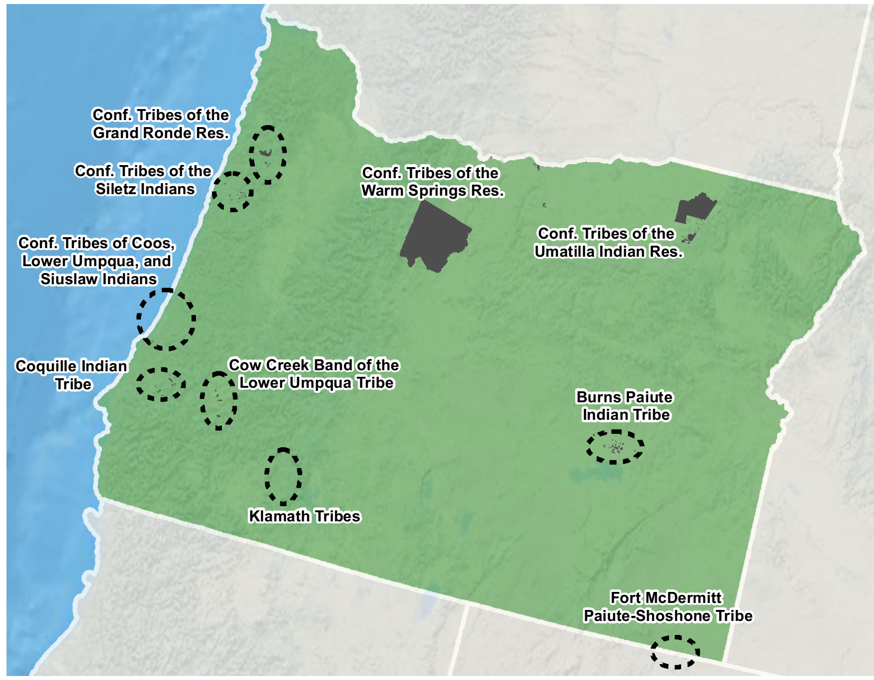

Figure 1. Tribes located in Oregon. Abbreviations: Conf., Confederated; Res., Reservation.

Traditional Ecological Knowledge

Recognition of the changing climate and subsequent identification of adaptation strategies is fostered and maintained through Indigenous or Traditional Knowledges—the collective knowledges of Indigenous peoples (Whyte 2013)—and especially through the direct application and utilization of TEK, which relates to the environment in a given traditional homeland or the Usual and Accustomed areas of Indigenous groups. TEK contains longstanding, direct observation and documentation of environmental conditions and events. This may include but is not limited to botanical knowledge; collection and administration of traditional medicinal species; hunting; fishing; gathering; processing of materials; caretaking, such as burning, coppicing, and thinning; astronomy; phenology and other ecological markers; and knowledge of weather and climate (Chisholm Hatfield et al. 2018, Hong et al. 2018). This process leads to interpretations and behavioral adaptations to environmental conditions over multiple generations.

For several decades, TEK has been used to inform conservation (Kimmerer 2011); to understand and manage species, ecological processes, and environmental sustainability (Reid et al. 2002, Lake 2007, Anderson 2013, Espinoza-Tenorio et al. 2013, Whyte 2017); for biological and ecological education (Kimmerer 2013); to conduct climate change vulnerability assessments and develop adaptation plans (TCAGWT 2018); and to document natural and cultural histories (Chisholm Hatfield et al. 2018). For example, in the early 1990s, hair loss in black-tailed deer (*Odocoileus hemionus*) was noted, but mechanisms were unknown. Tribal hunters suspected that the cause was an insect (Chisholm Hatfield et al. 2018), and shared their observation that deer at higher elevations were not losing hair, whereas the extent of hair loss among deer at lower elevations varied geographically. Only later did western scientists confirm that an invasive louse indeed was causing the hair loss (Bildfell 2004). Tribal applications of TEK also may include, at Tribal discretion, collaborative land management under state and federal guidelines. Tribes have data sovereignty and intellectual property rights, and therefore sacred TEK applications may not always be disclosed to non-Tribal individuals or representatives of government agencies. Longstanding Traditional Knowledges of landscapes, climate, and interactions among species allow Tribes to recognize ecological changes that may not be detected by western scientific methods (Chisholm Hatfield et al. 2018).

Changes in Phenology

TEK has proven useful in observing, documenting, and predicting ecological changes and changes in relations among species (Kimmerer 2002, Huntington et al. 2004). Cues from phenology (seasonal events in the life cycle of plants and animals, such as local arrival, departure, or migration) that affect Tribal use of natural resources have been illustrated clearly via TEK (Chisholm Hatfield et al. 2018). Tribes' responses to these seasonal patterns, such as seasonal migration by Tribes, have been documented since the late 1800s (Connolly et al. 2008, Dobkins 2017). TEK itself also is affected by substantial environmental changes. Changes in phenology may alter a Tribe's reliance on longstanding phenological cues. The resulting discrepancies with Tribal protocols, ceremonies, and harvesting times can lead to negative effects on culture and food sovereignty.

Policies and practices of non-Tribal institutions often assume that phenology is relatively consistent. However, as phenology changes, these policies and practices may create inequities, hamper Tribal rights to collect traditionally harvested species, and affect Tribal sovereignty (including food sovereignty) as outlined in treaties and alliances. For example, contemporary, state-administered licenses or permits for Tribes to harvest fish and game are seasonal and place-based, and may not reflect species' adaptations and migrations. To illustrate, in western Oregon, the timing of salmonid (*Oncorhynchus* spp.; Fig. 2) occupancy of particular streams and rivers is changing. Lower summer streamflows (*State of Climate Science*, this volume) are delaying the upstream migration of and arrival of salmon in traditional Siletz collection locations. Because salmon now routinely arrive after Tribal tags expire, Tribal members lose the ability to harvest a traditional food, and their food sovereignty may be threatened (Chisholm Hatfield 2009). Similarly, changes in hydrology in eastern Oregon hinder the ability of the Warm Springs Tribe to gather first foods (those that have been a part of traditional diets for millennia) consistent with the timing of traditional Tribal ceremonies (Macy 2016). Furthermore, temporal shifts in species occurrences can lead to asynchronies among interacting species (*Natural Systems*, this volume) (Lynn et al. 2013). These shifts can lead to the absence of certain species from traditional homelands. Changes in the availability of particular plants and animals that are traditional foods or materials may alter foundational religious ceremonies or practices for Tribal peoples.


Figure 2. Coho salmon (*Oncorhynchus kisutch*) spawning in the Salmon River, Oregon. Source: U.S. Geological Survey creative commons archive.

Factors that Contribute to Climate Impacts on and Facilitate Resilience of Oregon Tribes

Tribes may experience impacts of climate change that are common to many populations. However, Tribes also may experience distinct impacts of climate change that relate to their particular cultures, histories, recognition by state and federal governments, status as sovereign governments, rights, and land-holding status. Additionally, the stresses on Tribal economic, cultural, political, geographic, and environmental systems, and the interactions among them, may be greater than those on other populations. Addressing social and economic factors that may seem unrelated to climate change, such as investments in public safety, and local economic sustainability, allows Tribes to focus more capacity on climate resilience.

Oregon Tribes have been developing vulnerability assessments (e.g., Petersen et al. 2017), climate adaptation plans (e.g., Coquille Indian Tribe 2010, CTUIR n.d.), and hazard mitigation plans to prepare for and increase resilience to climate change. A review of the 15 available Tribal vulnerability assessments and adaptation plans in the Northwest (prepared for the Jamestown S'Klallam Tribe, Yurok Tribe, Lummi Tribe of the Lummi Reservation, Nooksack Indian Tribe, Puyallup Tribe, Karuk Tribe, Stillaguamish Tribe of Indians, Swinomish Indian Tribal Community, Fort Hall / Shoshone Bannock Tribe, Duck Valley Tribe, Fort McDermitt Tribe, and Burns Paiute Indian Tribe) identified 281 priority topics, species, and issues of concern to those Tribes (Jones 2018). These priorities included climate-related natural hazards such as flooding, landslides, erosion, wildfire, and sea level rise. Among the primary priorities identified by Tribes across the Pacific Northwest were changes in the distributions or status of native plants and animals, some of which are traditional food sources or culturally significant; alterations in riparian systems, wet meadows, springs, and wetlands; expansion of non-native invasive species; and community health, including respiratory disease (Jones 2018).

Many Tribal strategies for building resilience provide multiple benefits beyond climate adaptation. By addressing the myriad challenges posed by rapid climate change, Tribal climate adaptation strategies also help to reassert treaty rights, advocate for improved and equitable investment in civil infrastructure, and re-establish sovereignty over traditional Tribal lands and resources, economic futures, governance structures, and cultural, physical, and spiritual health.

Ancestral Lands

Tribes in Oregon are resilient in efforts to connect with traditional spaces and return to ancestral homelands. Because Tribal communities and cultures are place-based, with centuries of reliance on, knowledge of, and relationships with their environment, community relocation is not preferred. Many Tribes negotiated treaties with the United States government that were ratified, but have not been honored, whereas other Tribes negotiated treaties that never were ratified. Federally recognized Tribes were forced onto reservations; given access to lands less extensive than their traditionally held hunting, fishing, and gathering areas; or relocated, often to areas that were far from their traditional homelands. In many cases, Tribes were not given any reservation lands. Contemporary Tribal access to traditional resources is affected by state and federal law (Lynn et al. 2013). Such restrictions hamper thousands of years of Tribal adaptation measures and can stifle Tribes' economic stability, growth, and self-sufficiency (Steen-Adams et al. 2020).

Tribes routinely access Usual and Accustomed areas to fully satisfy the TEK aspects of relationships between their land and cultural protocols and to exercise their right of self-determination, which requires access to traditional food sources. In Oregon, some Tribes have acquired title, management rights, or access to ancestral lands—areas that historically were occupied or used by their ancestors—since regaining federal recognition in the 1970s (see geriatrics.stanford.edu/ethnomed/american_indian/learning_activities/learning_1/termination_relocation.html). Increasing Tribal land bases contributes to maintenance of Tribal economies while improving access to culturally valued traditional areas.

First Foods and Food Sovereignty

Traditional food systems are integral to Tribal culture and contribute substantially to the physical, emotional, and mental health of Tribal members. Climate change is significantly affecting Tribes' access to first foods. Maintenance of Indigenous access to land, water, and first foods is a federal trust responsibility. Tribes rely on traditional foods for physical health and well-being; sustenance; medicines for physical, spiritual, and mental health; ceremonies; community; and economic prosperity (Lynn et al. 2013, Sowerwine et al 2019). Accessing, harvesting, and processing first foods requires some members of Indigenous communities to take time off from jobs and other obligations. Access to landscape-scale gardens and community gardens that promote subsistence foods and culturally important species is a priority for many Tribes in the Pacific Northwest. For example, the Confederated Tribes of the Umatilla Indian Reservation structured their Tribal government and educational curricula around first foods, and the Klamath Tribes are installing greenhouses for growing first foods and planning to incorporate youth engagement into their food sovereignty program (Steinkopf-Frank 2017). The Confederated Tribes of Siletz has implemented a Healthy Foods program to teach healthy choices and traditional food harvesting, processing, and storage. The food sovereignty subcommittee of the Affiliated Tribes of Northwest Indians, an organization of approximately 57 member Tribes, promotes the implementation of first food concepts in Native communities throughout the Pacific Northwest.

The Willamette Falls in Oregon City, Oregon is a culturally significant location for Oregon Tribes to harvest Pacific lamprey (*Entosphenus tridentatus*), a traditional food source (Jones et al. 2020, Maine 2020). Access to the Falls currently is under the jurisdiction of the Oregon Department of Fish and Wildlife. Oregon Tribes make an annual migration to the Falls in late spring to collect the lamprey. The species historically was widespread and a seasonal staple, but its distribution has declined considerably, and the Falls are one of few areas in Oregon where they remain reasonably abundant. High incidence of diabetes, high blood pressure, and cancer among Indigenous populations is tied to lack of traditional foods (Fialkowski et al. 2012). By revitalizing Tribal culture and reestablishing traditional connections to the land and first foods, Oregon Tribal peoples are celebrating Tribal community, identity, and spirituality and fostering a more positive, healthy lifestyle, both within the Tribe and with the environment (Kawamoto 2001, Geib 2003).

Economic Sovereignty

Increases in and support for economic sovereignty and self-sufficiency would assist federally recognized Tribes and communities in increasing their resilience (Belcourt-Dittloff 2007) and proactively addressing their priorities, including infrastructure updates and improvements; and, in some cases, reducing dependence on the federal government (Ricci 2019, Dubb 2020). Many Oregon Tribes aim for diversification in economic sectors that can benefit the individual Tribe, and Tribal members and cultural sectors, in ways that extend beyond and may be considered more important than financial gain. As financial resources and sovereignty increase, Tribes become better positioned to protect community resources that are threatened by inland or coastal flooding and coastal storm surges; to hire staff, including scientists and cultural specialists; to conserve or manage culturally important plants and animals and their habitat; and to sustain the physical, emotional, spiritual, cultural, and mental well-being of their community.

Tribes achieve economic prosperity through varied business enterprises. Most Tribes have had, and many retain, an economic enterprise that has relied on some aspect of natural resources (NCAI 2013). However, environmental shifts caused by climate change have resulted in a focus on businesses separate from natural resources (NCAI 2013, Deol and Colby 2018). For example, owning and operating a casino is one aspect of the economic foundation of many Oregon Tribes. Nevertheless, casinos do not always provide the economic wealth needed for self-sufficiency. Casinos have been a fairly recent Tribal venture. Casinos near major population centers generally have been more profitable, providing increased benefits to Tribal governments and, through state-Tribal agreements for establishment and management of Tribal casinos, to the state and local governments. Some Tribes use their financial resources to invest in economic diversification. Examples include the Confederated Tribes of the Umatilla Indian Reservation's investment in Cayuse Technologies (www.cayusetechnologies.com), a Tribally owned software development company; the Umpqua Indian Utility Cooperative, an enterprise owned by the Cow Creek Band of the Umpqua Tribe of Indians; and the Confederated Tribes of the Grand Ronde's acquisition of Shasta Administrative Services, a third-party administrator of health care services.

Partnerships

Intertribal partnerships increase economic sovereignty and Tribal resilience. Because many Tribes have limited personnel and funding, partnerships increase collective capacity. Partnerships also can increase Tribes' ability to network outside of Native arenas, and to influence policy and decision makers. The power of Tribes is amplified when Tribes speak with a unified voice (Shreve 2009). At both state and national levels, various agencies and organizations collaborate and network with Tribes. The National Congress of American Indians, established in 1944, is the oldest, largest organization and the most representative of American Indian and Alaska Natives, and is highly trusted by Tribes. The Congress focuses on serving the broad interests of Tribal governments and communities. The Affiliated Tribes of Northwest Indians advocates for Tribes across the Pacific Northwest and promotes self-determination and sovereignty while recognizing the importance of the federal trust responsibility to the federally recognized Tribes.

Collaborations between Tribes and smaller organizations and businesses also are beneficial. For example, EcoTrust, a nonprofit organization based in Portland, seeks to improve and sustain the environmental, cultural, economic, and social conditions of Tribal communities. Other organizations regularly work with Tribal partners and intertribal organizations (e.g., Intertribal Timber Council, Columbia River Inter-Tribal Fish Commission) to enhance diversity in policy and management sectors and to increase academic and community understanding of TEK and its relevance to the science of and adaptation to climate change. Additionally, some intertribal organizations collaborate with federal entities. For example, the national network of Climate Adaptation Science Centers, sponsored by the U.S. Geological Survey, has a partnership with the Bureau of Indian Affairs and employs Tribal liaisons in each of the eight regional Centers. The liaisons assist cooperative efforts by Tribal and non-Tribal partners to co-produce and apply interdisciplinary science that increases Tribal resilience to climate change. In the Pacific Northwest, the Affiliated Tribes of Northwest Indians hosts a regional Tribal liaison.

Energy Sovereignty and Efficiency

Tribes in Oregon also are pursuing energy sovereignty. For example, Tribes or Tribal citizens are exploring the use of tidal energy and off-shore wind energy initiatives, such as the Oregon Coast Energy Alliance Network, to become more resilient. In the 1950s and 1960s, the Confederated Tribes of Warm Springs and Portland General Electric worked in partnership to allow construction of the Pelton Dam, the Reregulating Dam, and the Round Butte Dam. Since 2001, the Tribes' Warm Springs Power & Water Enterprises has owned the Pelton/Round Butte Hydroelectric Project in partnership with Portland General Electric, and sold electricity to the grid (Confederated Tribes of Warm Springs 2020). The Cow Creek Band of the Umpqua Indian Reservation also established an electric utility; they purchase electricity at wholesale and provide it to the reservation. The Affiliated Tribes of Northwest Indians and Bonneville Power Administration support Tribal citizens and governments in becoming more energy-efficient and reducing their energy costs.

Cultural Revitalization

Early Oregon settlement forced many Tribes off their traditional homelands (Jahoda 1975, Van Laere 2000, Wilkinson 2012). Some Tribes were detained in common areas in which assimilation was unavoidable. As a result, in some cases, knowledge of distinct, culturally significant ceremonies and practices, languages, clan system knowledge, and Tribal customs was lost. Pan-Indianism is an erroneous concept. Tribes are place-based peoples; the distinct geography, local ecological attributes and species, and longstanding trails of a Tribe's homeland area contribute significantly to a Tribe's distinct identity (Whyte 2018). Connections with traditional familial sites, homelands, and spaces, including burial grounds and sacred sites that generally are not disclosed outside the Tribe, remain vital and sacred aspects of Tribal identities. These connections and, often, Tribe- and location-specific hunting, gathering, and cultural practices, are essential to each Tribe's well-being and to Tribal members' senses of place and self (Burnette et al. 2018, Shea et al. 2019). For example, coastal Tribes may consider as a homeland a riverine or oceanic location, such as traditional mussel-gathering areas near Yaquina Lighthouse, or a field in which roots long have been collected. Severance of such connections, like those with Native foods, negatively can affect Traditional Knowledges, self-identity, and the emotional, physical, mental, and spiritual health of Tribal members. Climate grief is one of the ways in which climate change affects Tribal and myriad other communities. Tribal communities also have been experiencing grief with respect to loss of TEK and connections to places (Chisholm Hatfield 2009, Chisolm Hatfield et al. 2018). These forms of grief can be quite strong (Clark 1805, CRITFC 2020, Cunsolo et al. 2020).

The resurrection and revitalization of Tribal connections and cultural practices, and by extension community, identity, and health, is a priority for Oregon Tribes and has been a prominent effort since the mid to late 1970s. Contemporary initiatives include, for example, traditional language programs centered on traditional activities and natural resources, Tribal canoe journeys along the Pacific coast that include instruction on traditional carving and woodworking (Fig. 3), salmon ceremonies, first foods ceremonial practices, and spiritual or religious events.

Figure 3. Canoes are carried above the high tide line by upwards of 30 individuals during the annual Tribal Canoe Journey in the Pacific Northwest. Photograph by Chas Jones from the 2018 event hosted by the Puyallup Tribe.

Youth Engagement

Tribal cultures emphasize experiential learning to use, navigate, and understand water, land, animals, plants, and humans as kin. Tribes increasingly are developing youth engagement programs to increase Tribal resilience and to teach and maintain Traditional Knowledge. Most federally recognized Tribes in Oregon have such youth engagement programs and cultural enrichment activities designed to assist and re-teach Traditional Knowledges. Most Tribal education departments assist Tribal students with internships or culture activities. Many Tribal departments work in conjunction with natural resources or culture departments. Some Tribes hold annual events that allow young people to learn and reconnect with their ancestral traditions while participating in activities with their elders and families. Engaging youth and elders in subsistence cultural activities ensures that Traditional Knowledges tied to culture are passed along to future generations via TEK.

Jurisdiction, Co-management, and Cultural Burning

Native Americans' traditional land management practices can promote resilient landscapes. Indeed, one of the reasons the term TEK was introduced into the western science literature was to describe these successful and innovative approaches. Some profoundly intimate, spiritual components of management may not be shared outside the Tribe.

Figure 4. Rapid regrowth of native flowering plants following a prescribed fire. Photograph by Erica Fleishman.

Oregon Tribes sometimes co-manage land or waters with the federal, state, or local government via a memorandum of understanding. Co-management frequently occurs after government-to-government consultations, in which federal or other levels of government work with Tribes to offer jurisdiction over or implement co-management practices on their trust or fee lands under the Indian Trust Asset Reform Act of 2016 (Public Law 114–178, 25 USC 5601). In 2020, in its first demonstration project under that Act, the Bureau of Indian Affairs gave the Coquille Tribe management authority over its forested lands and other lands held in trust for the Tribe (BIA 2020). This example illustrates a foundation for increasing Tribal sovereignty.

Co-management can facilitate the use of prescribed fire or cultural burning, a traditional management practice in Oregon, throughout the United States and globally (Fig. 4). Tribal peoples in Oregon employed fire as a primary land management tool (LaLande and Pullen 1999, Frost and Sweeney 2000, Melten et al. 2018) throughout the year for multiple reasons (LaLande and Pullen 1999, Long et al. 2015). For instance, prior to non-Native settlement in the 1850s, many Tribes in Oregon moved across their homelands seasonally. Some grew edible plants along their routes to provide sustenance and cultural products. Fire cleared travel corridors, directed game into areas where they could be hunted more easily, and roasted sugar pine (*Pinus lambertiana*) nuts, tarweed (*Madia* spp.) seeds, and grasshoppers and crickets (Orthoptera), making future gathering easier (Roy et al. 2014, Long and Lake 2018, Oaster 2020).

Prior to non-Native settlement, the Kalapuya and other Indigenous people regularly set low-intensity fires in the Willamette Valley. Such fires can reduce the risk of large, severe wildfires (Armatas et al. 2016) and support growth of traditional foods such as camas (*Camassia* spp.), bracken fern (*Pteridium aquilinum*), Oregon white oak (*Quercus garryana*; acorns are harvested), California black oak (*Q. kelloggii*), hazelnuts (*Corylus cornuta*), mountain huckleberry (*Vaccinium* spp.), and blackberry (*Rubus ursinus*). Fire also promotes the growth of plants used for basketry, such as bear grass (*Xerophyllum tenax*) and hazel (*Corylus cornuta*) shoots, and habitat for native ungulates (hoofed mammals) such as deer (*Odocoileus* spp.) and elk (*Cervus canadensis*) (Roy et al. 2014, Long and Lake 2018). Collaborative, cultural burning pilot projects recently were implemented in northern California by the U.S. Forest Service and regional Tribes (Diver 2016).

Emergency Management and Hazard Mitigation Planning

Climate change impacts are being addressed through hazard mitigation and emergency management plans. Existing hazard mitigation plans (e.g., CCBUTI 2012) and emergency management plans (e.g., CTWS 2015, Coquille Indian Tribe 2016, Burns Paiute Indian Tribe 2019) developed by Oregon Tribes specify engineering actions that may mitigate particular climate-related natural hazards, such as flooding, coastal storm surges, or wildfire. However, many of these plans do not provide cost estimates, which impedes action. An indication of the level of funding necessary for implementation of a particular project can facilitate communication and action because it easily can be understood, and provides an opportunity for decision makers to address a priority through financial allocations.

Identity

Many Native people view their identity as an extension of the lands on which they reside and of their original homeland areas. Environmental conservation, sustainability, and ecological reciprocity are viewed as ways of life and survival, not as movements (Nadasdy 2005). Many of the Tribal strategies for building resilience are tied to land and natural resources in some way, and provide diverse benefits that extend beyond or coincide with climate adaptation measures. Tribal TEK has noted changes in climate and its effects on species and other environmental elements since the 1960s (Chisholm Hatfield 2009). In some cases, this growing documentation and awareness has led to implementation of adaptive actions.

Many traditional management practices are grounded in TEK. As noted above, for example, traditional burning was applied by Tribes in Oregon before non-Native settlement. Under Native stewardship, the Willamette Valley was dominated by grasslands, with stands of oaks and conifers (Oaster 2020). Support and development of Tribal Forest Management Plans and similar efforts not only may reduce the likelihood of large, severe wildfires, but enable Tribes to protect and monitor the physical, emotional, spiritual, cultural, and mental well-being of their community in a traditional manner. Healthy ecosystems often are regarded as ensuring a healthy Tribal system (Finn et al 2017, Harris et al 2000).

Tribal climate adaptation strategies also help to reestablish sovereignty to oversee Tribal resource bases, economic futures, governance structures, and cultural, physical, and spiritual health. Oregon Tribes are strengthening resilience by identifying distinct and innovative climate solutions. Efforts to mitigate and adapt to climate change in ways that address social and environmental justice, and that include both Indigenous peoples and allies, are most likely to achieve Native goals. Indigenous identities are complicated and, given the extent to which they are grounded in particular cultures or locations, often determine the way Native people conceptualize their relationship with the environment, including responses to climate change.

Roles, Traditional Knowledge value systems, and behaviors that are linked to certain environmental locations and conditions, such as coming-of-age and religious or spiritual ceremonies, contribute greatly to overall health and wellbeing of Tribal members. Being denied an aspect of heritage by policy regulation, pollution, or climate change causes a rift in Traditional Knowledge and its cultural transmission (Duran and Duran 1995, EchoHawk 1997, Thornton 1998, Jacobs 2006). This rift inhibits the maintenance of TEK and sustainable-management information, and can lead to its loss. When TEK is lost, adaptation actions and assessment of the effects of climate change impacts are disrupted. Cultural revitalization of traditions also includes language growth, cultural crafting, and ceremonial practices that maintain community identity and ensure continuity of cultural vitality.

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Social Systems

Idowu Ajibade, Chris Lower, Stephanie Salas, and Benjamin Galindo

This chapter focuses on the ways in which climate change may affect social systems and frontline communities in areas at high risk of climate change impacts and extreme weather events. In the context of Oregon's planning for adaptation to climate change (DLCD 2020), social systems refer to institutions, norms, infrastructure, services, needs, locations, and networks that bring people together and support social interaction and livability. This chapter focuses on equity considerations more broadly and with respect to food and agriculture, public health, wildfire, the COVID-19 pandemic, infrastructure, and urban areas. Other social issues not covered in detail in the chapter include migration, demographic change, education, and transportation. Climate change is likely to present Oregon with new challenges and opportunities in all of these areas.

Equity

Climate change is a social-ecological phenomenon in the sense that social, political, and economic forces within society exacerbate the causes of climate change and its effects on people, especially frontline communities (Davies et al. 2018). Oregon's climate equity blueprint defines frontline communities as those that generally experience negative effects of climate change earliest and most severely; such groups include communities of color, immigrants, rural and low-income communities, and Indigenous peoples (OHA 2020b). Equity and justice issues in climate change cannot be addressed effectively without attention to historical and contemporary disadvantages and injustices perpetuated by structural racism, poverty, gentrification, and uneven development (Chu et al. 2017). Oregon has a complicated history of racism. The violence of colonization, segregation, and inequity is part of that history, and its effects are apparent throughout the state's rural and urban areas. For example, gentrification and the proportion of unhoused individuals are on the rise in the Portland metropolitan region due to an influx of affluence and capital that has contributed to racialized poverty and the ongoing displacement of Black, Indigenous, and People of Color (Goodling et al. 2015, Harbarger 2017). Furthermore, in gentrifying areas of Portland, an increase in the prevalence of high-priced grocery chains has created differential access to food across income levels (Breyer and Voss-Andreae 2013). Communities of color and low-income residents not only are subject to socially induced displacement, food insecurity, and poverty, but are among the groups most vulnerable to the direct and indirect impacts of climate change, including higher exposure to wildfire smoke, urban heat, and flooding (Tripathi et al. 2014, Davies et al. 2018, Rosenzweig et al. 2018, Voelkel et al. 2018).

Nationally, an increasing number of tools are being created to analyze the geographic and spatial distribution of frontline populations. One such tool, the social vulnerability index (Cutter et al. 2003, Cutter and Finch 2008), uses data from the U.S. Census Bureau to evaluate spatial patterns of demographic characteristics, including but not limited to age, gender, race, education, and financial earnings, that may relate to potential vulnerability. Social vulnerability indices are helpful for mapping social-spatial and social-economic exposures at the community, city, county, and state levels, and can identify where certain populations are distributed in relation to projected food shortages, water insecurity, and extreme events such as flooding, wildfires, and heat waves (Wood et al. 2010, Davies et al. 2018). However, these types of tools may have little impact beyond their informational value if Oregon does not place equity and inclusion at the center of climate and natural-hazard adaptation strategies.

Food and Agriculture

Food affects social, cultural, and health benefits such as disease prevention, social functioning, and learning capacity (Neumann et al. 2003, Boyer and Liu 2004). Climate change may affect the distribution and abundance of some traditional Tribal foods that have high nutritional value, such as salmon, wild berries, and certain plants that are harvested for their roots and bulbs (Lynn et al. 2013, Norton-Smith et al. 2016; *Tribal Cultural Resources*, this volume). Loss of these foods can lead to changes in diet and to increased incidence of diet-related illnesses such as diabetes, obesity, hypertension, and heart disease (Norgaard 2005, Sarkar et al. 2020). Additionally, because many traditional foods hold cultural and spiritual relevance, their loss can have substantial effects on mental and spiritual well-being (Norgaard 2005, Lynn et al. 2013).

From 2001 through 2015, insurance losses for wheat in the inland Northwest (Fig. 1) exceeded $1.4 billion, over $700 million of which was attributed to drought (Seamon 2019). Crop insurance premiums are expected to rise in areas where prolonged heat can reduce mean yields of commonly insured commodity crops such as wheat and corn (Tack et al. 2018). These increases can be problematic for small farms that receive lower levels of insurance subsidies than large corporate farms, and the lower-yield crops of which are insufficiently protected by the Noninsured Crop Disaster Assistance Program (Gough 2018). These inequities might decrease diversity in farm ownership. In Oregon, farmers of color tend to own less land than White farmers. This situation reinforces the need for an equity lens to better assess responses and adaptation to climate vulnerability in the food and agricultural sectors in Oregon and the Northwest.

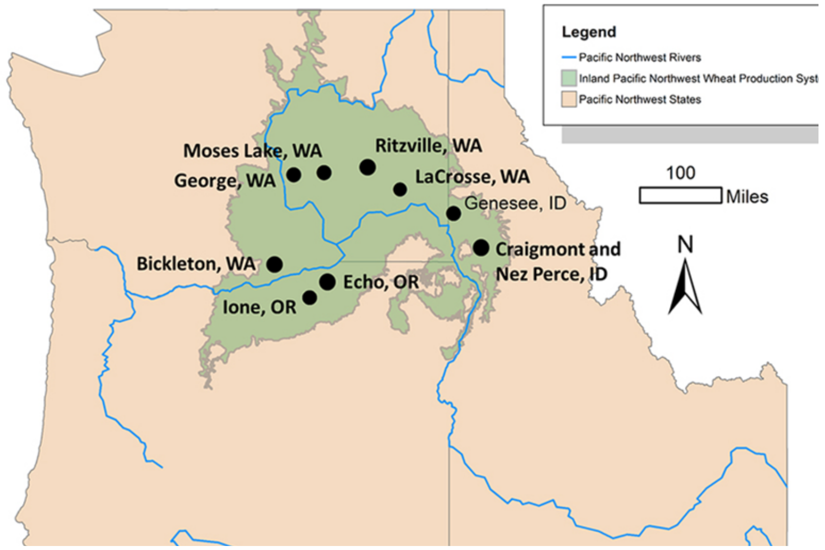

Figure 1. The major wheat producing area of the inland Pacific Northwest. Source: REACCH 2020, created be Kaelin Hamel-Rieken at Washington State University.

Without sufficient irrigation, water stress during periods of high temperatures is likely to cause declines in major cash crops such as wheat, soy, and corn (Schauberger et al. 2017). Any increases in productivity as a result of higher atmospheric concentrations of carbon dioxide are likely to be too small to offset drought-based reductions in yields (Schauberger et al. 2017). As a result, producers may have to adopt strategies for maintaining yields and minimizing economic losses (Dalton et al. 2013, Houston et al. 2017). For instance, they may control for the disparity between crop growth and seasonal weather conditions, invest in more-efficient sprinkler technologies, or increase irrigation to mitigate the risk of crop damage from drought and extreme heat (Olen et al. 2016, Houston et al. 2017). However, the extent to which irrigation can be intensified is unclear given projections of decreasing snowpack and summer stream flows (May et al. 2018, Qin et al. 2020; *State of Climate Science*, this volume).

Climate variability also will impact distribution and processing centers as farmers adapt to changes in crop production and higher transportation costs (SBA 2015). Along with later first freezes in autumn and earlier last freezes in spring, the growing season is expected to lengthen. As a result, the development and adoption of more cost-effective strategies will hinge on farmers' knowledge about projected climate variability, risks, and the effects these might have on their operations (May et al. 2018, Mote et al. 2019). Thirty-two percent of farmers in Oregon's southern Willamette Valley with gross annual incomes less than $250,000 reported that they have enough resources and current information to make sound decisions when planning for extreme and variable weather (Roesch-McNally et al. 2019). This suggests that local farmers may need more robust, place-based information to develop effective climate adaptation and management practices. Needs identified among southern Willamette Valley farmers included the identification of new farming techniques and water management systems (Roesch-McNally et al. 2019).

Given that Oregon's agricultural sector will be affected substantially by an array of climate effects, gauging farmers' willingness to make operational changes is relevant. About 20–30% of major wheat producers in the inland Pacific Northwest (Fig. 1) believe it is necessary to make moderate to large operational changes in response to climate change (Roesch-McNally 2018). These producers identified five primary adaptive responses motivated by perceived economic and environmental risks: changing the spatial and temporal sequence in which crops are planted, rotating crops more frequently, adopting different tillage methods, improving soil conservation, and increasing crop insurance coverage (Table 1). According to Roesch-McNally (2018), only a small proportion of Pacific Northwest farmers were willing to make these changes because most believed that the financial burden associated with taking action outweighed any risks associated with inaction. The costs farmers incur from adopting new technologies, implementing operational changes, and switching crop types most likely will be passed on to consumers. Rising food costs have the greatest financial impact on frontline communities and those with low incomes (Beyer and Voss-Andreae 2013). Therefore, many of Oregon's residents who already are struggling financially will have increasing difficulty affording nutritious produce and other staple foods.

Adaptive strategy	2013 (%)	2016 (%)
Cropping system changes	18	23
Crop rotation	20	25
Tillage practices	23	27
Soil conservation	23	25
Increase crop insurance	28	24

Table 1. The five most common adaptive strategies that inland Northwest wheat farmers identified as potential responses to climate change in surveys during January 2013 (760 respondents) and January 2016 (449 respondents). Source: Roesch-McNally 2018.

Public Health

The literature on health and climate change has not sufficiently addressed the public's ability to identify, respond, and prepare for health problems caused by climate change and extreme weather events (Kreslake et al. 2018). This is especially true among frontline communities that acknowledge climate change is a problem, but lack the information necessary to mitigate the direct and indirect effects on their health, safety, and well-being (Maibach et al. 2015). Lack of knowledge not only impedes adaptation in healthcare, but is a matter of inequity. Although Maibach et al. (2015) was not specific to Oregon, it was nationally representative, and therefore is likely to reflect regional attitudes (McCright et al. 2016, Smith et al. 2017).

Previous Oregon Climate Assessments (e.g., Bethel et al. 2013, Dalton et al. 2017) identified populations that might be at greatest risk of climate-related health issues, including the elderly, young children, pregnant women, low-income individuals, people with disabilities or chronic medical conditions (e.g., diabetes, asthma, obesity and mental illness), and outdoor and seasonal workers. Immigrants and those with limited English proficiency also may require support (Dalton et al. 2017). This Assessment acknowledges the social, physical, demographic, residential, and occupational attributes that may lead to disproportionate effects of climate change on some populations or groups (*Public Health*, this volume). Additional attributes not explicitly acknowledged in previous Oregon climate assessments include racial marginalization, lack of housing, service as first responders and health care workers, and other place-based residential attributes.

Agricultural laborers' incidence of heat-related illnesses (Kearney et al. 2016) and exposure to particulate matter from wildfires are expected to increase as the climate changes (Austin et al. 2020). However, the effects of increased temperatures on agricultural workers are often overlooked, especially given that at least 48% of those in the United States are undocumented (Kearney et al. 2016, NIOSH 2017). In Oregon, 28% of agricultural workers are undocumented (NAE 2016), and approximately 45% do not have health insurance (KFF 2020). This places numerous undocumented agricultural workers at risk for heat-related illnesses, with insufficient resources to access medical care. Furthermore, the extent to which agricultural workers across the United States are trained on heat-related illnesses and hydration varies considerably (Bethel et al. 2017). Many do not understand their workplace rights and are hesitant to report occupational hazards (Flynn et al. 2015).

Unhoused people are disproportionately susceptible to illness and mortality from climate change. For example, high proportions of mental illness, cardiovascular disease, respiratory conditions, and social isolation among unhoused people increase their risk of disease and death from heat waves (Ramin and Svoboda 2009). Additionally, given the amount of time that unhoused residents spend outdoors, they are relatively susceptible to the negative effects of air pollutants such as ground-level ozone, acid aerosols, particulate matter, and carbon monoxide. Poor air quality not only exacerbates existing respiratory conditions within unhoused communities, but can lead to asthma, chronic bronchitis, and emphysema (Snyder and Eisner 2004). Similarly, floods and storms are likely to have disproportionate effects on unhoused people who live in coastal and underprepared urban areas (Snyder and Eisner 2004). Following floods and storms, these communities are the most likely to experience disease, death, post-traumatic stress disorder, and anxiety (Snyder and Eisner 2004).

Black communities in Oregon historically were ostracized politically, structurally, and socially (Goldman 2020). For decades, environmental toxicants were concentrated in the community of Albina in Portland, Oregon, which is home to many Black and Hispanic residents (Gibson 2007, McCord 2016, Goldman 2020). Albina was heavily affected by commercial and industrial projects that were concentrated in this part of the city (Gibson 2007, Goldman 2020). Albina residents were exposed to toxicants in their air and water from local disposal over decades, especially in the Columbia River Slough (McCord 2016). Across the United States, Black peoples' exposure to toxicants is 21% greater than the overall population average, while they contribute less than 23% of the national exposure (McCord 2016). Proximity to sources of toxicants has adverse effects on the reproductive health and respiratory systems of families who live in unhealthy environments as a result of their social and economic status (Carpenter et al. 2008, Kihal-Talantikite et al. 2017). Incarcerated people also are disproportionately susceptible to the effects of climate change due to high rates of chronic illness in prisons (Holt 2015). Heat can be detrimental to inmates whose medications may affect central thermoregulatory processes (Martinez et al. 2002, Holt 2015). Furthermore, healthcare costs for inmates who are over the age of 55 and have a chronic or terminal illness were estimated to double or triple (Anno et al. 2004). Although adaptation plans are required to ensure safety and avoid inhumane conditions, only the Federal Bureau of Prisons is required to conduct climate change adaptation planning; similarly rigorous planning has not been reported at the state or local level (Holt 2015).

Wildfires are likely to occur with increasing frequency due to climate change (Halofsky et al. 2020). The impacts of the 2018 Eagle Creek Fire along the Columbia River Gorge (Hunter et al. 2018, Kohn 2018) and the fires of 2020 make this likelihood salient to Oregonians. In September 2020, 9 people in Oregon were killed and about 127,000 were told to evacuate (OEM 2020a, b). The cities of Phoenix and Talent, near central Jackson County, were severely damaged by the Almeda Fire (Crombie 2020). The majority of businesses and homes in the resort community of Detroit also were destroyed when the Lions Head Fire swept through east Marion County (Paul 2020). As noted in previous Oregon Climate Assessments (Dello and Mote 2010, Dalton et al. 2013, 2017), multiple respiratory and other health complications from wildfire smoke disproportionately harm frontline workers, low-income communities, the elderly, people with disabilities, and others with pre-existing conditions, such as asthma (see also *Public Health*, this volume). Data integration and analysis from the U.S. Census Bureau and U.S. Forest Service suggested that nationwide, communities of color and people currently living in poverty are more likely to live in census tracts with the highest likelihood of experiencing a wildfire event (Davies et al. 2018).

The Northwest chapter of the Fourth National Climate Assessment discussed opportunities for increasing community-level resilience in the region by incorporating health and wellness strategies into climate planning models (May et al. 2018). Examples include investments in active transportation, such as bicycling and walking, and green amenities, such as parks, both of which improve air quality by reducing reliance on automobiles while increasing the activity levels of participating citizens (May et al. 2018). However, several parks in Portland are within historic floodplains and at risk of flooding (Bencivengo et al. 2017). Additionally, green infrastructure often is distributed unequally in the United States, including Oregon: Black, Indigenous, and People of Color and those with low incomes frequently lack equitable access to green spaces (Nesbitt et al. 2019). In Portland, many frontline communities lack access to parks and green spaces compared to more affluent communities (Bencivengo et al. 2017).

COVID-19 and Climate Change

Much of Oregon, like many states and countries, has experienced substantial and far-ranging effects from COVID-19. Oregon's unemployment rate increased from 3.5% in February 2020 to 8% in September 2020 (Lehner 2020); the number of jobs that pay $40,000 or less per year decreased by 12% during the same time period (Lehner 2020). Moreover, pandemic-related school closures increased food insecurity for families with currently low incomes (Romero 2020) and, as of December 2020, more than 1400 Oregonians had died from the coronavirus (OHA 2020a). COVID-19 mortality rates can increase as a result of local disasters, such as wildfires that increase concentrations of fine particulate matter ($PM_{2.5}$) (McClure and Jaffe 2018). For instance, mortality from the respiratory effects of COVID-19 can increase by 8% with a 1 μg/m3 increase in $PM_{2.5}$ exposure (Wu et al. 2020). The availability of healthcare resources such as personal protective equipment and ventilators, both of which are in demand for treatment of COVID-19, further will be constrained by climate-related health conditions.

In Oregon, COVID-19 has affected communities of color disproportionately; in September, 2020, the per capita infection rate for Black people was 3208, compared to 1294 for White people (OHA

2020a). Latinos represent 13% of Oregon's population but in September, 2020, accounted for almost 30% of COVID-19 cases (OHA 2020a). As of late 2020, the infection rate among Native Americans was four times that among Whites (McPhillips 2020), and Native Americans accounted for 8% of COVID-related hospitalizations despite representing 1% of Oregon's population (OHA 2020a). These health disparities are symptomatic of longstanding inequities in public systems that have left communities of color exceptionally vulnerable to the impacts of COVID-19 (CDC 2020). For example, not only are Black people more likely to be underinsured (Fortuna et al. 2020), but factors such as inadequate transportation, poverty, and a higher likelihood of living in crowded, multiple-family dwellings place these communities at higher risk during emergency events such as a pandemic (Gaynor and Wilson 2020). Black Americans also are overrepresented in essential workforce and frontline jobs (Black Demographics 2020), including public transportation (31%), postal services (25%), health care (17%), and food delivery and courier services (25%). Many of these jobs place Black people in close contact with the public and do not provide opportunities to work safely from home. Therefore, social distancing is not always practical or feasible (Fortuna et al. 2020). Major shifts in social and health policies will be required to slow infection and fatality rates among Black, Indigenous, and People of Color, with considerable efforts to reduce systemic and everyday health-related inequalities.

Public Opinion on Climate Change

The majority of Oregonians (73%) recognize that the climate is changing, and nearly two-thirds (63%) are worried about it. Although less than half (43%) of Oregonians think global warming will harm them personally, almost three-quarters (73%) believe it will harm future generations (YPCCC 2020). These percentages have increased since a 2015 public opinion poll published in the third Oregon Climate Assessment (Dalton et al. 2017) (Fig. 2). Furthermore, data collected in 2020 indicated that a sizeable majority (86%) of Oregonians support funding for research into renewable energy sources, with nearly three-quarters (66%) in favor of regulating carbon dioxide as a pollutant (YPCCC 2020). Additionally, approximately two-thirds of Oregonians (65%) believe that fossil fuel companies should be required to pay a carbon tax. Slightly less than half (49%) of Oregonians think that the Governor needs to do more to address global warming, and more than half (53%) believe that local officials should be doing more.

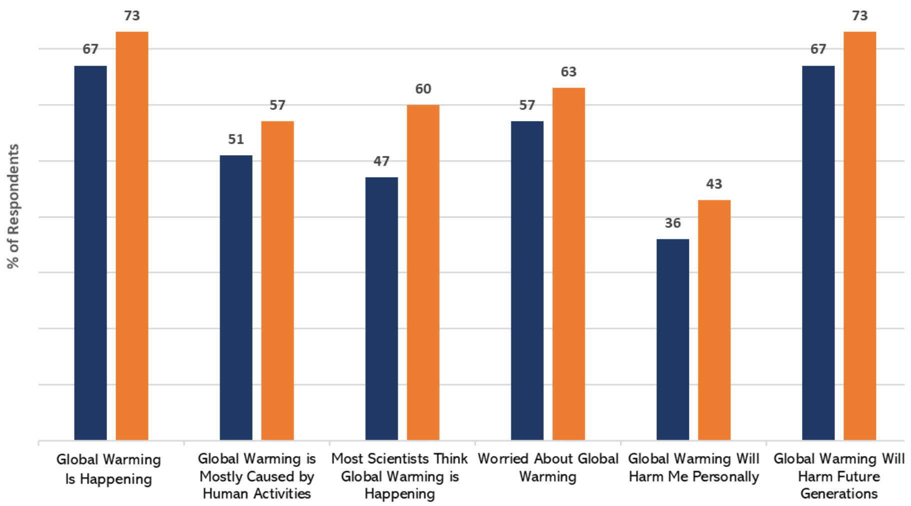

Figure 2. Changes in public opinion on climate change in Oregon over the past decade. Sources: Dalton et al. 2017, Yale Program on Climate Change Communication 2020.

Infrastructure

A great deal of adaptation research highlights the ways in which infrastructure will be affected by climate stressors (*Built Environment*, this volume). Often overlooked, however, are the ways in which disparate assets (e.g., roads, water treatment facilities, energy production centers) are interdependent, and how damage to one infrastructure component creates or magnifies problems for others. These dependencies have potential to cause system-wide failures (Wilbanks et al. 2015) that increase mortality, impede urgent repairs, and prolong economic and social malaise. To illustrate, a flooded transportation route can impede repairs to a wastewater treatment plant, which in turn can jeopardize public health. In Portland, Oregon, rain-on-snow flooding might affect city infrastructure via cascading effects, where damage to one system can magnify failures in others (ISS 2018).

Green infrastructure increasingly is being employed to adapt to climate change in Oregon and other states. Green infrastructure imitates or uses components of natural systems, such as green roofs, rain gardens, urban forests, and bioswales, for mitigation and adaptation (EESI 2019). Benefits of green infrastructure are varied and include environmental-based educational opportunities for children and teenagers (Cole et al. 2017), increased land values (Kim and Song 2019), and more-effective stormwater management through the use of permeable pavement and biological retention strategies (Kim and Song 2019). Moreover, because green infrastructure provides many need-specific options, it can be applied to address a broad range of issues. For instance, artificial wetlands can reduce wave energy caused by storms, urban tree canopies can give shade and reduce heat caused by the urban heat island effect, and green roofs can reduce stormwater surges by capturing precipitation (EESI 2019, Kim and Song 2019). Additionally, green infrastructure often is cheaper than conventional adaptation strategies. For example, North Carolina municipal planners found that artificial wetlands minimized stormwater runoff at a cost of $0.47 cents per thousand gallons (3785 liters) of treated water, whereas the cost of traditional stormwater controls averaged $3.24 per thousand gallons (Talberth et al. 2013).

Urban Areas

Cities serve as key actors in the global market. Interactions among their economic, transportation, industrial, cultural, social, and political systems account for the bulk of their respective states' financial, political, and social capital (Lower 2014). Moreover, state populations, assets, and infrastructure frequently are concentrated in urban areas, and regional capacities for the distribution of food, goods, and emergency relief tend to be centered in cities and radiate to rural and exurban environments (Field et al. 2014). These dynamics suggest that large areas could be isolated if one or more cities are affected by a disaster. Additionally, rapid urbanization has contributed to the growth of highly vulnerable communities that live in those cities (Field et al. 2014). Metropolitan regions are distinct from other populated areas because most large cities are along coasts or major rivers, making them highly susceptible to flooding (Grimm et al. 2008). Buildings, roads, and other structures and infrastructure with high albedo contribute to the urban heat island effect (Makido et al. 2019). Moreover, dense populations are at risk of mass infection from air-, food-, and waterborne pathogens (Neiderud 2015).

More-frequent heat waves, and the increased likelihood of heat stress associated with urban heat islands, are expected to increase heat-related illness and death (Dalton et al. 2017; *Extreme Heat* and *Public Health*, this volume). The severity of these effects and the communities at greatest risk vary. Some evidence suggests that those most vulnerable to urban heat islands are the elderly;

unhoused; Black, Indigenous, and People of Color; and those with currently low incomes (Anderson and McMinn 2019). Similarly, frontline communities in Portland, Oregon appear to be the most susceptible to increased temperatures caused by urban heat islands (Bencivengo et al. 2017), where temperature differences between a city's hottest and coolest neighborhoods can approach 10˚F (~5.6 °C) (Anderson and McMinn 2019). Residents exposed to the greater heat and humidity produced by urban heat islands often report that existing health problems, such as cardiovascular disease and asthma, are exacerbated, or that they are impacted by a range of new problems including stroke, dehydration, and heat exhaustion (Shahmohamadi et al. 2011).

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