The Third Oregon Climate Assessment Report

January 2017

Oregon Climate Change Research Institute

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As per Oregon State Legislature House Bill 3543

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RECOMMENDED CITATION:
Dalton, M.M., K.D. Dello, L. Hawkins, P.W. Mote, and D.E. Rupp (2017) *The Third Oregon Climate Assessment Report*, Oregon Climate Change Research Institute, College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, OR.

Cover photo: Snowy Trees by Emily Wisler

ACKNOWLEDGMENTS

We give many thanks to all the subject matter expert reviewers for their helpful comments on various sections and chapters: John Abatzoglou (University of Idaho), Dominique Bachelet (Conservation Biology Institute), Jeffrey Bethel (Oregon State University), Karin Bumbaco (Office of the Washington State Climatologist), Francis Chan (Oregon State University), Laurie Houston (Oregon State University), Kathy Lynn (University of Oregon), Guillaume Mauger (University of Washington), Holly Prendeville (US Forest Service), Gabrielle Roesch-McNally (US Forest Service), Peter Ruggiero (Oregon State University), Katherine Serafin (Oregon State University), Sarah Shafer (US Geological Survey), John Stevenson (Oregon State University), Beatrice Van Horne (US Forest Service), Julie Vano (National Center for Atmospheric Research), Laurie Weitkamp (Northwest Fisheries Science Center), Beth Willhite (US Forest Service), Emily York (Oregon Health Authority).

We give thanks also to the staff at the Oregon Climate Change Research Institute, in particular to Emily Wisler for her assistance in citation management and layout, and to Susan Osredker for acquiring copyright permissions. We acknowledge funding for this report from the State of Oregon and from the College of Earth, Ocean and Atmospheric Sciences at Oregon State University. Credit is due to Ian Dalton for clever and assiduous copyediting.

This report is dedicated to two young boys in the hope that their future may benefit from our knowledge and our actions.

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Legislative Summary

Burning fossil fuels to run our factories, heat our homes, and drive our cars produces heat-trapping gases that unequivocally warm the planet. Effects of warming are evident on physical, biological, and human and managed systems across the globe, and here in Oregon.

This report presents strengthening evidence that Oregon is already experiencing the effects of climate change.

The key climate risks facing Oregon remain the same as before

Effects of declining snowpack include lower summer streamflow and soil moisture, as illustrated by 2015's record low snowpack. Forest disturbances (wildfires, drought, and insect outbreaks) transform forests. Rising sea levels will exacerbate coastal flooding and erosion hazards, while changes in the ocean will alter its ecosystems. For agriculture, beneficial longer growing seasons may be offset, for some places and crops, by insufficient water and by insect and disease stress.

Key climate risks vary across Oregon

On **the Coast**, sea level rise will increase the risk of coastal erosion and flooding; warming waters and ocean acidification will degrade estuarine habitat crucial for salmon and shellfish and negatively affect nearshore fisheries; and forest vegetation in the Coast Range may shift. In the **Willamette Valley**, declining snowpack, earlier snowmelt, and greater summer water demand may increase summer water scarcity; and wildfire activity is expected to increase. In the **Cascade Range**, diminishing snowpack leads to larger, earlier peak flow events and lower summer low flows; more wildfires and changes in climate suitability may shift forest vegetation types. In **Eastern Oregon**, declining snowpack has similar effects; warming streams will limit ranges for salmon and trout; disturbances and changes in suitability are expected to shift forest vegetation; and rangeland and sagebrush habitat may experience greater invasion of non-native weeds and more frequent fires.

Scientists formally linked climate trends and events to human activity

Human emissions of greenhouse gases dominated the warming trend of average annual temperature in the Pacific Northwest during 1901–2012, contributed an additional 16,000 square miles of wildfire burned area in the western United States during 1984–2015, contributed to the 2014–2015 snow drought in Oregon through warmer temperatures, and made Oregon's coastal waters more acidic in 2013.

The 2015 snow drought foreshadows mid-century normal conditions

Oregon's warmest winter on record, 2015, was so warm that the near-normal amount of precipitation fell as rain in most of the mountains, resulting in record low snowpack and widespread drought declarations. Impacts included insufficient water supply in reservoirs, the most severe wildfire season in the Pacific Northwest's history, warm streams that reduced salmon returns, and agricultural crop losses. With continued warming, this type of drought is expected to occur more often in the future.

Oregon will continue to warm

Under continued increasing greenhouse gas emissions, Oregon's climate is projected to warm on average 3–7°F by the 2050s and 5–11°F by the 2080s. If greenhouse gas emissions level off by mid-century, warming would be limited to 2–5°F by the 2050s and 2–7°F by the 2080s. Annual precipitation is projected to increase slightly, although with a high degree of uncertainty. Summers are expected to warm more than the annual average and are likely to become drier. Extreme heat and precipitation events are expected to become more frequent.

Warming is already changing hydrology

Summer low flows have decreased and streamflow timing has shifted earlier at many sites in the Pacific Northwest. Driven by loss of snowpack and drier summers, these trends are expected to continue in the future, particularly for snow-dominated basins. As snowfall gives way to rainfall, fall and winter flood risk is also expected to increase in most basins, particularly in mixed rain-snow basins with near-freezing winter temperatures. Future changes in water supply and demand are expected to strain the ability of existing infrastructure and operations to meet all the varied water needs of Oregonians.

Oregon's coast will face more flooding and erosion hazards as sea levels rise
At Newport, sea level is projected to rise by 12 to 47 inches under a high emissions pathway by the end of the 21st century. Such sea levels would place thousands of Oregonians and homes, and over 100 miles of roads in Oregon, at risk of inundation from annual flood events reaching 4 feet above high tide.

Changes in the ocean environment will result in substantial ecosystem shifts
Greater ocean acidity, less dissolved oxygen, and warmer water temperatures are expected in Oregon's coastal waters. Ocean acidification is already challenging shell-forming species, such as oysters and crabs, and disruptive conditions are expected to be commonplace in Oregon coastal surface waters by mid-century. These conditions are expected to cause cascading effects throughout the entire marine food web, particularly for shellfish and Pacific salmon, which are of important economic and cultural value.

Forests are changing
Changing climate will shift ideal growing zones for many important tree species and vegetation types, with conifer forests shifting to mixed-forests west of the Cascade Range and subalpine forests shrinking. The observed increase in wildfire activity is partially due to human-caused climate change; increasing wildfire activity is expected under future warming. Mountain pine beetle, western spruce budworm, and Swiss needle cast remain major disturbance agents in Oregon's forests that are expected to expand. Managing forests to reduce wildfire hazards, to promote forests resilient to insects and diseases, and to maintain a suitable habitat for Oregon's wildlife will be critical in the future.

Some crops will benefit, but long-term outcomes for agriculture are complex
Over the next few decades, warming winters, expanding growing seasons, and carbon dioxide enrichment may boost yields for some Oregon crops and create opportunities to grow new crops and varieties. Such benefits hinge on having adequate water supply, which is projected to dwindle, especially in areas that rely on snowpack. For other crops such as tree fruits, warming winters may prevent adequate chilling needed for a healthy crop yield. In the long-term, increased heat and drought stress, water shortage, and pressure from pests and diseases may supersede the positive benefits of increased crop yield. Improved irrigation water management strategies will be necessary to handle heat and drought stress and longer growing seasons. Consideration of alternative crops and varieties and farm management strategies will be important to maintain reliable operations under a changing climate.

The health of Oregonians is threatened
More frequent heat waves are expected to increase heat-related illness and death. More frequent wildfires and poor air quality are expected to increase respiratory illnesses. Warmth and extreme precipitation are expected to increase the risk of exposure to some vector- and water-borne diseases. Access to sufficient, safe, and nutritious food may be jeopardized by climate change. Extreme climate or weather events can diminish mental health. Certain populations will be disproportionately affected by such climate-related health impacts. However, adaptation strategies may reduce the projected adverse health outcomes.

Climate change uniquely affects the culture, sovereignty, health, economy, and ways of life of American Indian tribes
Changes in terrestrial and aquatic ecosystems will affect resources and habitats that are important for the sovereignty, culture, economy, and community health of many American Indian tribes. Tribes that depend upon these ecosystems, both on and off reservation, are among the first to experience the impacts of climate change. Of particular concern are changes in the availability and timing of traditional foods such as salmon, shellfish, and berries, and other plant and animal species important to tribes' traditional way of life.

Climate change will impact Oregon's economy, but more research is needed
Some economic assessments have been done at national and global levels, but more information is needed about the regional, state, and local economic impacts of climate change.

Chapter 1: Introduction

Oregon is warming and the consequences are, and will be, notable.

Three years have past since the previous Oregon Climate Assessment Report (Dalton *et al.*, 2013). These years have been the three warmest years globally (NOAA, 2016), and the last three decades have been the warmest three decades (IPCC, 2013). The Earth's climate undoubtedly is warming. The warming observed since the mid-20th century is largely due to an increase in greenhouse gas concentrations caused by human activities (IPCC, 2013).

Oregon is warming, too. Consequences of this warming are already being felt by Oregonians. Snowpack is declining, summer streamflow is lowering, wildfire activity is increasing, sea level is rising, and coastal waters are acidifying. Such consequences and others are expected to continue into the decades to come. Indeed, the year 2015, in which global and Oregon temperatures were the warmest on record, foreshadows what typical conditions may look like by the middle of this century.

A majority of Oregonians thinks that global warming is happening and is worried.

The scientific evidence is overwhelming that human-caused climate change is happening (IPCC, 2013), a conclusion affirmed by 97% of climate scientists (Cook *et al.*, 2016). Despite such a consensus, only two-thirds (67%) of Oregonians believe that climate change is happening, and only about half (51%) believe that it is caused by human activities (Howe *et al.*, 2015). Just under half (47%) of Oregonians believe that most scientists think global warming is happening. However, a majority (57%) of Oregonians is indeed worried about global warming. Although only about a third (36%) think that global warming will harm themselves personally, two-thirds (67%) think that global warming will harm future generations (Howe *et al.*, 2015).

Adaptation is necessary, as mitigation alone will not prevent serious impacts.

In order to avoid negative impacts, now and in the future, we must both mitigate climate change and adapt to climate change. That is, we must try to reduce or even eliminate greenhouse gas emissions, and we must make preparations and adjustments that will be needed to meet new environmental conditions, doing so at all levels of government and society, from the highest international agreements down to our own personal actions (Bierbaum *et al.*, 2014). International and local mitigation efforts are already underway, but these are not yet sufficient to limit global warming to 2°C (3.6°F) above pre-industrial levels and to avoid the serious impacts of climate change. Accounting for the future emissions reduction pledges by countries participating in the 2015 Paris Agreement, the globe would still likely warm by 3°C (5.4°F) above pre-industrial levels by 2100 (Le Quéré *et al.*, 2016).

Oregon is making an effort to reduce greenhouse gas emissions.

In Oregon, greenhouse gas emissions peaked in 1999 and declined about 12% between 2005 and 2012 (Oregon Global Warming Commission, 2015). However, because Oregon's emissions by the year 2020 are projected to be higher than the target set by the state legislature, additional actions to reduce greenhouse gas emissions may be needed (Oregon Global Warming Commission, 2015). Oregon is a leader in renewable energy policies; its government, by passing Senate Bill 1547, set a goal to become the first state to be coal-free by 2030 (Oregon Congress Senate, 2016). The city of Portland also is a leader in community mitigation efforts; it has set an ambitious goal of an 80% reduction in greenhouse gas emissions by 2050 compared to 1990 levels (Geiling, 2015; *World Wildlife Fund*, 2015).

Oregon must do more to adapt to climate changes already underway.

Climate change is happening here, now. The climate in our dear state is already changing and will continue to change. We know much about the expected effects of climate change that Oregon is likely to see. We must strive, in our governments and in our communities, to build resilience to climate change, and we must do so now. Although building resilience could be costly, it could be even more costly to suffer the losses and the damage that come from not being prepared for new conditions. A few state agencies, such as the Oregon Health Authority and the Oregon Department of Transportation, have already begun planning; and there are opportunities to build preparedness for climate change into existing planning efforts such as the Oregon Water Resources Strategy and the Natural Hazards Mitigation Plan. Furthermore, implementing climate adaptation actions can be compatible with other societal goals, such as sustainable development and disaster risk reduction (Bierbaum *et al.*, 2014).

What this report covers

In this third Oregon Climate Assessment Report (OCAR3), we build on the previous two assessment reports (Dalton *et al.*, 2013; Dello and Mote, 2010) by summarizing recent published literature between 2013 and 2016 on climate change science and impacts as it relates to the state of Oregon. The breadth of published literature from the past few years generally covers the breadth of topics discussed in previous assessments; however, the depth of the current assessment is intentionally less than in previous assessments as the previous assessments provide rich content that is still pertinent and useful. As such, the reader is encouraged to read the relevant sections of the previous reports for greater background and depth.

Key findings from previous assessments are largely confirmed, but more regionally specific details are included. The bulk of this third assessment covers the three key climate change risks facing Oregon and the Pacific Northwest, namely water resources, forest ecosystems, and coastal issues (Dalton *et al.*, 2013). Shorter chapters summarize recent literature about climate changes in Oregon and impacts on agriculture and human health. Where a comprehensive chapter was devoted to tribal issues in the second assessment (Lynn *et al.*, 2013), here updated information relevant to tribes is incorporated within the other chapters of OCAR3. Economic analyses that exist are included within various relevant chapters. In addition to the topical-based chapters, there is a short chapter summarizing the key climate-related risks facing different regions within Oregon including the Oregon Coast, the Willamette Valley, the Cascade Range, and eastern Oregon.

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Chapter 2: Climate Change in Oregon

Summary

Oregon's climate has already warmed considerably, and the cause is most likely rising greenhouse gases. Future warming depends on how much global greenhouse gas emissions rise. Under continued increasing greenhouse gas emissions, Oregon's climate is expected to warm on average 3–7°F by the 2050s and 5–11°F on average by the 2080s. However, under scenarios that level off greenhouse gas emission by mid-century, Oregon's climate is expected to warm 2–5°F by the 2050s and 2–7°F by the 2080s. Annual precipitation is projected to increase slightly, although climate scientists have less confidence in precipitation projections than temperature projections. Summers are expected to warm more than the annual average and are likely to become drier. Extreme heat and extreme precipitation events are expected to become more frequent. In many respects, 2015 was a notable year in its record warmth and snowpack drought that resembles what climate model projections indicate would be normal conditions by middle of this century.

Introduction

Warming, already apparent in Oregon, is likely due to rising greenhouse gas concentrations caused by human activities. Future warming depends on how much global greenhouse has emissions rise. Under scenarios aligned with the Paris agreement of 2015 (and Oregon's own greenhouse gas emissions goals), it may be possible to limit warming to just another 1–3°F. Under continued increasing greenhouse gas emission, however, Oregon's climate is expected to continue to warm throughout this century and beyond. In general, Oregon can expect warmer temperatures year round with greater warming during the summer. A modest increase in annual precipitation is expected along with precipitation decreases in summer and increases during winter, spring, and fall. Precipitation projections are more uncertain than temperature projections.

Future climate projections in this chapter and most impacts analyses in subsequent chapters are based on the latest global climate models from the 5th Coupled Model Intercomparison Project (CMIP5) (Taylor *et al.*, 2012) forced with future emissions pathways called representative concentration pathways (RCPs) (van Vuuren *et al.*, 2011) (fig. 2.1). Under the very low emissions pathway (RCP 2.6), it could be possible to limit global warming to 2°C in line with the 2015 Paris agreement (UNFCCC, 2015), but net global emissions would need to be negative by 2100. The two most commonly cited future emissions pathways are the low emissions pathway (RCP 4.5), representing a moderate effort to reduce global greenhouse gas emissions which peak near mid-century then decline, and a high emissions pathway (RCP 8.5), representing a business-as-usual continuation of emissions throughout the 21st century. The previous generation of global climate models and emissions scenarios (SRES) is occasionally used in recent literature cited in this report. In addition, some recent economic analyses have taken advantage of a coordinated policy scenario framework using a reference scenario (REF) greater than RCP 8.5 and two mitigation policy scenarios (POL), one equivalent to RCP 4.5 and the other between RCP 4.5 and RCP 2.6 (Paltsev *et al.*, 2013). Table 2.1 gives a comparison between the SRES and RCP and REF/POL emissions pathways.

Figure 2.1 The representative concentration pathways (RCPs) are numbered according to the change in radiative forcing (from +2.6 to +8.5 watts per square meter) that results by 2100. This figure shows annual carbon emissions (top) and carbon dioxide equivalent levels in the atmosphere (bottom). (Figure source: Walsh *et al.*, 2014)

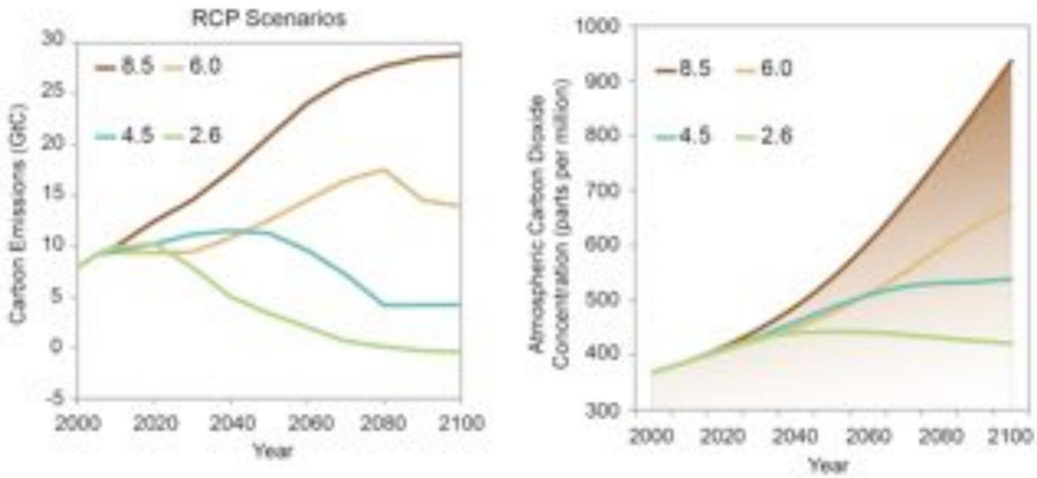


Table 2.1. Descriptors for emissions scenarios used in this report.

Descriptor	Scenario
Very Low	RCP 2.6, POL 3.7
Low	RCP 4.5, SRES B1, POL 4.5
Medium	RCP 6.0, SRES A1B
Medium High	SRES A2
High	RCP 8.5, SRES A1FI
Very High	REF 10

Sources of Variability

Year-to-year variability in Oregon's climate is influenced by the El Niño–Southern Oscillation (ENSO)— linked to variations in the atmosphere and ocean in the tropical Pacific Ocean—and other patterns of North Pacific variability (Abatzoglou *et al.*, 2014a; Halpert and Ropelewski, 1992; Newman *et al.*, 2016). The warm ENSO phase—El Niño—tilts the odds for a warmer, drier than normal winter in Washington whereas the cool phase—La Niña—makes a colder, wetter than normal winter more likely; the opposite is true for California. However, not every El Niño is alike, nor is its impact on Oregon's climate. In particular, in some El Niño years Oregon's winter climate is a little warmer and drier than usual like Washington's, in other El Niño years it's in the normal range, and occasionally southern Oregon is wetter than usual along with California. There is some evidence suggesting that the way it goes may depend upon the characteristics of El Niño itself—that is, upon where along the equator the sea surface temperatures are farthest from normal (Capotondi *et al.*, 2015; Yu *et al.*, 2012). However, the number of events of each type may be too small to draw robust conclusions.

Under a warmer climate, future changes in ENSO activity are uncertain as some models project ENSO amplitude to increase and others project it to decrease. The response of ENSO in CMIP5 climate models to global warming depends on the pattern of sea surface warming in the Tropical Pacific (Zheng *et al.*, 2016). Models with greater warming in the eastern Tropical Pacific, similar to the pattern during El Niño events, displayed an increase in ENSO amplitude in the future (Zheng *et al.*, 2016). Greater warming of the eastern tropical Pacific in a suite of climate models results in increases in the occurrence of extreme El Niño events (Cai *et al.*, 2014), which also contributes to greater occurrence of subsequent extreme La Niña events (Cai *et al.*, 2015). Furthermore, one study has shown that ENSO's remote connections between tropical Pacific sea surface temperature patterns and West Coast rainfall may intensify (Zhou *et al.*, 2014).

The dominant pattern of sea surface temperature in the North Pacific Ocean—the so-called Pacific Decadal Oscillation (PDO)—has been an important research topic for both scientists and resource managers alike. A consensus following the last 15 years of research has emerged that the PDO is not a single, independent phenomenon, but rather a combination of different processes including ENSO (Newman *et al.*, 2016). How the PDO might change under a warmer climate remains unclear; however, one study using a single climate model shows PDO amplitude weakening and the time scale shortening under a warmer climate (Zhang and Delworth, 2016).

Mean Temperature

Oregon's mean temperature warmed by 2.2°F per century during 1895–2015 (fig. 2.2). In fact, 2015 was the warmest year on record in Oregon (NOAA, 2016). The Pacific Northwest (Washington, Oregon, Idaho, and western Montana) warmed by about 1.1°F to 1.5°F between 1901 and 2012 largely due to increases in greenhouse gas concentrations (Abatzoglou *et al.*, 2014a). Other sources of regional climate variability cannot account for the observed long-term upward trend (Abatzoglou *et al.*, 2014b; Johnstone and Mantua, 2014). Warming in the Pacific Northwest has accelerated: trends in recent decades from the 1970s onward are larger than trends over the last century (Abatzoglou *et al.*, 2014a).

Going forward, Oregon's mean annual temperature is projected to increase by 2.1°–10.7°F by the 2080s (2070–2099 average) compared to the historical baseline (1970–1999 average) (fig. 2.2; table 2.2). The range in future temperature projections reflects the different climate model responses across both the low and high emissions pathways. Under the low emissions pathway (RCP 4.5), mean annual temperature in Oregon is projected to increase on average 3.6°F with a range of 1.8°–5.4°F by the 2050s and 4.6°F on average with a range of 2.1°–6.7°F by the 2080s (table 2). Under the high emissions pathway (RCP 8.5), annual temperature increases are higher: 5.0°F (2.9°–6.9°F) by the 2050s and 8.2°F (4.8°–10.7°F) by the 2080s. Summers are projected to warm more than other seasons (table 2.2), with average warming of 10.2°F (6.5°–13.9°F) by the 2080s under the high emissions pathway (RCP 8.5).

Figure 2.2 Projected changes in Oregon's mean annual temperature (top), winter (bottom left), and summer (bottom right) temperature from the baseline 1970–1999 under a low (RCP 4.5) and a high (RCP 8.5) future emissions pathway. The thicker solid lines depict the mean annual temperature of 35 climate models while the shading depicts the minimum and maximum annual temperatures from the 35 models. The mean, minimum, and maximum have been smoothed to emphasize long-term (greater than year-to-year) variability. Orange shading indicates where RCP 4.5 and RCP 8.5 overlap. Temperature observations using NCEI data for Oregon is shown by the thin black line (Figure source: David Rupp; data source: Rupp *et al.*, 2016)

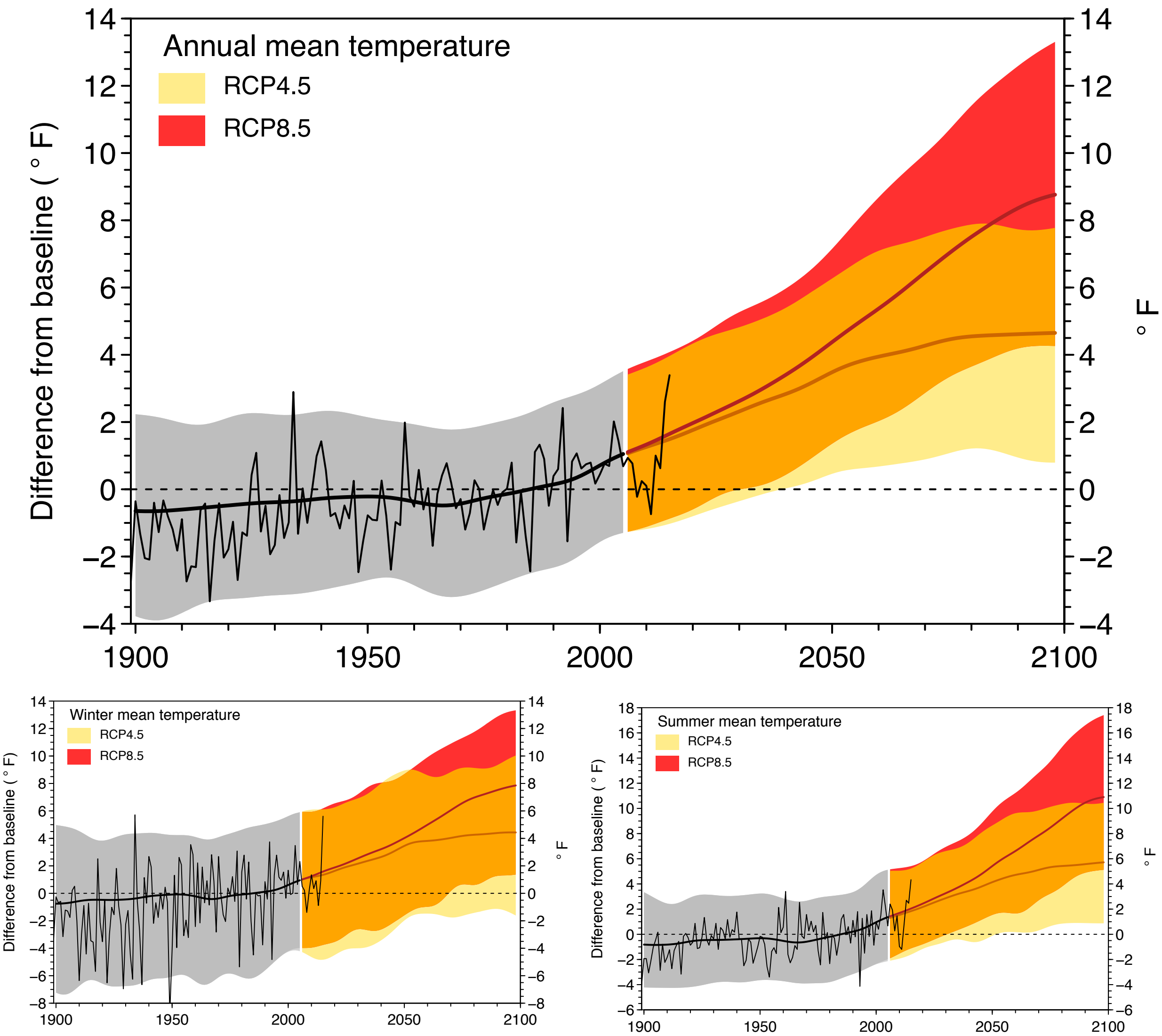


Table 2.2 Projected future changes in Oregon's mean annual and seasonal temperature (°F) from the historical baseline (1970–1999) for mid- and late-21st century under a low (RCP 4.5) and a high (RCP 8.5) future emissions pathway. Given are the average changes (bolded) from 35 global climate models and the 5th to 95th percentile range across the 35 models. (Data source: Rupp *et al.*, 2016)

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

Extreme Temperature

During 1920–2012, trends in the magnitude of the hottest day of the year varied across Oregon; some sites had warming and others cooling trends (Abatzoglou *et al.*, 2014a). Cooling trends were observed because many of the hottest day records were set in the 1930s during widespread drought (Abatzoglou and Barbero, 2014). However, warming trends were apparent in the coldest night of the year at all sites across Oregon and were quite large, exceeding 1.8°F per decade during 1970–2012 (Abatzoglou *et al.*, 2014a). During 1930–2010, many stations in the Pacific Northwest experienced increasing trends in extreme heat events defined by minimum temperature thresholds (Oswald and Rood, 2014), consistent with previous findings (Mote *et al.*, 2013).

In the future, extreme heat events are expected to increase in frequency, duration, and intensity due to warming temperatures. In fact, the hottest days in summer are projected to warm by 1°–2°F more than the change in mean summer temperature over the Pacific Northwest by late-century under the high emissions pathway (RCP 8.5) (Rupp, 2014). However, synoptic conditions that drive extreme heat events in the Pacific Northwest, such as upper-level ridges—or large areas of high atmospheric pressure—and strong offshore flow, are projected to weaken (Brewer and Mass, 2016a). Most CMIP5 climate models suggest reductions in ridging over the eastern Pacific during summer (Brewer and Mass, 2016b) leading to a weakening of the strong offshore flow events that result in heat waves for western Oregon and Washington by late-century under the high emissions pathway (RCP 8.5) (Brewer and Mass, 2016a). Increased frequency of ridging, however, is projected by most models for inland of the coast, which could enhance near-surface warming events in the western United States (Brewer and Mass, 2016b). These results suggest that increases in extreme heat events are likely to be greater for eastern Oregon than for western Oregon (Brewer and Mass, 2016a).

Precipitation

During 1895–2015, annual precipitation totals averaged over the state of Oregon ranged from 22” in 1930 to about 49” in 1996 with hardly a trend—0.73” increase per century—in annual totals (NOAA, 2016). Likewise, averaged over the Pacific Northwest, there was no significant trend in annual precipitation from 1901–2012, although a positive trend was noted for spring. Interannual-to-decadal variability dominated any long-term signal in precipitation (Abatzoglou *et al.*, 2014a).

Future precipitation trends are expected to continue to be dominated by large natural variability (fig. 2.3). Still, annual precipitation in Oregon is projected to increase on average by 1.9% by the 2050s, and 3.4% by the 2080s under the low emissions pathway (RCP 4.5). Under the high emissions pathway, increases in annual precipitation are a bit larger for each time period: 2.7%, and 6.3%, respectively. However, the range of responses from individual global climate models surrounds zero (table 2.3). Larger changes are projected for seasonal precipitation. Oregon’s already dry summers are projected to become drier while winter, spring, and fall are projected to become wetter, albeit some models project increases and others project decreases in each season (table 2.3). Climate models that are better at simulating historical climate in the Pacific Northwest (Rupp *et al.*, 2013) project a larger increase in precipitation during October–January than climate models with less skill (Rupp *et al.*, 2016). However, climate models’ representation of changes in Northern Hemisphere winds under global warming may be overestimated, on average, suggesting that future winter wetting along the West Coast may actually be less than the average of the wetting projected by CMIP5 models (Simpson *et al.*, 2015).

Figure 2.3 Projected changes in Oregon's annual total precipitation (top), winter (bottom left), and summer (bottom right) precipitation from the baseline 1970–1999 under a low (RCP 4.5) and a high (RCP 8.5) future emissions pathway. The thicker solid lines depict the mean annual precipitation of 35 climate models while the shading depicts the minimum and maximum annual precipitation from the 35 models. The mean, minimum, and maximum have been smoothed to emphasize long-term (greater than year-to-year) variability. Medium blue shading indicates where RCP 4.5 and RCP 8.5 overlap. Precipitation observations using NCEI data for Oregon is shown by the think black line. (Figure source: David Rupp; data source: Rupp *et al.*, 2016)

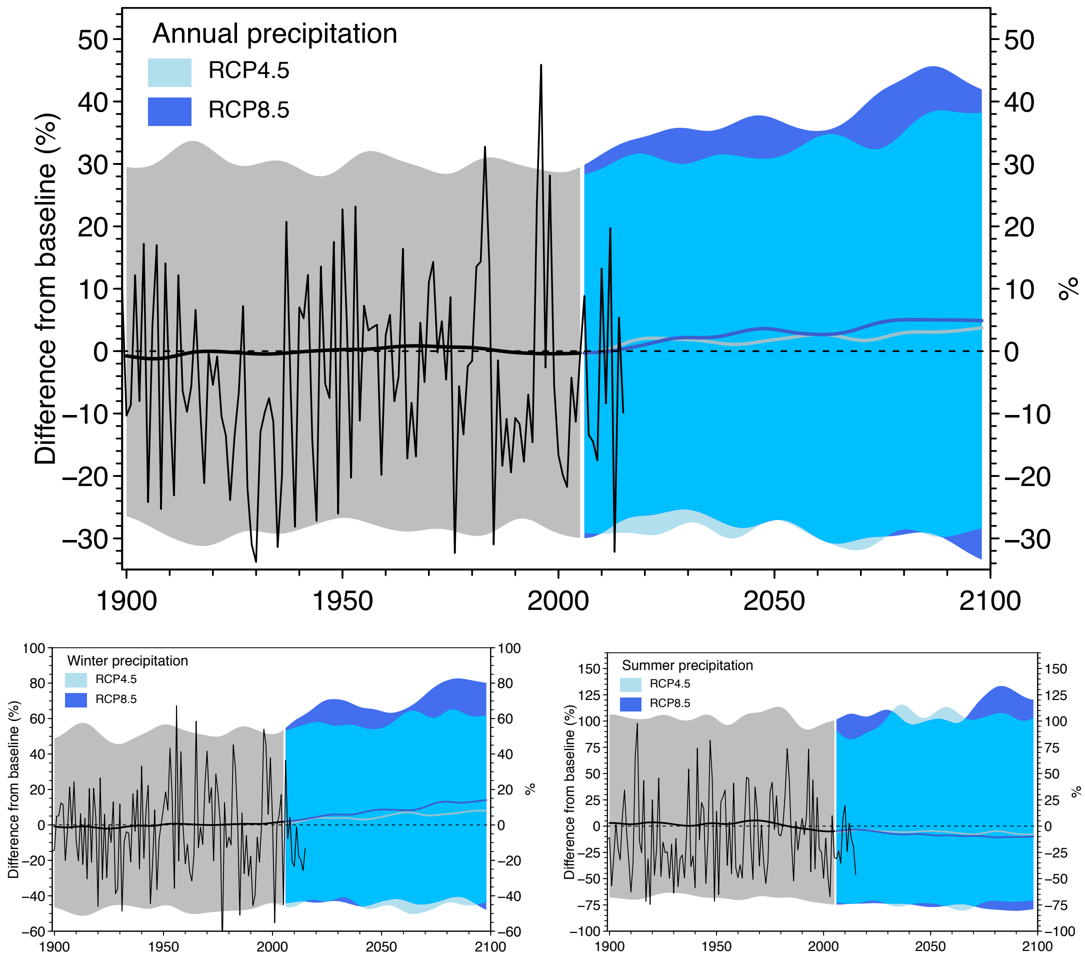


Table 2.3 Projected future relative changes in Oregon's total annual and seasonal precipitation (%) from the historical baseline (1970–1999) for mid- and late-21st century under a low (RCP 4.5) and a high (RCP 8.5) future emissions pathway. Given are the average changes (bolded) from 35 global climate models and the 5th to 95th percentile range across the 35 models. (Data source: Rupp *et al.*, 2016)

	2050s		**2080s**	
	Low	High	Low	High
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 (DJF)	**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 (MAM)	**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 (JJA)	**−6.3%** (−28.5, 16.1)	**−8.7%** (−33.1, 22.5)	**−4.6%** (−24.2, 22.3)	**−7.7%** (−38.7, 33.5)
Fall (SON)	**0.5%** (−17.0, 14.4)	**−0.8%** (−17.1, 14.9)	**1.5%** (−15.0, 18.1)	**1.9%** (−17.2, 24.2)

Extreme Precipitation

Extreme precipitation events in the Pacific Northwest are governed both by atmospheric circulation and by how it interacts with complex topography (Parker and Abatzoglou, 2016). Atmospheric rivers—long, narrow swaths of warm, moist air that carry large amounts of water vapor from the tropics to mid-latitudes—generally result in coherent extreme precipitation events west of the Cascade Range, while closed low pressure systems often lead to isolated precipitation extremes east of the Cascade Range (Parker and Abatzoglou, 2016). Detection of past trends in extreme precipitation events across Oregon and the Pacific Northwest has depended on the location, time frame, and metric considered; some areas have seen increases and others decreases (Mote *et al.*, 2013). Two recent papers evaluating past extreme precipitation events over the Pacific Northwest using different metrics and time periods concluded that the frequency of extreme precipitation events did not change substantially (Hoerling *et al.*, 2016; Janssen *et al.*, 2014).

In the future, however, extreme precipitation events are expected to become slightly more frequent or intense in the Pacific Northwest. Under the high emissions pathway (RCP 8.5), both global and regional climate modeling project increases in the frequency of 2-day duration events with a 5-year return interval—that is, such events that have a 20% chance of occurring in a given year—on the order of a few more days per year by the end of the 21st century over the Pacific Northwest (Janssen *et al.*, 2014; Wang and Kotamarthi, 2015). Under a high emissions pathway (RCP 8.5), the amount of precipitation falling on extreme precipitation days is projected to increase by 15%–39% along the West Coast compared with an 11%–18% increase in winter mean precipitation (Warner *et al.*, 2015). Multiple regional climate modeling simulations over the Willamette River Basin, however, project only a slight increase in the magnitudes of the 2-year and 25-year extreme daily precipitation event by mid-century under a medium-high (SRES A2) emissions pathway (Halmstad *et al.*, 2013).

Box 2.1: The 2015 snow drought as a glimpse into Oregon's future

In 2015, Oregon was the warmest it has ever been since record keeping began in 1895 (NOAA, 2017). Precipitation during the winter of that year was near normal, but winter temperatures that were 5–6°F above average caused the precipitation that did fall to fall as rain instead of snow, reducing mountain snowpack accumulation (Mote *et al.*, 2016). This resulted in record low snowpack across the state, earning official drought declarations for 25 of Oregon's 36 counties (fig. 2.4).

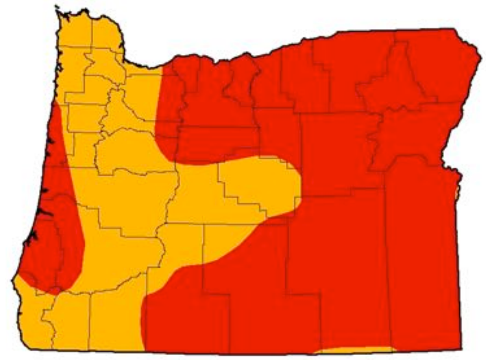


Figure 2.4. US Drought Monitor for August 25, 2015. All of Oregon was in severe (orange) or extreme (red) drought. Map courtesy of NDMC-UNL.

Drought impacts across Oregon were widespread and diverse:

- Farmers in eastern Oregon's Treasure Valley received a third of their normal irrigation water because the Owyhee reservoir received inadequate supply for the third year in a row (Stevenson, 2016).
- The 2015 fire season was the most severe in the Pacific Northwest's recorded history with more than $560 million in fire suppression costs (Sexton *et al.*, 2016).
- After not opening at all in 2014, Mount Ashland Ski Area had to make snow in order to open in 2015 (Stevenson, 2016).
- Detroit Lake saw a 26% decrease in visitation due to low water levels and unusable boat ramps (Wisler, 2016).
- People near the Upper Klamath Lake were warned not to touch the water as algal blooms that thrived in the low flows and warm waters produced extremely high toxin levels (Marris, 2015).
- More than half of the spring spawning salmon in the Columbia River perished, likely due to a disease that thrived in the unusually warm waters (Fears, 2015).
- In Washington, the 2015 snow drought resulted in crop losses amounting to an estimated $212.4 million for wheat, $86.5 million for apples, $13.9 million for raspberries, and $10.6 million for blueberries (McLain and Hancock, 2015). Similar analysis is not available for Oregon.

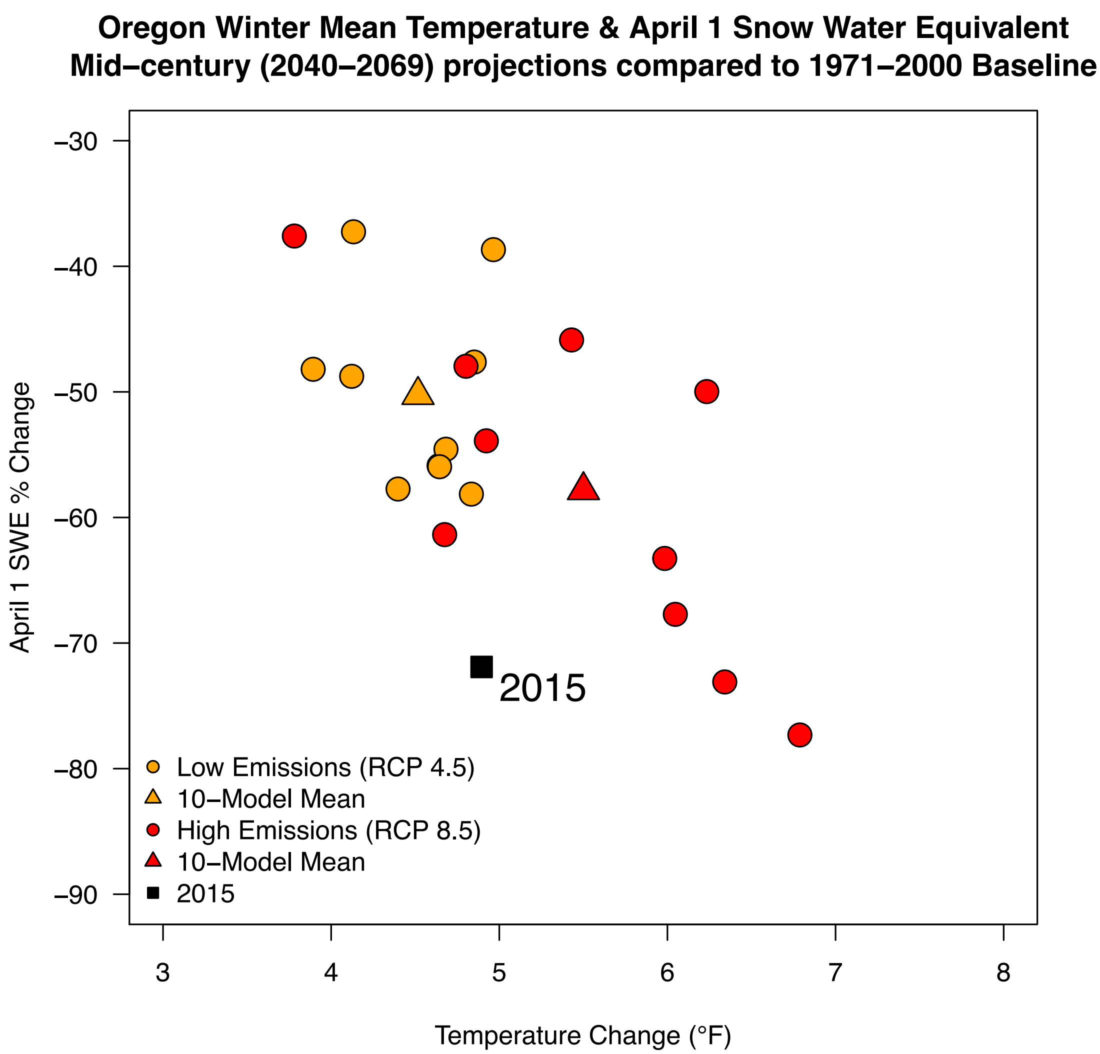
The West Coast–wide drought developed alongside a naturally-driven large, persistent high-pressure ridge (Wise, 2016). However, anthropogenic warming exacerbated the drought, particularly in Oregon and Washington (Mote *et al.*, 2016; Williams *et al.*, 2015). The 2015 snow drought in Oregon and Washington was also influenced to a larger degree by the persistent warm sea surface temperatures off the Pacific Northwest's coast (Mote *et al.*, 2016).

This mass of warm water off the coast—coined "the Blob"—began off the coast of southeast Alaska in fall of 2013 and, being maintained by the persistent high-pressure ridge, spread toward the West Coast in spring of 2014 and persisted through 2015 (Bond *et al.*, 2015). This was the largest ever recorded multi-year marine heat wave in the northeast Pacific (Di Lorenzo and Mantua, 2016). Remote connections between tropical Pacific and northeast Pacific sea surface temperatures during the weak El Niño of 2014–

15, and strong El Niño of 2015–16 helped this "blob" persist (Di Lorenzo and Mantua, 2016; Hu *et al.*, 2016).

Oregon's temperatures, precipitation, and snowpack in 2015 are illustrative of conditions that, according to climate model projections, may be considered "normal" by mid-century (fig. 2.5). With continued warming, this type of drought in which snowpack is low, but precipitation is near normal, should be expected more often in the future. In fact, for each 1.8°F of warming, peak snow water equivalent in the Cascade Range can be expected to decline 22%–30% (Cooper *et al.*, 2016). The 2015 drought in Oregon provided a salient test on the capacity of existing systems to tolerate such drought and gave insights into potential future adaptation priorities.

Figure 2.5 Projected future changes in winter (DJF) mean temperature and April 1 snow water equivalent (SWE) averaged over Oregon for mid-century (2040–2069) compared to the 1971–2000 historical baseline. The departure of year 2015 from the 1971–2000 baseline is noted. (Figure source: Meghan Dalton; data source: Mote *et al.* 2016, updated Livneh *et al.*, 2015, and http://climate.nkn.uidaho.edu/IntegratedScenarios/)



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Chapter 3: Water Resources

Summary

Warming temperatures, changes in precipitation, and decreasing snowpack are already having, and will continue to have, significant impacts on hydrology and water resources in Oregon. Changes in the amount and seasonal timing of water in rivers and streams, changes in winter flood risk, and changes in summer extreme low flows are expected under future climate change. These hydrologic impacts will vary across watersheds. Watersheds that accumulate winter snowpack are most vulnerable to earlier peak streamflow timing. Watersheds with winter temperatures near the freezing level, such as intermediate to low elevations in the Oregon Cascades are particularly vulnerable. Projected future changes in water supply and demand are expected to strain the ability of existing infrastructure and operations to meet the many and varied water needs of Oregonians. In addition, changes in streamflow timing and amount and warming streams are expected to degrade freshwater fish habitat.

Introduction

Warming temperatures, changes in precipitation, and decreasing snowpack are already having, and will continue to have, significant impacts on hydrology and water resources in Oregon. Changes in the amount and seasonal timing of water in rivers and streams, changes in winter flood risk, and changes in summer extreme low flows are expected under a future warmer climate. These hydrologic impacts will vary across watersheds, depending largely on whether the watershed receives precipitation mostly as rain or snow, or a combination of both. Projected future changes in water supply and demand are expected to strain the ability of existing infrastructure and operations to meet the many and varied water needs of Oregonians, namely irrigation, municipal drinking water, industrial activities, hydropower, flood control, fisheries, wildlife, and recreation (Reclamation, 2016).

This chapter provides an overview of potential changes in snowpack, streamflow amount and timing, groundwater, and atmospheric rivers. It then discusses flood and drought risks, and concludes with implications these changes could have on water resources management and fish habitat.

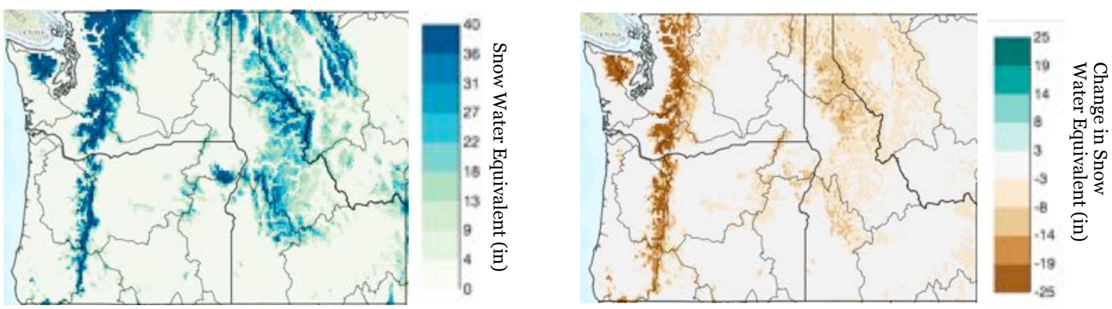
Snowpack

As the climate warms, precipitation will fall more as rain and less as snow. By mid-century under the high emissions pathway (RCP 8.5), 30% of the area of the western United States normally conducive to snowfall is projected to become part of the rain-snow transition zone, including the Cascade Range and the Blue Mountains (Klos *et al.*, 2014). Likewise, areas presently in the rain-snow transition zone, including the Klamath Mountains, are projected to become largely rain-dominated (Klos *et al.*, 2014). These projected changes in precipitation type represent a fundamental hydrologic regime shift. By the 2080s, all of Oregon, except for parts of the Blue Mountains, is projected to become rain-dominant (Raymondi *et al.*, 2013).

Indeed, snow covers the ground for a much shorter season than it used to all across the United States (Knowles, 2015). In the western United States, the annual count of snow-covered days is projected to decrease on average by 25 days by 2011–2050 compared to 1961–2005 under the high emissions pathway (RCP 8.5) (Naz *et al.*, 2016). In Oregon, these decreases would be predominantly in the Cascade Range and the Blue Mountains. Declines in annual snowfall amount and frequency are projected for the western United States (Danco *et al.*, 2016; Lute *et al.*, 2015) along with more frequent low-snowfall years and less frequent high-snowfall years (Lute *et al.*, 2015).

A dependable mountain snowpack is crucial for annual water supply in many watersheds in Oregon (Raymondi *et al.*, 2013). Spring snowpack, measured on April 1 by the snow water equivalent (SWE)—the amount of water contained in the snowpack—decreased at nearly all stations in Oregon over the period 1955–2015 with an average decline of about 37% (Mote and Sharp, 2015). Going forward, SWE is projected to decrease by 30% by mid-century and by 40–50% by late-century in the Pacific Northwest under low to high emissions pathways (Mote *et al.*, 2014). The largest declines would be in the lower-elevation, mixed rain-snow watersheds in the Oregon Cascades and central and northeastern Oregon mountain ranges (fig. 3.1). Across the western United States, April 1 SWE is projected to decrease by more than 50% by 2011–2050 compared to 1961–2005 under the high emissions pathway (RCP 8.5) (Naz *et al.*, 2016).

Figure 3.1 Snow water equivalent on April 1 as simulated by the Variable Infiltration Capacity hydrologic model in the Integrated Scenarios project for the (left) historical baseline (1971–2000) and (right) projected mid-century (2040–2069) change for a high (RCP 8.5) emissions pathway. (Source: http://climate.nkn.uidaho.edu/IntegratedScenarios/vis_summarymaps.php#)



Spring and summer snowmelt runoff is a vital water source for many communities in the mountainous Pacific Northwest because it meets the human water demands unmet by rainfall runoff alone (Mankin *et al.*, 2015). As less precipitation falls as snow and more as rain, and as snowmelt runoff occurs earlier, the Pacific Northwest may experience a decline in "snow resource potential" by the 2060s under a high emissions pathway (RCP 8.5) (Mankin *et al.*, 2015). Snow resource potential is defined as the ability of spring and summer snowmelt runoff to supply the water demand unmet by rainfall alone. Climate models disagree on whether snow resource potential would increase or decrease in the future. In the Klamath Basin, however, a majority of models agree that there is a 79%–93% risk of declining "snow resource potential" (Mankin *et al.*, 2015). Mixed rain-snow watersheds at intermediate elevations between about 3300–6600 feet are most vulnerable to declining snowpack (Tennant *et al.*, 2015) and shifts in streamflow timing (Vano *et al.*, 2015).

Streamflow Amount & Timing

In Oregon, most watersheds west of the Cascade Range receive most of their precipitation as rain, except for the high-elevation tributaries that receive a mix of both rain and snow. Streamflow in rain-dominant watersheds reflects the seasonal pattern of precipitation, with peak flows occurring during the winter and low flows occurring in summer. Therefore, Oregonians in these places rely on constructed reservoirs to store winter precipitation for use during the warm season. Most watersheds east of the Cascade Range receive a mix of both rain and snow during the cool season and rely on mountain snowpack to provide meltwater in spring and summer. Streamflow in mixed rain-snow watersheds is characterized by two peaks, one in winter and one during the spring associated with snowmelt.

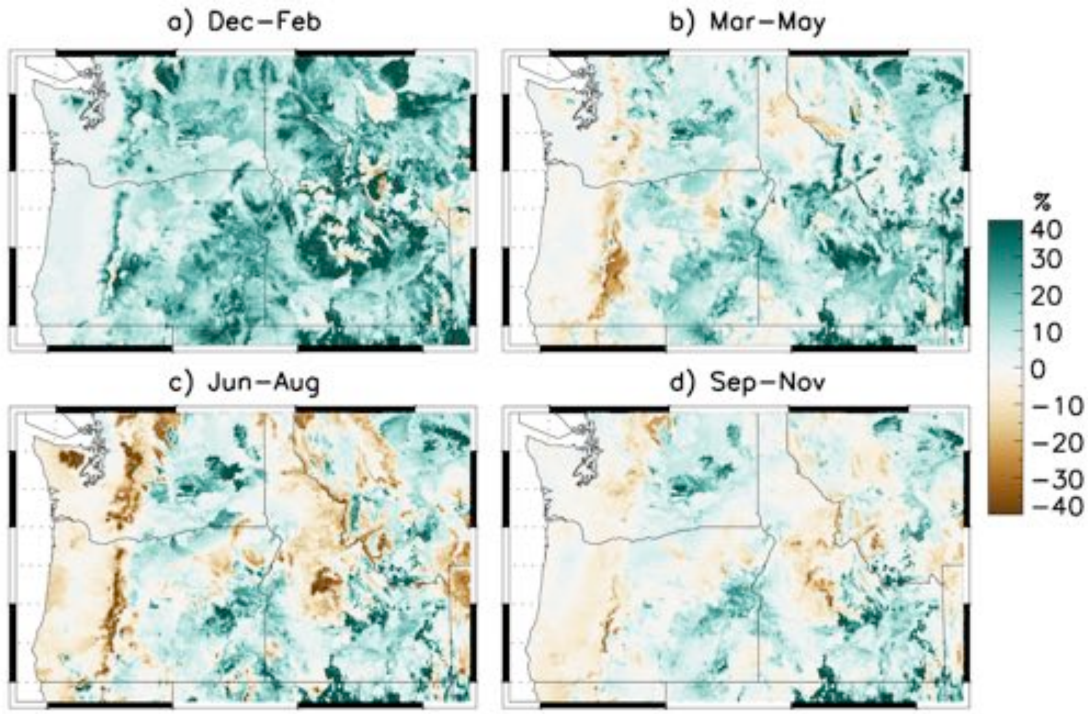
Mean annual streamflow across the Pacific Northwest has decreased between the mid-20th century and the early-21st century, with the greatest decreases in summer (McCabe and Wolock, 2014; Sagarika *et al.*, 2014). Future changes in mean annual streamflow by the end of the century are expected to change very little, being balanced by increases during the cool season and decreases during the warm season (Mote *et al.*, 2014).

Year-to-year variability in annual streamflow across western Oregon and Washington is influenced by variability in ocean temperature patterns. Specifically, warmer sea surface temperatures in the tropical Pacific (El Niño) and in the northeast Pacific (the warm phase of Pacific Decadal Oscillation, or PDO) are weakly associated with lower than normal annual streamflow (McCabe and Wolock, 2014). One study suggests that El Niño's effect on runoff in the Pacific Northwest may depend upon where along the equator the tropical Pacific sea surface temperatures are farthest from normal (Tang *et al.*, 2016).

Despite large year-to-year variability, statistically significant changes in historic streamflow in some sub-basins of the Columbia River Basin have been detected and were largely consistent with prior western US streamflow trend analyses (Dittmer, 2013). In sub-basins in northeastern Oregon, several gages within snowmelt-dominated basins measured trends toward earlier spring peak streamflow and snowmelt, increased extreme high flows in the fall, and more frequent low flows in late summer (Dittmer, 2013). In the many of the mixed rain-snow headwaters of the Willamette basin, snowmelt timing shifted to a few days earlier over the period 1950–2010 (Hatcher and Jones, 2013).

Future streamflow magnitude and timing in the Pacific Northwest is projected to shift toward higher winter runoff, lower summer and fall runoff (Figure 3.2), and an earlier peak runoff, particularly in snow-dominated regions (Naz *et al.*, 2016; Raymondi *et al.*, 2013). Already, streamflow timing has shifted nearly eight days earlier between mid-20th century and early-21st century averaged across the Pacific Northwest (Kormos *et al.*, 2016). Summer (June-August) runoff is projected to decline 5.3% for the multi-model ensemble median in the Pacific Northwest by 2011–2050 compared to 1966–2005 under a high emissions pathway (RCP 8.5), particularly in the Cascade Range and the Blue Mountains (Figure 3.2) (Naz *et al.*, 2016).

Figure 3.2 Percentage change in mean seasonal runoff for 2011–2050 under the high (RCP 8.5) emissions pathway relative to 1966–2005 for (a) winter, (b) spring, (c) summer, and (d) fall from hydrologic simulations using dynamically and statistically downscaled climate from 11 CMIP5 models. Mean seasonal runoff was averaged over all models prior to calculating changes (Figure source: David Rupp; data source: Naz *et al.*, 2016)



Groundwater

Climate change is also expected to affect the timing and amount of water in the ground. Groundwater is an important water source to communities and is often closely connected to water in streams. Groundwater recharge occurs through diffuse precipitation or concentrated runoff infiltrating the soil, through mountain system recharge related to snowpack, or through excess irrigation water percolating back to the water table (Meixner *et al.*, 2016). In mountain basins across the western United States, reduced snowpack is expected to result in declines in mountain groundwater recharge, which will affect aquifers that are recharged from mountain systems (Meixner *et al.*, 2016). Recharge in the Columbia Plateau aquifer, which includes parts of northeast Oregon, is dominated by infiltration of diffuse precipitation and excess irrigation water. By the end of the 21st century, the projected wetter winters are expected to increase winter recharge as precipitation exceeds evapotranspiration, whereas during the growing season a decrease in recharge is projected for excess irrigation water due to increasing evapotranspiration (Meixner *et al.*, 2016). This results in uncertainty in whether future recharge in the Columbia Plateau will increase or decrease. Changes in groundwater recharge dynamics could shift the timing of groundwater discharge to some streams, leading to late summer reductions in baseflows, although streamflow sensitivity to climate change depends on the hydrogeologic setting (Pitz, 2016). Deep groundwater systems feeding some streams, such as in the high-elevations of Oregon's Cascade Range, may somewhat buffer the projected declines in summer streamflow from declining snowpack (Safeeq *et al.*, 2014).

Atmospheric Rivers

Atmospheric rivers are narrow, elongated swaths of warm, moist air originating in the tropics that carry large amounts of water vapor to mid-latitudes. Atmospheric river events can have both negative and positive impacts. Many of the flood-producing extreme precipitation events in the Pacific Northwest are associated with cool season (October–March) atmospheric river events, which tend to be warmer and rainier than typical extratropical storms. On the other hand, atmospheric rivers often bring an end to drought conditions in the Pacific Northwest (Dettinger, 2013). A growing body of evidence indicates that land-falling atmospheric river events are likely to increase in frequency and intensity over the Pacific Northwest under future climate change, largely due to the fact that a warmer atmosphere can accommodate more moisture (Hagos *et al.*, 2016; Warner *et al.*, 2015).

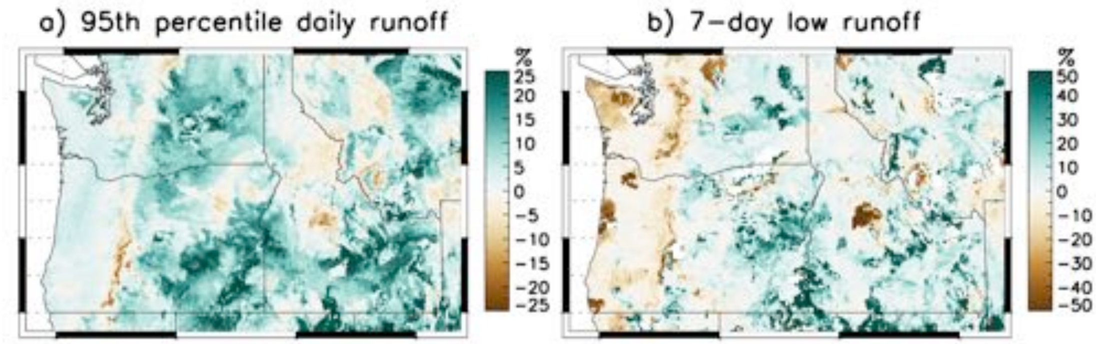
By the end of the century under a high emissions pathway (RCP 8.5), the number of extreme precipitation days associated with land-falling atmospheric rivers along western North America is projected to increase 28% (Hagos *et al.*, 2016). Similarly, the number of "most extreme" atmospheric river days (that is, those atmospheric rivers that made up the 1% most extreme atmospheric rivers historically) during winter are projected nearly to quadruple by the end of the century under the high emissions pathway (RCP 8.5) (Warner *et al.*, 2015). Furthermore, precipitation on such extreme atmospheric river days is projected to increase by 15–39%, which is more than then mean winter precipitation increase of 11–18% (Warner *et al.*, 2015). While extreme atmospheric river days is projected to increase during all winter months, there would be a shift toward heavier precipitation events earlier in the season in October and November (Warner *et al.*, 2015).

Flood Risk

Warming temperatures and increased winter precipitation are expected to increase flood risk for many basins in the Pacific Northwest, particularly mixed rain-snow basins with near freezing winter temperatures (Tohver *et al.*, 2014). The greatest changes in peak flow magnitudes are projected to occur at intermediate elevations in the Cascade Range and the Blue Mountains (Safeeq *et al.*, 2015). Recent advances in regional hydro-climate modeling confirm this expectation, projecting increases in extreme high flows for most of the Pacific Northwest, especially west of the Cascade Crest (fig. 3.3) (Najafi and Moradkhani, 2015; Naz *et al.*, 2016; Salathé *et al.*, 2014). One study, using a single climate model, projects flood risk to increase in the fall due to earlier, more extreme storms, including atmospheric river events, and to a shift of precipitation from snow to rain (Salathé *et al.*, 2014).

Some of the Pacific Northwest's largest floods occur when copious warm rainfall from atmospheric rivers combine with a strong snowpack, resulting in rain-on-snow flooding events (Safeeq *et al.*, 2015). During 1998–2014 in the California Sierra Nevada, atmospheric rivers were associated with half of all rain-on-snow events (Guan *et al.*, 2016). As a result of climate warming, rain-on-snow events are projected to decline at lower elevations, due to decreasing snow cover, and to increase at higher elevations as the number of rainy as opposed to snowy days increase (Safeeq *et al.*, 2015).

Figure 3.3 Percentage change in mean (a) high runoff (the 95th percentile of daily total runoff) and (b) low runoff (7-day average lowest flow per year). Changes are for 2011–2050 under the high (RCP 8.5) emissions pathway relative to 1966–2005. The 95th percentile runoff and the 7-day average lowest flows were averaged over 11 CMIP5 models models prior to calculating changes (Figure source: David Rupp; data source: Naz *et al.*, 2016)



Drought Risk

Hydrologic drought—defined by low streamflow extremes—in the Pacific Northwest has intensified (Kormos *et al.*, 2016). During 1948–2013, the minimum 7-day flow in summer with a 10-year return period (7q10) decreased by 27% on average (Kormos *et al.*, 2016). In the future, low streamflow extremes are expected to be even lower (fig. 3.3), with the strongest declines west of the Cascade Range driven by loss of snowpack, decreases in summer precipitation, and increasing evapotranspiration (Naz *et al.*, 2016; Tohver *et al.*, 2014).

The standard precipitation-evaporation index (SPEI) is a useful predictor of year-to-year streamflow variability in the Pacific Northwest (Abatzoglou *et al.*, 2014) and a meaningful way to characterize drought within the context of climate change (Ahmadalipour *et al.*, 2016). The frequency and intensity of the 3-month summer SPEI drought, in which the index drops below -1, in the Pacific Northwest is projected to increase in the future, driven largely by reduced precipitation and increased potential evapotranspiration under both a low (RCP 4.5) and a high (RCP 8.5) emissions pathway (Ahmadalipour *et al.*, 2016). The area under summer SPEI drought has increased during the last several decades and is projected to increase in the future, with nearly all of the Pacific Northwest being in summer SPEI drought by century's end under the high emissions pathway and about three-quarters on average under the low emissions pathway (Ahmadalipour *et al.*, 2016). Small increases in drought frequency are projected to extend into the spring and fall in southern and eastern Oregon by the latter half of the century under the high emissions pathway (Ahmadalipour *et al.*, 2016). In the Pacific Northwest, the median summer drought extent across multiple climate models is less than 15% in the historical period, but jumps to over 50% during the 21st century under both low and high emissions pathways; similarly, the largest droughts which cover nearly half of the region in the historical period, cover nearly the entire region in future projections (Ahmadalipour *et al*., 2016).

Water Management Implications

Balancing multiple water uses under an increasingly uncertain water supply is expected to become more challenging and may require complex tradeoffs. The following are some examples of water management implications of climate change found in recent literature.

Many reservoirs in Oregon are managed for annual refill. Earlier runoff timing and greater extreme runoff events are expected to fill reservoirs earlier in the year. Water managers may need to reconsider their operating rules in order to better manage flood risks while maximizing storage opportunities (Reclamation, 2016). For example, in the Willamette Basin, starting reservoir refill earlier, but at a slower rate could balance flood risk and summer water demand in light of earlier snowmelt and increasing winter precipitation (Moore, 2015).

There is also expected to be greater reliance on stored water to meet the summer season's increasing water demands (Reclamation, 2016). For example, the Klamath Basin is expected to experience more years with water shortages as runoff occurs earlier in the season, as more precipitation falls as rain rather than snow, and as reservoir evaporation increases (Reclamation, 2016). Irrigation and drinking water may have to rely more on groundwater as surface water supplies become more variable or uncertain (Reclamation, 2016). Large increases in climate-driven groundwater extraction in order to meet increasing summer water demand are likely to result in further negative effects on groundwater storage, baseflow discharge to streams, supported aquatic ecosystems, and water quality (Pitz, 2016).

Water is also managed to meet hydro-electric demands. Warmer year-round temperatures are expected to increase electricity demand during summer, but decrease demand during winter. However, changes in water runoff timing and reduced summer flows may reduce peak-season hydropower generation in summer (Reclamation, 2016), although the Pacific Northwest will likely see smaller impacts to hydroelectric power supply than California and the Southwest, where greater future declines in precipitation are expected (Bartos and Chester, 2015).

There is extensive literature examining tribal water rights and tribal treaty and reserved rights in the context of climate change including water needs for agriculture, livestock, recreation, cultural use, and even in-stream flows for salmon (Kronk Warner, 2016; Osborn, 2013; Royster, 2013). "As climate change continues to affect the availability and quality of water resources, tribal water rights become increasingly important" (Norton-Smith *et al*., 2016). There is a need to more fully understand the implications of climate change on water resources in relationship to tribal treaty and reserved rights.

Fish Habitat Implications

Fish habitat is expected to degrade due to increasing peak flows, earlier streamflow timing, reduced summer low flows, and warming summer stream temperatures that could shift preferred habitats, alter the timing of life history stages, and exacerbate current stressors for the Pacific Northwest's salmon and steelhead (*Oncorhynchus spp*.) and other aquatic wildlife.

A greater risk of scouring shallow-buried eggs from the streambed, particularly from fall-spawning salmon, and of displacing juvenile salmon (Goode *et al*., 2013; Wainwright and Weitkamp, 2013) is expected due to greater high winter streamflows from increasing winter precipitation and precipitation falling less as snow and more as rain. However, scour risk is reduced when stream channel morphology changes concurrently with streamflow (Goode *et al*., 2013).

Migration timing for smolts getting ready to migrate to the ocean could be desynchronized by earlier peak streamflow timing from earlier melting of the snowpack (Wainwright and Weitkamp, 2013).

Upstream migration of adult salmon returning from the ocean to spawn in the summer or fall could be delayed by lower summer flows from declining snowpack and reduced summer precipitation. At many sites in Oregon's Willamette and Southern Coastal basins, Chinook salmon (*O. tshawytscha*) spawning is projected to occur later by mid-century effectively shortening the growing period by a few days (Beer and Anderson, 2013).

Stream temperatures that are lethal to fish (generally greater than 68°F, although this varies among populations) can occur with declining snowpack and warmer summers (Service, 2015). Higher stream temperatures place adults at higher risk of failing to spawn and succumbing to diseases (Service, 2015). Spring Chinook enter freshwater and hold in cold-water refugia until spawning in the fall. Warmer stream temperatures increase their metabolic rate therefore draining their energy stores (they don't eat during this period). High pre-spawn mortality was observed in 2015 in some Columbia River basins (L. Weitkamp, pers. comm.). Warming streams are expected to have mixed results on the early life stage development of Chinook salmon and steelhead (*O. mykiss*) (Beer and Anderson, 2013), and likely other salmon species too. In the Columbia River basin, fish in streams typically cooled by snowmelt will likely experience less growth, whereas fish in currently cold mountain streams will experience the same or higher growth by mid 21st century (Beer and Anderson, 2013). In addition, warmer streams and reduced summer flows can limit summer juvenile rearing areas and increase risk of diseases and predation (Wainwright and Weitkamp, 2013). Co-occurring stressors, such as pesticide exposure combined with warmer stream temperatures, can amplify Chinook salmon and other salmon species susceptibility to diseases (Dietrich *et al*., 2014).

Many mountain headwater streams in the Pacific Northwest are likely to remain cold enough under future warming scenarios to support current salmonid and other cold-water fish populations due to topographic controls on water temperature (Isaak *et al*., 2016). Such cold-water refugia along with healthy riparian zones may limit invasion of non-native species and sustain current salmon rearing habitat (Isaak *et al*., 2015; Lawrence *et al*., 2014).

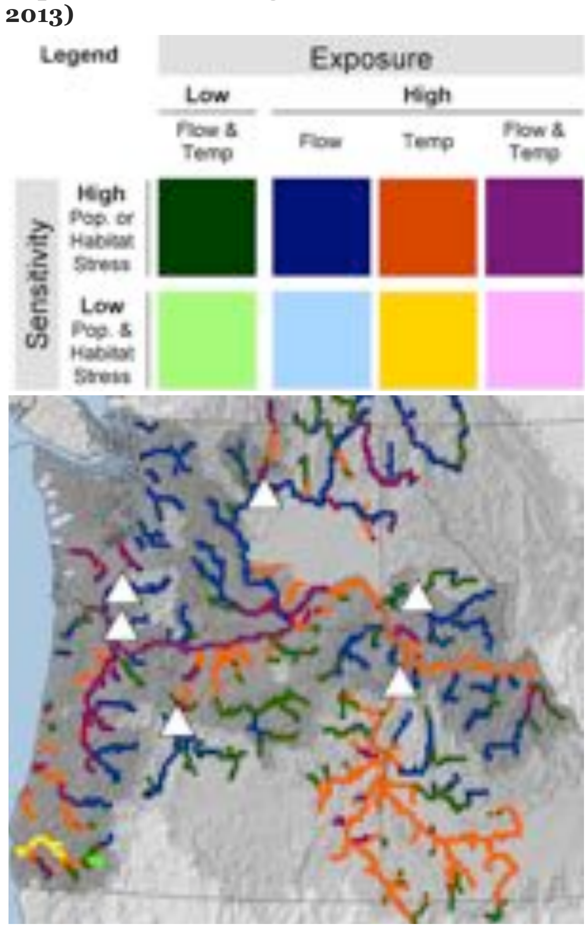
Although there may be some positive outcomes, the overall effect of climate and hydrologic change on salmon during all life cycle stages is likely to be unfavorable. This would result in at least moderate declines for most salmon populations in the Pacific Northwest, especially when accounting for existing stressors and natural variability, which can exacerbate climate impacts (Crozier, 2015; Wainwright and Weitkamp, 2013). During the last sixty years, streamflow variability increased and, compared with other environmental changes, had the largest negative effect on Chinook salmon populations in the Northwest (Ward *et al*., 2015). Increasing hydrologic variability projected for the future may limit the recovery of exposed salmon populations (Ward *et al*., 2015). Behavioral and physiological adaptations are possible, such as earlier migration (Mantua *et al.*, 2015) and increasing thermal tolerance (Muñoz *et al.*, 2015), but these are unlikely to prevent long-term population declines (Crozier, 2015).

A relative ranking of steelhead vulnerability to changes in streamflow and warming temperatures in streams throughout the Pacific Northwest (fig. 3.4) reveals that exposure to warmer stream temperatures is greatest in the southern coastal and interior Columbia Basin during all life stages (Wade *et al.*, 2013). Steelhead in western Cascade streams face the greatest exposure both to extreme low flows and extreme high flows, the latter particularly threatening steelhead (and some other species') incubation and migration life stages (Wade *et al.*, 2013).

While less studied, bull trout (*Salvelinus confluentus*) are also negatively affected by low streamflows and high fall and summer stream temperatures (Kovach *et al.*, 2015a). Some evidence suggests that bull trout in the Rocky Mountains have begun to abandon low elevation warm sites in favor of cooler high elevation sites as predicted by bioclimatic models (Eby *et al.*, 2014). In the Columbia River Basin, genetic diversity was lowest in areas with high summer temperatures and high frequency of winter flooding and such populations are most vulnerable to future expected climate changes (Kovach *et al.*, 2015b). In the interior Columbia River Basin (largely in Idaho and western Montana), suitable bull trout habitat is projected to decline about 90% by the 2080s compared with present suitable habitat area (Wenger *et al.*, 2013).

Changes in suitable freshwater fish habitat are of interest to recreational and commercial fishermen. By 2100 under a very high emissions pathway (REF 10), much of Oregon's "cold water"—less than about 75°F—and most desirable recreational fishing habitat is projected to shift to "warm water" habitat, save the high-elevation regions in the Cascade Range and the Blue Mountains. However, under the low emission pathway (POL 4.5) assuming global mitigation, virtually all of Oregon's cold water recreational fishing habitat remains (Lane *et al.*, 2015). In terms of maintaining recreational fishing services, the total future economic benefit of avoiding the

Figure 3.4 Estimated relative steelhead vulnerability to climate change summarized by combinations of steelhead sensitivity and exposure to changes in stream temperature and flow. Greens and purples represent locations with both temperature and flow exposure values lower or higher than the median across the Pacific Northwest, respectively. Blues represent locations where steelhead exposure to flow changes is relatively high but exposure to temperature stress is relatively low, and oranges illustrate the reverse. White triangles show locations of impassable dams. (Figure source: Wade *et al.*, 2013)



very high emissions pathway (REF 10) in favor of the low emissions pathway (POL 4.5) is projected to be nearly $1.1 billion (2005$) between 2011 and 2100 for cold water fishing in the United States based on fishing days and average expenditure (Lane *et al.*, 2015). Note that thermal thresholds for many salmonid species are lower than the threshold used by this study, so habitat losses would be greater and thus economic benefit to global mitigation could be larger.

A 2015 study of Columbia River Basin tribes, including the Confederated Tribes of Warm Springs (CTWS) and the Confederated Tribes of the Umatilla Indian Reservation (CTUIR), found that the primary concerns regarding climate change impacts included the quantity and quality of water resources, snowpack, water temperatures for spawning conditions, and fishing rights (Sampson, 2015). Pacific salmon have great cultural, subsistence, and commercial value to tribes in the Pacific Northwest, and are central to tribal cultural identity, longhouse religious services, sense of place, livelihood, and the transfer of traditional values to the next generation (Dittmer, 2013). During the last 150 years, culturally important salmon populations have declined (Dittmer, 2013). Continuation of past trends of earlier spring peak, more extreme high flows and more frequent low flows in the low elevation basins of northeast Oregon, home to the CTWS and CTUIR, may force earlier migration of juvenile salmon, challenge returning adults in low flow conditions, and increase scour risk for emerging young salmon (Dittmer, 2013). One study suggests that monitoring climate change impacts to salmon and their importance for tribal cultural and societal health could be achieved with indicators such as percent of successful tribal fishing trips, ability to obtain sufficient fish for traditional feasts, or percent of streams still with spawning salmon (Burger *et al.*, 2015).

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Chapter 4: Coastal Issues

Summary

Oregon's coastline is expected to face greater coastal flooding and erosion hazards as sea levels rise. At Newport, sea level is projected to rise by 12 to 47 inches under the high emissions pathway by the end of the 21st century. Such sea levels would place thousands of people and homes, and over 100 miles of roads, in Oregon at risk of inundation from annual flood events that reach four feet above high tide. Multiple changes in the ocean environment—warmer temperatures, less oxygen, greater ocean acidity—are expected to result in substantial ecosystem shifts in Oregon's coastal waters. Ocean acidification is already affecting Oregon, caused in part by increasing greenhouse gas concentrations.

Introduction

The ocean, often overlooked, in fact bears a great burden due to global climate change. The ocean retains the majority of the extra heat trapped by the Earth due to extra greenhouse gases emitted by the burning of fossil fuels. It receives half of the extra water that melts from ice on land. It absorbs nearly one-third of the extra carbon dioxide emitted to the atmosphere. But, bearing this burden comes at a cost. Warmer temperatures can alter ecosystems; more water raises global sea levels; more carbon dioxide acidifies the ocean (Stocker, 2015). These effects, already seen in Oregon, are projected to increase in the future, likely threatening coastal habitats, food supply, economic livelihood, and development.

Sea level rise

Changes in global sea levels occur due to ocean thermal expansion, glacier and ice sheet mass loss, and land water storage. Regional and local sea levels on the Pacific Northwest's coast are governed by the global mean sea level, but also by natural variability (El Niño–Southern Oscillation affects ocean currents and wind fields), by vertical land motions from subducting ocean plates, and by post-glacial isostatic adjustment (Reeder *et al.*, 2013).

Past Trends

Global mean sea level rose about 7.5 inches during 1901–2010. Of that rise, 75% since the 1970s was due to melting glaciers and thermal expansion of sea water (IPCC, 2013). Sea level rise has been accelerating: most analyses suggest that global mean sea level rose at a rate of 1.7 mm/year during 1901–2010, 2.0 mm/year during 1971–2010, and 3.2 mm/year during 1993–2010 (IPCC, 2013). However, a recent reanalysis of global sea level rise suggests that sea level rise rates during 1901–1990 were smaller (1.2 mm/year) than previous estimates, bringing it in line with the sum of contributions from glacier and ice sheet mass loss, ocean thermal expansion, and changes in land water storage during that period (Hay *et al.*, 2015). These adjusted estimates in sea level rise imply even greater acceleration in recent decades. Trends in global and regional sea level changes beyond natural variability are now detectable. At a minimum, anthropogenic sea level rise very likely contributed about 1 mm/year to global sea level rise during 1880–2002, or more than half the observed trend (Becker *et al.*, 2014). There is, however, regional variability; the minimum anthropogenic sea level change signal at Seattle during 1899–2012 was only 15% of the observed trend (Becker *et al.*, 2014). In parsing out the contributions to global and regional sea level change as detected by satellite altimetry and gravity observations, one study found that sea level during 2002–2014 along the West Coast changed very little, with the cooling ocean trend (lack of thermal expansion) balancing contributions from melting ice sheets and glaciers (Rietbroek *et al.*, 2016). However, local tectonics was not accounted for in this study but is important for local sea level analysis.

Future Projections

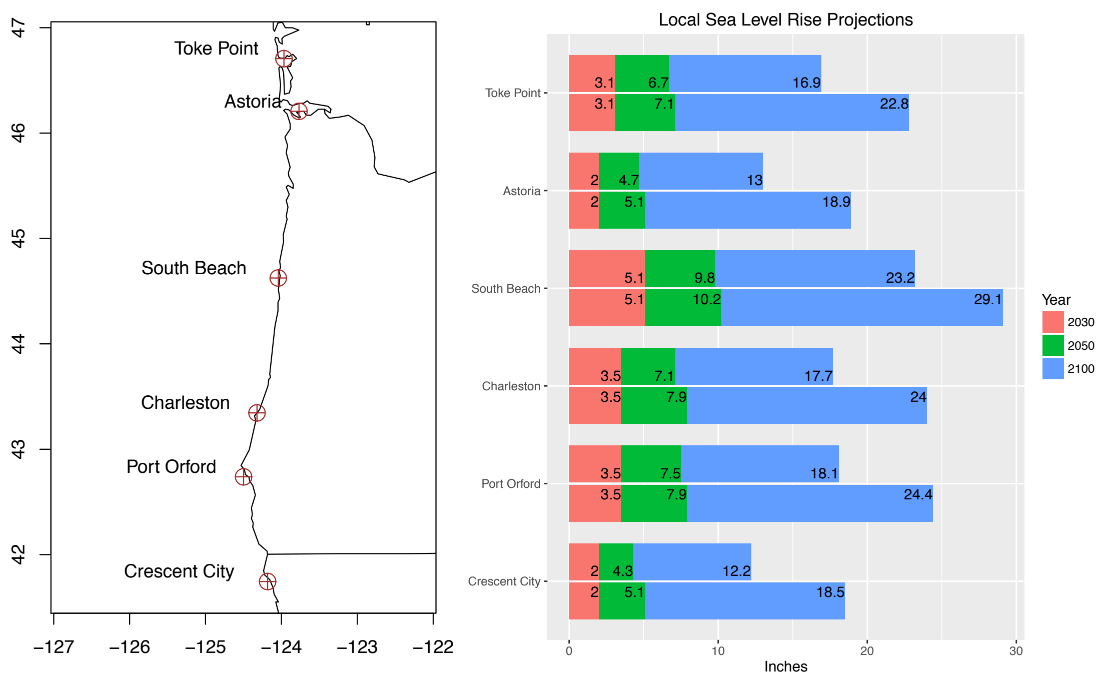
Global mean sea level is expected to continue to rise throughout this century at a faster pace than observed over the past several decades (IPCC, 2013). Under the high emissions pathway (RCP 8.5), sea levels will likely rise by 17.7–32.3 inches between the periods 1986–2005 and 2081–2100, and this rise will vary across regions (IPCC, 2013). Loss of the West Antarctic ice sheet would result in much higher sea level rise estimates than these (Clark *et al.*, 2016; DeConto and Pollard, 2016; Hansen *et al.*, 2016). In a large ensemble of simulations coupling climate and ice sheet dynamics, the West Antarctic Ice Sheet is projected to collapse within 250 years for the high emissions pathway (RCP8.5) and within 500 years for the low emission pathway (RCP4.5), contributing about 30.3 inches and 12.6 inches of global sea level rise by 2100, but 40.4 feet and 16.4 feet by 2500, respectively (DeConto and Pollard, 2016).

Local sea level change projections for the West Coast from the National Research Council 2012 report were quoted in the previous Oregon Climate Assessment Report (Reeder *et al.*, 2013). Based on the range of the previous generation of models (CMIP3) and scenarios (SRES), local sea level at Newport, Oregon, relative to the year 2000 was projected to change -1.4 to +8.9 inches by the 2030s, -0.8 to +18.9 inches by the 2050s, and +4.6 to +56.1 inches by 2100 (Reeder *et al.*, 2013). Local sea level change projections from the latest generation of models (CMIP5) and scenarios (RCP), taking into account glacial isostatic adjustment, tectonics, and other non-climatic local effects for gages in or near Oregon, are shown in figure 4.1 and listed in table 4.1 (see Chapter 2 for a description of scenarios). These local projections correspond to “very likely” (90% probability range) global sea level projections between 2000 and 2100 of 15.7 to 35.4 inches under the low emission pathway (RCP 4.5) and 19.7 to 47.2 inches under the high emissions pathway (RCP 8.5) (Kopp *et al.*, 2014).

Table 4.1 The 90% probability range of local sea level change projections across the low (RCP 4.5) and high (RCP 8.5) emissions pathways for each time period in inches (Data source: Kopp *et al.*, 2014)

	2030	2050	2100
Toke Point	1.2–5.1	2.8–11.8	5.9”–40.2”
Astoria	<0–3.9	0.8–9.8	2.4–35.8
South Beach	2.8–7.1	5.9–15.0	12.2–46.5
Charleston	1.2–5.5	3.1–12.6	6.7–41.7
Port Orford	1.2–5.9	3.1–12.6	6.7–42.5
Crescent City	-0.4–3.9	0.4–9.4	0.8–36.6

Figure 4.1 Median sea level projections in inches for Oregon Coast locations for a low (RCP 4.5, top bar) and a high (RCP 8.5, bottom bar) emissions pathway for 2030, 2050, and 2100. (Figure source: Meghan Dalton; data source: Kopp *et al.*, 2014)



Extreme storms and wave climate

Tall waves, intense storms, and El Niño–Southern Oscillation (ENSO) events can combine with sea level rise to produce coastal erosion and inundation hazards (Reeder *et al.*, 2013). During El Niño events the Pacific Northwest's coast can experience elevated sea levels, but both the top six El Niño and top five La Niña events during 1979–2016 amplified coastal erosion and wave energy in the Pacific Northwest (Barnard *et al.*, 2015, 2017). If ENSO becomes more extreme (see Chapter 2), coastal erosion may increase in the future irrespective of sea level rise (Barnard *et al.*, 2015).

Upward trends were seen in storm frequency and intensity during the cold season across the Northern Hemisphere since 1950, but these trends were significant only in some areas and not off the Pacific Northwest's coast (Vose *et al.*, 2014). Twenty-first century projections of changes in storm intensity are still inconclusive, although storm tracks are expected to shift slightly poleward (Vose *et al.*, 2014).

Wave heights have increased in the northeast Pacific over the past several decades (Reeder *et al.*, 2013), as have extreme wave events (Bromirski *et al.*, 2013); such waves have been largely responsible for recent increases in coastal flooding and erosion (Ruggiero, 2013). However, attributing increasing wave heights to climate change may not be possible until the second half of the 21st century because natural variability is quite large (Dobrynin *et al.*, 2014). Future projections of average and extreme wave heights along the West Coast are mixed (Erikson *et al.*, 2015; Wang *et al.*, 2014) as they rely on predictions that are difficult to make about extratropical storms and extreme winds (Vose *et al.*, 2014).

Coastal Hazards Vulnerability

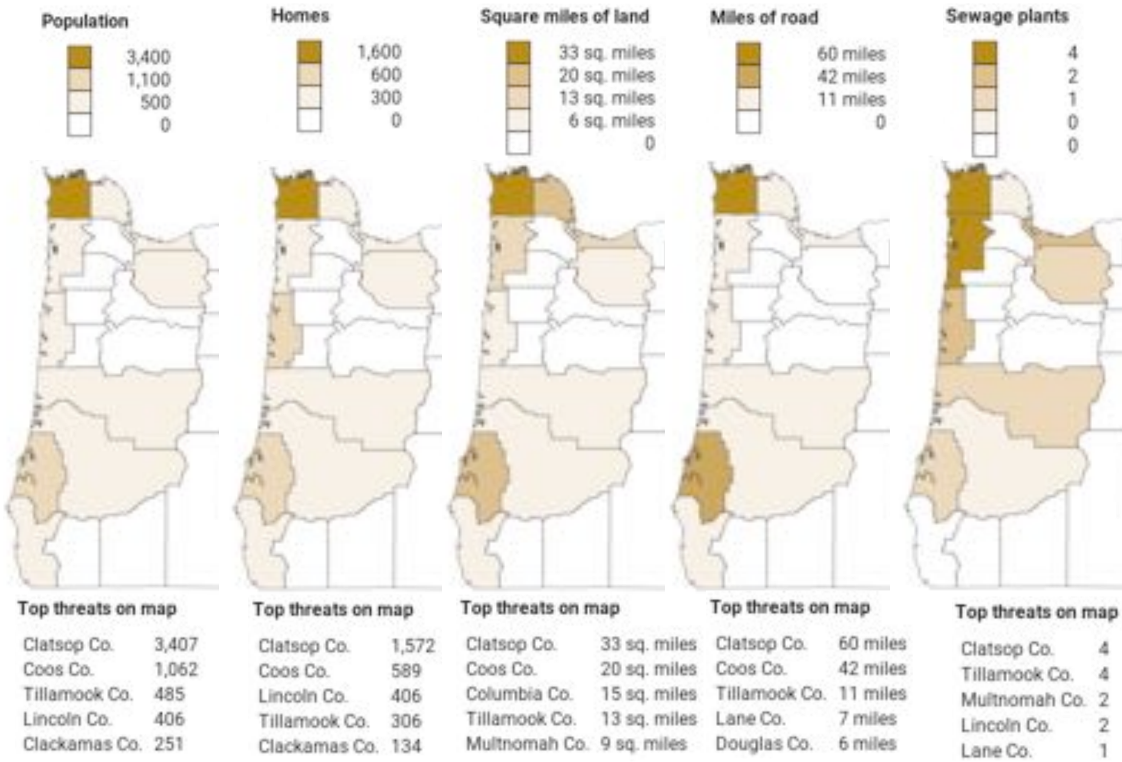
In US coastal communities, more than 2.2 million people currently live in areas within reach of the mean highest high tide projected for 2100 if global sea levels rise 35.4 inches (Hauer *et al.*, 2016). In Oregon, more than 7,400 people currently live in this inundation zone, but accounting for population growth could place more than 12,700 people at risk by 2100 (Hauer *et al.*, 2016). Nuisance flooding events, in which water levels exceed local thresholds for minor impacts, are also projected to increase, placing even more people and property at risk of frequent inundation. In Seattle, for example, the projected likely range of local sea level rise of 19.7–35.4 inches by 2100 (Kopp *et al.*, 2014) would result in 30 nuisance flooding days per year by the 2040s or 2050s (Sweet and Park, 2014). Coastal risk is amplified when considering other factors that influence extreme sea levels, such as storm surge, sea level anomalies, and intense rainfall (Serafin and Ruggiero, 2014; Wahl *et al.*, 2015). Accounting only for changes in mean sea level, for example, may be inadequate for ensuring that coastal infrastructure projects remain safe for the lifetime of the structure (Wahl and Chambers, 2015).

By 2100, assuming median local sea level projections under the high emissions pathway (RCP 8.5) of 18.9, 29.1, and 24 inches for Astoria, South Beach, and Charleston (fig. 4.1) (Kopp *et al.*, 2014), respectively, there is a 70%, 100%, and 86% risk of at least one flood per year reaching 4 feet above the current high tide line (Strauss *et al.*, 2014). At this level, 6118 people, 3346 homes, $779 million in property value, 138 miles of roads, 15 sewage plants, and 110 square miles of land would be at high risk of annual flooding in Oregon by 2100 (Strauss *et al.*, 2014). Figure 4.2 breaks these numbers down by county.

Globally, under 9.8–48.4 inches of global mean sea level rise, 0.2–4.6% of the population would experience annual flooding leading to losses of global gross domestic product of 0.3–9.3% by the end of the 21st century (Hinkel *et al.*, 2014). The adaptation cost of protecting coasts is estimated to be $12–$71 billion per year, a much lower total than the cost of avoided damages (Hinkel *et al.*, 2014). In the United States, the total cost of adaptation (including armoring, nourishment, abandoned property, and elevating) increases when considering storm surge on top of sea level rise and is estimated to range from $930 billion to $1.1 trillion through 2100 under a very high emissions pathway (REF 10). Low (POL 4.5) and very low (POL 3.7) emissions pathways have the potential to lower this cost by $84–$140 billion (Neumann *et al.*, 2015). In Oregon, the cost of adaptation to sea level rise and storm surge may be on the order of $1.5 billion through 2100; consideration of storm surge makes little difference for Oregon (Neumann *et al.*, 2015), but adding wave climate variability might.

Perhaps the greatest coastal hazard facing the West Coast this century is the possibility of a large magnitude Cascadia Subduction Zone earthquake. The latest estimate gives a 16–22% chance of a magnitude 8 or higher earthquake off the central and northern Oregon coast in next 50 years (Goldfinger *et al.*, 2016). Should the earthquake and subsequent tsunami occur, significant loss of life and profound damage to coastal development and infrastructure is anticipated (*Oregon Natural Hazards Mitigation Plan*, 2015).

Figure 4.2 Exposure of assets below 4 feet above mean high tide level in Oregon
http://riskfinder.climatecentral.org/state/oregon.us?comparisonType=county&forecastType=NRC_Medium&level=4&unit=ft



Ocean acidification and hypoxia

The world's oceans have absorbed about a third of the carbon dioxide (CO_2) emitted as a result of human activity. Absorption of this CO_2 has led to increased ocean acidity, a fundamental shift in ocean chemistry that is a growing concern for coastal ecosystems and the people that depend on them. The West Coast Ocean Acidification and Hypoxia Science Panel recently issued a scientific consensus report on the state of ocean acidification and hypoxia along the West Coast and recommended actions for managing and reducing their effects (Chan *et al*., 2016). Ocean acidification and hypoxia tend to co-occur, as they are both driven by increased atmospheric CO_2 levels and local nutrient and organic carbon inputs, and together they comprise a challenge that can be managed synergistically (Chan *et al*., 2016).

Ocean acidification (OA) is often expressed in terms of a decrease in pH or increase in acidity. OA also reduces the concentration of carbonate ions, which impairs the ability of calcifying organisms, such as oysters and crabs, to build shells. By 21st century's end assuming the current rate of global CO_2 emissions, the surface ocean's average acidity is expected to double (Chan *et al*., 2016). But although it negatively affects some physiological processes, pH may not be the most useful number by which to monitor the biological effects of OA, particularly on calcifying organisms (Chan *et al*., 2016; Waldbusser *et al*., 2015). Furthermore, biologically-relevant thresholds of mineral carbonate saturation state are expected to be crossed much sooner than pH thresholds for some organisms (Waldbusser *et al.*, 2015). Even before it declines enough to corrode calcium carbonate shells, a lowered carbonate saturation state can "make it more difficult and energetically costly for larval bivalves to build shells" (Waldbusser *et al.*, 2015). Reductions in calcifying organisms at the base of the marine food web could have cascading effects on higher trophic marine fish, birds, mammals, and the people who rely on this resource. In a simple projection of ocean water saturation state changes, the mean annual surface seawater aragonite saturation state off the Oregon coast is projected to reach a threshold known to disrupt calcification and development in larval bivalves by the 2030s (Ekstrom *et al.*, 2015). However, the West Coast has already reached a threshold and negative impacts are already evident, such as dissolved shells in pteropod populations (Feely *et al.*, 2016) and impaired oyster hatchery operations (Barton *et al.*, 2012) (see box 4.1). Furthermore, 60% of the dissolved inorganic carbon in surface waters off Oregon's coast in 2013 is attributed to increasing greenhouse gas concentrations (Feely *et al.*, 2016).

Hypoxia—low oxygen levels—tend to accompany high ocean acidity, and the combined effects can be worse than the effects either of hypoxia or acidification independently (Chan *et al.*, 2016). Hypoxic waters along the West Coast have expanded upward into shallower depths and are already affecting marine ecosystems (Somero *et al.*, 2016). Natural climate variability exercises strong control on dissolved oceanic oxygen levels, but detection of a deoxygenation trend beyond natural variability may be possible by the 2030s and 2040s in the north Pacific Ocean and along the US West Coast according to earth system modeling results (Long *et al.*, 2016).

The West Coast of North America is one of the first places in the world to experience severe environmental, ecological, and economic consequences of OA and hypoxia largely due to the naturally occurring CO_2-enriched, low-oxygen deep water that wells up along the continental shelf of the West Coast (Chan *et al.*, 2016). How the region manages these ongoing changes will likely influence management choices of other coastal regions of the world. OA is a global problem, and reducing global levels of CO_2 emissions will be the most effective strategy to lessen the effect of OA (Chan *et al.*, 2016). However, better management of local nutrient and organic matter inputs to the coastal environment can lessen exposure to OA where those local stressors are having impacts. Furthermore, managing ecosystems to increase resilience—the ability to withstand impacts—to OA represent an important path for local adaptation actions. Time is of the essence because delayed action will reduce management options in the future and more greatly diminish ecosystem services (Chan *et al.*, 2016).

Ocean temperature

Most of the greenhouse-gas-driven warming of the Earth since the late 18th century has occurred in the ocean, consistent with previous interglacial warming periods (Rosenthal *et al.*, 2013). Since 1970, more than 90% of the extra heat taken up by the Earth has accumulated in the ocean (Gleckler *et al.*, 2016). Ocean warming is accelerating, particularly in the deep ocean: half of the increase in ocean heat content since the late 18th century occurred in recent decades (Gleckler *et al.*, 2016). By absorbing vast amounts of heat, the deep ocean provides a buffer to greenhouse gas warming experienced by land ecosystems, but at the cost of highly vulnerable biodiversity in ocean ecosystems (Levin and Bris, 2015).

There is, however, considerable regional variability in ocean temperature trends as ocean currents redistribute heat throughout the world ocean. Surface waters off the West

Coast have warmed and are expected to continue warming in the future; however, there will continue to exist large annual variability via seasonal upwelling and interannual variability from ENSO-related changes in wind patterns (Reeder *et al.*, 2013).

Coastal Upwelling

Coastal upwelling in the California eastern boundary upwelling system, which runs along the West Coast from Victoria to Baja, occurs during the spring and summer when the wind predominately blows southward and interacts with the Earth's rotation to push surface waters offshore, allowing cold, nutrient-rich waters at depth to well up toward the surface, spurring productivity that supports the marine food web. Observed evidence suggests that upwelling-favorable winds have intensified in the California upwelling system over the past 60 years (Sydeman *et al.*, 2014). However, the majority of climate models project future weakening of upwelling-favorable winds along the California upwelling system by the end of this century under a high emissions pathway (RCP 8.5) (Rykaczewski *et al.*, 2015). This projection is in contrast to a projected intensification of upwelling-favorable winds in other eastern boundary upwelling systems of the world. Theory suggests that upwelling in eastern boundary currents would intensify under climate change due to strengthening ocean high-pressure systems and greater relative warming over the land than over the ocean, which could produce upwelling-favorable winds locally, although there will continue to be large year-to-year variability in upwelling (Bakun *et al.*, 2015). The lack of upwelling intensification projected for the California upwelling system suggests that other regional controls are at play (Wang *et al.*, 2015). If upwelling does intensify, the cooler waters could potentially counteract the effects of habitat warming; however, that water would likely be more acidic and with less oxygen (Bakun *et al.*, 2015).

Impacts to Marine & Coastal Ecosystems

Ocean acidification (OA)—decreasing pH, increasing partial pressure of CO_2 dissolved in water (pCO_2), and decreasing aragonite saturation—in combination with changes in ocean temperature and dissolved oxygen levels will have varying effects on the physiology of marine species from the microscopic plants and bugs (i.e., plankton) at the base of the marine food web to shellfish, fish, and larger mammals, leading to substantial and potentially irreversible changes in marine ecosystems species assemblages (Somero *et al.*, 2016; Wittmann and Pörtner, 2013). Such ecosystem shifts will likely affect the coastal economy and the communities that rely on traditional coastal resources. In Oregon, commercial fishing and seafood manufacturing accounted for 0.2% of Oregon jobs and $614 million in sales in 2013 (Sorte *et al.*, 2016). The range of organisms for which evidence of sensitivity to OA exists has continued to grow, but more research is still needed to understand the complex interactions and outcomes of multiple changing stressors on multiple interconnected species within the marine environment (Busch and McElhany, 2016).

Phytoplankton

Warmer oceans will likely alter the metabolic functioning of some phytoplankton (Toseland *et al.*, 2013), and OA is expected to favor some types over others (Eggers *et al.*, 2014). The thousands of phytoplankton species at the base of the marine food web will likely each respond a little differently to these climate stressors spurring competition among species and resulting in substantial changes in phytoplankton community composition (Dutkiewicz *et al.*, 2015). This in turn would lead to the alteration of ocean biogeochemical nutrient cycling, with cascading effects on the marine food web as different phytoplankton types perform different and essential functions.

Zooplankton

Pteropods—tiny sea snails with aragonite shells that serve as a major food source for many commercially important fishes (Somero *et al.*, 2016)—are strong indicators of the cumulative effects not only of OA, but also of warming and of declining oxygen levels (Bednaršek *et al.*, 2016). Suitable habitat for pteropods is already declining off the West Coast (Bednaršek *et al.*, 2014). OA, by increasing the extent of aragonite undersaturation, has already increased severe pteropod shell dissolution incidences along the West Coast compared with pre-industrial conditions (Bednaršek *et al.*, 2014; Feely *et al.*, 2016). By mid-21st century such dissolution incidences are expected to triple (Bednaršek *et al.*, 2014). Such impacts to pteropods will alter available food sources for a number of commercially-important species of fish along the West Coast (Somero *et al.*, 2016).

Invertebrates

OA threatens the growth and survival of most classes of shell-forming invertebrates, including bivalves and crabs, although some are more sensitive than others, and sensitivity varies among species (Busch and McElhany, 2016). During the larval stage, bivalves—clams, mussels, oysters—are highly sensitive to reduced carbonate saturation during the crucial hours or days in which initial shells are formed (Waldbusser *et al.*, 2015). Changes in pH and pCO_2 can also affect invertebrate physiology (Somero *et al.*, 2016). Cephalopods (e.g., octopus, squid) that spend time in both shallow oxygen-rich water and deep oxygen-poor waters are generally considered tolerant of increasing pCO_2, as they can tolerate a wide range of water chemistry conditions, but this tolerance varies with water temperature (Doubleday *et al.*, 2016; Somero *et al.*, 2016). In addition, other classes of squid may be more sensitive to declining ocean pH (Busch and McElhany, 2016).

Fishes

Fishes will exhibit varied responses to changing water conditions (e.g., temperature, OA, hypoxia, food source) depending on differences in vulnerability and adaptive capacity (Pörtner *et al.*, 2014). Increases in pCO_2 has been found to be a relevant indicator for many fish: higher pCO_2 affects fish behavior and their ability to navigate (Chan *et al.*, 2016), with little capacity for some fish to acclimate (Welch *et al.*, 2014). The eggs and larvae of some north Pacific commercial flatfish species are also affected by elevated CO_2 levels (Hurst *et al.*, 2016). OA and hypoxia can also affect the metabolism of fish species; slow swimming and larval stages are particularly vulnerable, as they are less able to move away from such impaired conditions (Somero *et al.*, 2016).

For salmon, warmer ocean waters could alter their ranges and migration, could lead to thermal stress and susceptibility to disease and predation, and could increase stratification that would change the habitat structure and reduce food supply (Wainwright and Weitkamp, 2013). During warmer Pacific ocean regimes when food availability is generally lower, returning Chinook salmon (*Oncorhynchus tshawytscha*) were smaller and fewer, but they appeared to need to eat more in order to maintain energy to forage for the lower food availability (Daly and Brodeur, 2015). Increases in ocean acidity would also disrupt food supply and shift the ecosystem, while changes in upwelling could result in greater nutrients but a desynchronization between food supply and arrival to the ocean (Wainwright and Weitkamp, 2013).

As temperatures warm, the range of many marine fishes is projected to shift poleward in the northeast Pacific, and an influx of warm water species along the Oregon coast is expected (Cheung *et al.*, 2015). Species assemblages are projected to change, potentially resulting in mis-matches between co-evolved species, which could cause cascading effects up the marine food web and a shifting of traditional fishing grounds (Cheung *et al.*, 2015). Declines in northeast Pacific fisheries catch is projected under climate change; however, poleward range shifts may open new recreational and commercial fishing opportunities (Weatherdon *et al.*, 2016a).

Indigenous fishing communities are particularly vulnerable as climate change has the potential to reduce their capacity to harvest traditional marine resources for their economic and cultural livelihood (Weatherdon *et al.*, 2016a). Ranges of the many commercially and culturally important marine fishes for First Nations in coastal British Columbia are projected to shift north by about 6–112 miles per decade by 2050, with accompanying projected declines in abundance of -15% to -21%, with the greatest impacts toward the south (Weatherdon *et al.*, 2016b). Under such projections, catch potential is expected to decline for most commercial fisheries, leading to revenue reductions of 16% to 29% by 2050 (Weatherdon *et al.*, 2016b).

Mammals

Climate change is likely to impact marine mammals indirectly through alteration in food availability and prey communities over time (Okey *et al.*, 2014). For example, migrating Humpback whales seem to be spending more time in Arctic ice-free waters where the warmer waters appear to be benefitting krill blooms (Groc, 2016). Such indirect responses are potentially long-lasting, but difficult to predict (Sydeman *et al.*, 2015).

Estuaries

Oregon's estuaries are crucial habitat for many species, including juvenile salmon and shellfish larvae. West Coast estuarine managers are most concerned about how sea level rise and OA will affect conservation of tidal wetland habitat and threatened species (Thorne *et al.*, 2016). Climate change is expected to alter estuarine habitat through changes in sea level, OA, water temperature, upwelling, freshwater runoff, and sedimentation. Higher sea levels would reduce wetland habitat for salmonid, and warmer waters would increase thermal stress and susceptibility to disease and predation (Wainwright and Weitkamp, 2013). In the Tillamook Bay estuary, for example, changes in relative sea level, wind, waves, and freshwater input were projected to result in higher total water levels everywhere, with some areas more exposed than others (Cheng *et al.*, 2015). Increases in coastal marsh vegetation due to fertilization by increasing CO_2 may provide some resilience to relative sea level rise inundation (Ratliff *et al.*, 2015). In the Yaquina Estuary at Newport, a 5.4°F increase in air temperature was projected to result in 1.3–2.9°F warming in the estuarine waters, with the upper portion experiencing up to 40 more days not meeting water temperature criteria for the protection of rearing and migrating salmonids (Brown *et al.*, 2016).

Box 4.1: West Coast Shellfish Industry Adapting to Ocean Acidification

Oregon's coastal waters are highly exposed to global ocean acidification (OA). Already, naturally occurring deep acidic waters upwell seasonally along the coast, which will be amplified by additional absorption of atmospheric carbon dioxide (CO_2) by the ocean. The Pacific Northwest's coastal waters are some of the first to experience the severe impacts of OA, exemplified during the repeated production failures experienced by the West Coast shellfish industry in the mid-2000s in which economic losses were substantial (Chan *et al.*, 2016; Mabardy *et al.*, 2015). For example, overall production at the Whisky Creek Shellfish Hatchery in Netarts Bay, Oregon, was 25% of normal in 2008 (Barton *et al.*, 2015).

Shellfish production is important to the West Coast economy, including the northern Oregon coast (Ekstrom *et al.*, 2015). Oregon's Whiskey Creek Shellfish Hatchery in Netarts Bay is one of three major commercial hatcheries in the Pacific Northwest that supplies shellfish larvae to the West Coast shellfish industry (Barton *et al.*, 2015). In Oregon, shellfish production in 2009 generated more than $3 million in sales (Barton *et al.*, 2015). For many Indigenous coastal communities, shellfish and traditional clam beds are integral to their culture, economy, and diets (Weatherdon *et al.*, 2016a).

In a 2013 survey of West Coast shellfish producers, the vast majority believed that OA is occurring, more than 80% noted that OA will have consequences today, and about half have already personally experienced its negative impacts (Mabardy *et al.*, 2015). More than half of West Coast shellfish producers in the 2013 survey felt they would be able to adapt, at least in the short-term (Mabardy *et al.*, 2015).

In response to OA impacts in the mid-2000s, the West Coast shellfish industry partnered with academic researchers to understand and implement strategies to mitigate OA effects (Barton *et al.*, 2015). As a global problem, the long-term solution to ocean acidification is global reductions in CO_2 emissions, but until then local adaptation measures will be necessary (Ekstrom *et al.*, 2015). Adaptation strategies for the shellfish industry have included: 1) monitoring water quality and understanding the influence of water chemistry on shellfish production, 2) treating water to improve water chemistry for production, 3) moving hatchery operations away from the highly exposed coastal waters of the Pacific Northwest—to Hawaii in one case, and 4) an emerging strategy to selectively breed for oyster strains more resistant to OA (Barton *et al.*, 2015; Chan *et al.*, 2016). In addition, several coastal tribes in the Pacific Northwest are beginning to investigate impacts and adaptation strategies of OA on their traditional shellfish harvests, including the Confederated Tribes of the Siletz Indians on Oregon's coast (Kathy Lynn, pers. comm.).

"The Pacific Northwest shellfish industry cannot treat the entire coastal ocean, and the general deterioration of coastal water quality is a pressing concern for the entire industry" (Barton *et al.*, 2015).

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Chapter 5: Forest Ecosystems

Summary

Future warming and changes in precipitation may considerably alter the spatial distribution of suitable climate for many important tree species and vegetation types in Oregon by the end of the 21st century. Changing climatic suitability and forest disturbances from wildfires, insects, diseases, and drought will drive changes to the forest landscape in the future. Conifer forests west of the Cascade Range may shift to mixed forests and subalpine forests would likely contract. Human-caused increases in greenhouse gases are partially responsible for recent increases in wildfire activity. Mountain pine beetle, western spruce budworm, and Swiss needle cast remain major disturbance agents in Oregon's forests and are expected to expand under climate change. More frequent drought conditions projected for the future will likely increase forest susceptibility to other disturbance agents such as wildfires and insect outbreaks. Adaptive forest management will be critical going forward in order to reduce wildfire hazards, to promote forests that are resilient to insects and diseases, and to maintain a suitable habitat for Oregon's wildlife.

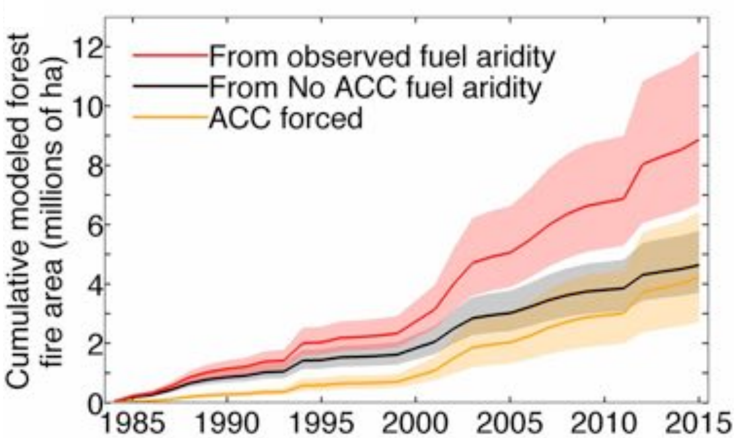
Introduction

Future warming and changes in precipitation may considerably alter the spatial distribution of suitable climate for many important tree species and vegetation types in Oregon by the end of the 21st century (Littell *et al.*, 2013). Furthermore, the cumulative effects of changes due to wildfire, insect infestation, tree diseases, and the interactions between them, will likely dominate changes in forest landscapes over the coming decades (Littell *et al.*, 2013). Forest management practices will continue to affect the forest economy and the resilience to climate change of forests and the wildlife they support.

Wildfire

Over the last several decades, warmer and drier conditions during the summer months have contributed to an increase in fuel aridity and enabled more frequent large fires, an increase in the total area burned, and a longer fire season across the western United States, particularly in forested ecosystems (Dennison *et al.*, 2014; Jolly *et al.*, 2015; Westerling, 2016; Williams and Abatzoglou, 2016). The lengthening of the fire season is largely due to declining mountain snowpack and earlier spring snowmelt (Westerling, 2016). In the Pacific Northwest, the fire season length increased over each of the last four decades, from 23 days in the 1970s, to 43 days in the 1980s, 84 days in the 1990s, and 116 days in the 2000s (Westerling, 2016). Recent wildfire activity in forested ecosystems is partially attributed to human-caused climate change: during the period 1984–2015, about half of the observed increase in fuel aridity and 4.2 million hectares (or more than 16,000 square miles) of burned area in the western United States were due to human-caused climate change (Abatzoglou and Williams, 2016) (fig. 5.1).

Figure 5.1 Attribution of western US forest fire area to anthropogenic climate change (ACC). Cumulative forest fire area estimated from the (red) observed fuel aridity record and (black) the fuel aridity record after exclusion of ACC (No ACC). The (orange) difference in the forest fire area forced by anthropogenic increases in fuel aridity. (Figure source: Abatzoglou and Williams, 2016)



The extent of the area burned in forests of the Pacific Northwest is highly correlated with the summer water balance deficit, or fuel aridity (Littell *et al.*, 2016). Summer water balance deficit is defined as the difference between potential evapotranspiration (how much moisture evaporation from vegetation is possible given the conditions of the atmosphere) and actual evapotranspiration (how much moisture actually evaporates from the vegetation). Larger differences indicate drier vegetation. In the future, the summer water balance deficit is projected to increase across most of Oregon, with the most pronounced increases in southern Oregon, the eastern Cascade Range, and parts of the Blue Mountains (Littell *et al.*, 2016). In non-forested areas of the Pacific Northwest, a strong predictive indicator of potential burn area is high antecedent winter precipitation (conducive to large fuel accumulation) coupled with low summer precipitation (Littell *et al.*, 2016).

Under future climate change, wildfire frequency and area burned are expected to continue increasing in the Pacific Northwest (Barbero *et al.*, 2015; Sheehan *et al.*, 2015) (fig. 5.2). Model simulations for areas west of the Cascade Range, including the Klamath Mountains, project that the fire return interval, or average number of years between fires, may decrease by about half, from about 80 years in the 20th century to 47 years in the 21st century (Sheehan *et al.*, 2015). The same model projects an increase of almost 140% in the annual area burned in the 21st century compared to the 20th century, assuming effective fire suppression management and a high emissions pathway (RCP 8.5) (Sheehan *et al.*, 2015). In the eastern mountains of the Pacific Northwest, an area that includes the northern Rocky Mountains and the Blue Mountains, the mean fire return interval is projected to decrease on average by 81%, while the annual percent area burned is projected to increase by 36%, assuming that effective fire suppression can be maintained under the high emissions pathway (RCP 8.5) (Sheehan *et al.*, 2015). In the Northwestern Plains and Plateaus region, which includes parts of the Columbia Basin and Great Basin, fire frequency and annual percent area burned are projected to decrease under fire suppression but increase under non–fire suppression management scenarios (Sheehan *et al.*, 2015). Furthermore, the probability of climatic conditions conducive to very large wildfires is projected to increase by the end of the century in the western United States (Barbero *et al.*, 2015; Stavros *et al.*, 2014).

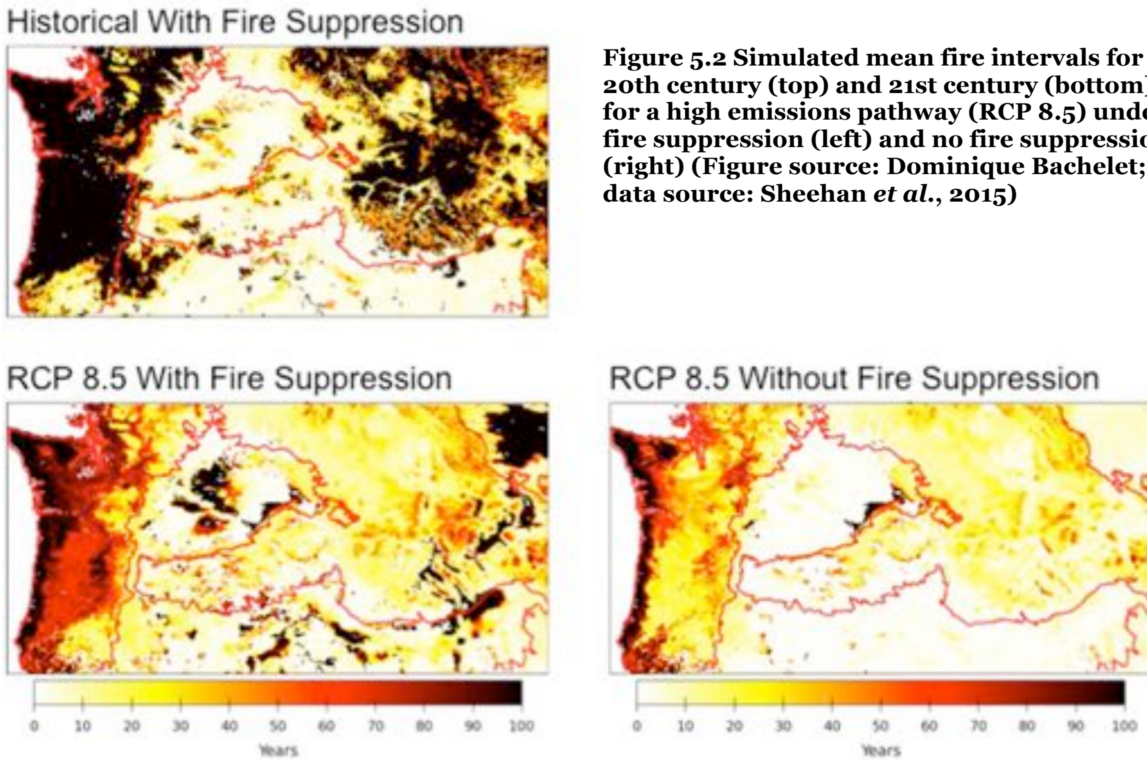


Figure 5.2 Simulated mean fire intervals for 20th century (top) and 21st century (bottom) for a high emissions pathway (RCP 8.5) under fire suppression (left) and no fire suppression (right) (Figure source: Dominique Bachelet; data source: Sheehan *et al.*, 2015)

Monitoring the severity of wildfires is useful for determining the ecosystem impact of fires, but research on future changes in wildfire severity has been lacking (Littell *et al.*, 2013). In an analysis of recent large fires in the Rocky Mountains, burn severity was influenced more by vegetation and topography than by weather and fire danger, suggesting that climate change may have different effects on fire severity than on fire extent or frequency, which have clearer relationships to climate (Birch *et al.*, 2015). However, in the north Cascade Range, large fire extent was associated with higher severity fires, the strongest relationships being observed in contiguous sub-alpine forests (Cansler and McKenzie, 2014). A recent study projects decreasing fire severity for the western US, assuming an equilibrium between climate and vegetation, largely due to decreasing biomass from increasing aridity and fire activity (Parks *et al.*, 2016). However, active fire suppression has resulted in a disequilibrium between climate and vegetation such that fire severity may increase due to the accumulation of fuels where suppression is maintained. Fire suppression has resulted in less frequent fires than would naturally occur in many western US forested areas, particularly in lower-elevation forests (Parks *et al.*, 2015); but, in non-forested regions, fires are more frequent than would occur naturally, likely due to increases in introduced annual invasive grasses (Balch *et al.*, 2013). Management practices that reestablish natural disturbance regimes may assist in transitioning current vegetation types to ones more in equilibrium with climate, which could help to reduce future fire severity (Parks *et al.*, 2016).

Projected increases in wildfires will have far-reaching effects on: aquatic ecosystems (Bixby *et al.*, 2015), snow and glacier hydrology (Gleason and Nolin, 2016; Kaspari *et al.*, 2015), air quality (Liu *et al.*, 2016) (see Chapter 7), ecosystem services (Lee *et al.*, 2015), and the economy (Mills *et al.*, 2015). Managing forest fuels over the 21st century in order to reduce fires and to minimize losses in ecosystem services on conservation lands in the

United States is projected to cost $3.5 billion more under a very high emissions pathway (REF 10) compared to a very low emissions pathway (POL 3.7) (in 2005 dollars discounted at 3%) (Lee *et al.*, 2015). In other words, substantial global greenhouse gas mitigation would benefit future forest management costs. Forest management cost benefits may be greatest in the Pacific Northwest, compared to other US regions, in which substantial global mitigation would result in nearly $1.3 billion of benefits, or 37% of the total benefits to the United States (Lee *et al.*, 2015).

To face the increase in burned area and fire severity projected for forests in the Pacific Northwest, particularly eastern dry forests, key adaptation strategies include: 1) being prepared to manage larger burned areas, 2) increasing the resilience of existing vegetation by reducing hazardous fuels, forest density, and homogeneity, and 3) managing forest landscapes toward an equilibrium between fire occurrence and the environment (Halofsky and Peterson, 2016). Prescribed burning and frequent, judicious thinning in dry forest types can be an effective way to reduce fire severity, but there is little known about how such management actions will interact with climate change and growing human populations (Wimberly and Liu, 2014). Although removal of small trees may reduce wildfire risk, small trees increase forest resilience to insect outbreaks (Baker and Williams, 2015). Planned diversity in tree sizes, ages, and species would provide the heterogeneity that provides greater resilience to a broad array of future disturbances in dry forests (Baker and Williams, 2015).

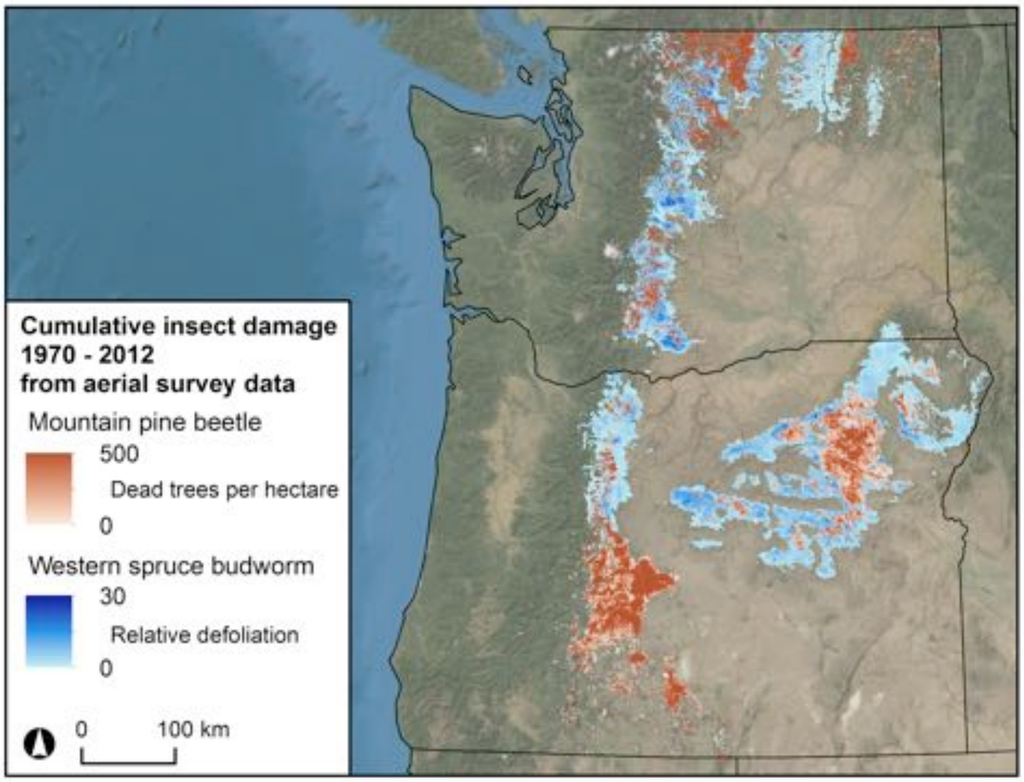
Insects & diseases

Warming and more frequent drought will likely lead to a greater susceptibility among trees to insects and pathogens, a greater risk of exotic species establishment, more frequent and severe forest insect outbreaks (Halofsky and Peterson, 2016), and increased damage by a number of forest pathogens (Vose *et al.*, 2016). In Oregon and Washington, mountain pine beetle (*Dendroctonus ponderosae*) and western spruce budworm (*Choristoneura freemani*) are the most common native forest insect pests, and both have caused substantial tree mortality and defoliation over the past several decades (Meigs *et al.*, 2015b) (fig. 5.3). Western spruce budworm has had a greater impact on forests in terms of extent infested, especially in the Blue Mountains region, even though the mountain pine beetle, causing mortality particularly in the central Oregon eastern Cascade Range, often receives more management attention (Meigs *et al.*, 2015b). Climate, along with forest structure and host-pest interactions, affects the outbreaks of these insects.

Climatic warming has facilitated the expansion and survival of mountain pine beetles, particularly in areas that have historically been too cold for the insect (Littell *et al.*, 2013). Across the western United States, the time between generations among different populations of mountain pine beetles is similar; however, the amount of thermal units required to complete a generation cycle was significantly less for beetles at cooler sites (Bentz *et al.*, 2014). Winter survival and faster generation cycles could be favored under future projections of decreases in the number of freeze days (Rawlins *et al.*, 2016).

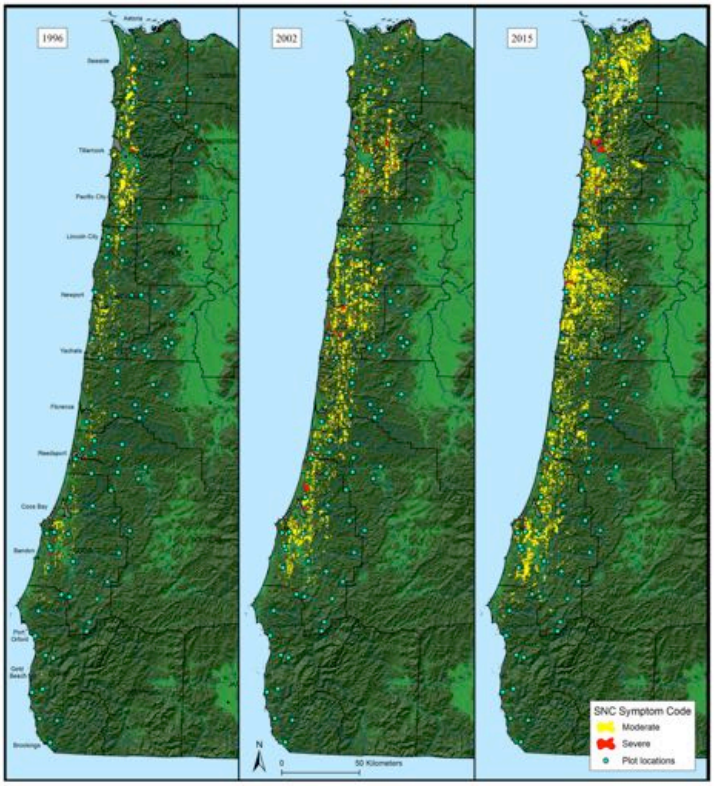
Western spruce budworm is a destructive defoliator that sporadically breaks out in interior Oregon Douglas-fir (*Pseudotsuga menziesii*) forests (Flower *et al.*, 2014). An analysis of three hundred years of tree ring data reveals that outbreaks tended to occur near the end of a drought, when trees' physiological thresholds had likely been reached. This analysis suggests that such outbreaks would likely intensify under the more frequent drought conditions that are projected for the future (Flower *et al.*, 2014), unless increasing atmospheric carbon dioxide, which may enhance water use efficiency, mitigates drought stress.

Figure 5.3 Cumulative effects of western spruce budworm and mountain pine beetle on tree defoliation and mortality in forests of Oregon and Washington (1970–2012). Total forested area is about 25 million hectares, and these two insects affected 8 million hectares according to aerial surveys. Beetle overlaps budworm activity in this display. (Figure source: Garrett Meigs; data source: Meigs *et al.*, 2015)



Recent findings suggest that wildfire likelihood is not consistently affected by mountain pine beetle outbreaks across Oregon and Washington forests east of the Cascade Range, but that the likelihood of wildfire following western spruce budworm outbreaks is lowered (Meigs *et al.*, 2015a). Furthermore, wildfires following both types of insect outbreaks were generally less severe, contrary to common assumptions, because the outbreaks reduce the amount of live vegetation susceptible to wildfire (Meigs *et al.*, 2016). In the first few years following mountain pine beetle outbreaks, however, fire severity could potentially increase due to the abundance of highly flammable red needles in the canopy layer, but further studies are needed to investigate this relationship. Fire events during this early post-outbreak period have been relatively rare in Oregon and Washington (Meigs *et al.*, 2016). While both mountain pine beetle outbreaks and fire activity have increased in the western United States during recent decades, current evidence demonstrates that bark beetle activity has not directly influenced annual area burned (Hart *et al.*, 2015).

Figure 5.4 Spatial pattern of Swiss needle cast-symptomatic Douglas-fir in the Coast Range of Oregon as determined by aerial detection survey in 1996, 2002, and 2015. Yellow indicates moderate symptoms, while red indicates severe symptoms. The blue dots represent new plot network (Figure source: Ritóková *et al.*, 2016).



Certain tree diseases with known climate associations are also expected to increase in the future (Littell *et al.*, 2013). One such disease is Swiss needle cast (*Phaeocryptopus gaeumannii*), which affects Douglas-fir and can have significant economic impacts. In the Oregon Coast Range, warmer temperatures and increasing spring precipitation has contributed to a greater severity and distribution of Swiss needle cast (Littell *et al.*, 2013). The distribution of Swiss needle cast increased from about 205 square miles in 1996 to about 922 square miles of affected trees in 2015 in the Coast Range (fig. 5.4) (Ritóková *et al.*, 2016). Swiss needle cast stunts Douglas-fir growth by 23% on average (Ritóková *et al.*, 2016). Swiss needle cast disease severity is expected to increase with warmer winters at higher elevation coastal sites and at inland sites where fungal growth is currently limited by cold winter temperatures (Lee *et al.*, 2013). The changing incidence of Swiss needle cast can affect mixed-species forest stands by allowing increased western hemlock (*Tsuga heterophylla*) growth in stands where severe Swiss needle cast affects Douglas-fir growth (Zhao *et al.*, 2014).

In order to minimize the impacts from insect and disease outbreaks, important adaptation strategies include increasing forest stand and landscape resilience by increasing tree vigor, promoting a diverse mix of tree ages and sizes, and re-vegetating with native plant species (Halofsky and Peterson, 2016). For example, planting western hemlock and other tree species can limit the spread of Swiss needle cast (Zhao *et al.*, 2014).

Direct climate effects

Temperature

Trees have direct physiological responses to climate. Cool fall temperatures and shorter day lengths help trigger dormancy, where all growth is suspended, to help the tree withstand freezing winter temperatures. Once a sufficient cold "chilling" period has been experienced, warm spring temperatures prompt the tree to come out of dormancy and begin to grow again. There is a tradeoff between the amount of chilling and the warm temperatures required for trees to grow actively. Trees that receive adequate chilling require less forcing from warm spring temperatures in order to come out of dormancy (Harrington and Gould, 2015).

Some of Oregon's more prevalent tree species, such as Douglas-fir and western hemlock, must experience a chilling period before sufficient spring warming can bring them out of dormancy. If the chilling requirement is not met during winter, the warm spring temperatures may not bring trees out of dormancy or the tree may not grow normally (Harrington and Gould, 2015). By the 2080s under a medium-high emissions pathway (SRES A2), the chilling requirement for Douglas-fir in Oregon is still projected to be met, despite warming winter minimum temperatures (Harrington and Gould, 2015). Spring onset and bud burst of Douglas-fir is expected to occur earlier throughout Oregon, with the greatest changes expected to be seen at higher elevations where temperatures have often been the most important limiting factor to growth (Harrington and Gould, 2015).

In the Pacific Northwest, warm spring temperatures are coming earlier in the year, resulting in earlier spring plant growth (Peterson and Abatzoglou, 2014). This early spring onset may put trees at risk to cold damage when hard freezes occur after the trees have come out of dormancy, creating what is referred to as a "false" spring. However, over the past 30 years, the last spring freeze has also started occurring earlier in the year. This shift has in fact resulted in fewer false springs over the past 30 years in the Pacific Northwest (Peterson and Abatzoglou, 2014). Averaged over the United States, spring onset is projected to occur 23 days earlier under a high emissions pathway (RCP 8.5) by the end of the century, with the largest changes in the western United States (Allstadt *et al.*, 2015). The risk of false springs is projected to continue to be mitigated by earlier last freezes in the future under the high emissions pathway (RCP 8.5), as temperatures would be warm enough by the time of spring onset in order to avoid hard freezes (Allstadt *et al.*, 2015).

Drought

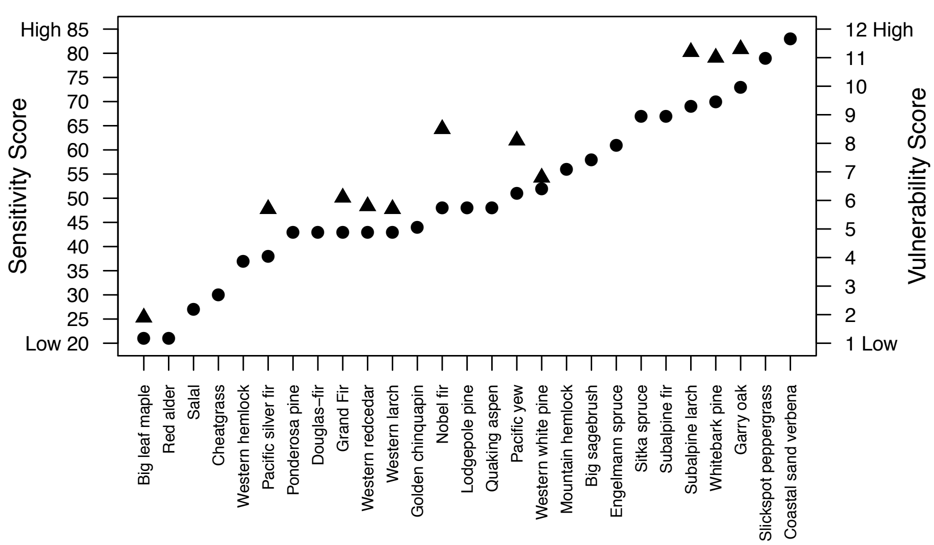
Oregon has in the past experienced droughts of varying frequency and magnitude. In the future, drought conditions during the growing season are projected to become more intense and to occur more frequently under warmer temperatures, which will have implications for Oregon's current vegetation (Littell *et al.*, 2013). Seasonal droughts are common in Oregon because the warmest time of the year receives the least amount of precipitation. Oregon's current vegetation is adapted to these relatively short, moderate droughts, but trees may become more vulnerable to mortality under hotter, future droughts (Allen *et al.*, 2015). Warmer temperatures during drought can directly cause stress to trees by increasing the evaporative demand (since warm air can hold more moisture than cooler air), further exacerbating water limitations (Allen *et al.*, 2015). Increased evaporative demand during the growing season has been shown to decrease growth in Douglas-fir trees across the Pacific Northwest (Restaino *et al.*, 2016). During extreme drought, water stress can cause hydraulic failure through xylem cavitation, which has been shown to be a major mortality mechanism in warmer regions (Anderegg *et al.*, 2013). Under a high emissions pathway (RCP 8.5), warming is expected to cause mortality and to induce drought stress in arid climatic regions similar to southern Oregon by mid-century (Anderegg *et al.*, 2015). Drought stress may be partially moderated by increasing atmospheric carbon dioxide (CO_2) concentrations. Plants acquire CO_2 for photosynthesis through their stomata (pores on plant leaves and other plant parts), but they simultaneously may lose water to the atmosphere while their stomata are open. Under higher atmospheric CO_2 concentrations plants may be able to keep their stomata open for shorter amounts of time, acquiring the same amount of CO_2 while losing less water to evapotranspiration (Swann *et al.*, 2016).

Prolonged periods of warm temperatures, low humidity, and low soil moisture can lead to tree mortality and make trees more susceptible to insect and disease outbreaks and wildfires (Clark *et al.*, 2016). In the western United States, drought impacts are already apparent, and climate change will continue to stress forests (Clark *et al.*, 2016). If climate change results in more frequent low-severity droughts, forests and rangelands may self-select for more drought-tolerant genotypes or even species without needing management intervention; however, more severe droughts combined with more frequent wildfires or insect outbreaks may cause large-scale transformation that would require management responses (Vose *et al.*, 2016). Adaptation measures to improve forest resilience to increasing drought stress can be achieved through forest management practices such as targeted and iterative thinning, selecting a broad range of drought-tolerant species and genotypes, protecting tree diversity by collecting seeds from trees exhibiting adaptation to water stress (seed banking), facilitating regeneration by planting or seeding with genotypes or species that are adapted to local conditions or that are perhaps more tolerant of drought, focusing on functional ecosystems rather than individual species to maintain forest productivity, and developing structurally complex stands (Clark *et al.*, 2016; Halofsky and Peterson, 2016).

Forest vegetation transformation

The spatial distribution of suitable climates for many important tree species and vegetation types in the Pacific Northwest may change considerably by the end of the 21st century (Littell *et al.*, 2013), and different trees have varying degrees of sensitivity to climate change and adaptive capacity (Case *et al.*, 2015; Case and Lawler, 2016) (fig. 5.5).

Figure 5.5 Climate sensitivity (circles) and vulnerability (triangles) of some Pacific Northwest tree and plant species. (Figure source: Meghan Dalton; data sources: Case *et al.*, 2015, Case and Lawler, 2016)



Vegetation can adapt to changing local environmental conditions in a variety of ways. First, individual trees have inherent survival mechanisms that enable them to respond and adapt to changing conditions. However, this ability to acclimate in place is limited even for the most tolerant species (Peterson *et al.*, 2014). Secondly, tree species can adapt by genetically evolving through natural selection. This type of evolution takes several generations, reducing the potential for rapid population acclimation (Peterson *et al.*, 2014), but a latitudinal or elevational gradient within the species range may provide the genetic diversity needed to manage future forests. Lastly, tree species can adapt to a changing climate by migrating to areas with more suitable climate conditions. This requires seed availability at the new site and suitable conditions for establishment and persistence (Peterson *et al.*, 2014). Seed availability declines toward the edges of most tree population ranges, and this limitation may inhibit migration (Kroiss and HilleRisLambers, 2015). These three mechanisms provide pathways for adaptation; however, the rate of climate induced shifts in habitat are expected to outpace the reorganization of forest stand structure and species composition through evolution and migration (Vose *et al.*, 2016). Subalpine forests are most at risk, as suitable habitat for these species is projected to be severely reduced or even non-existent by the end of the 21st century (Peterson *et al.*, 2014).

Disturbances such as wildfire, drought, and insect outbreaks are the primary agents for ecological change in forests and can catalyze forest transformations (Vose *et al.*, 2016). The combined impact of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are likely to cause additional forest mortality and long-term transformation of the forest landscape (Mote *et al.*, 2014). Between 1984 and 2012, moderate to high severity fires and bark beetle outbreaks accounted for about 4% and 2% mortality in Oregon forested land, respectively (Hicke *et al.*, 2016). Disturbance dynamics have shifted from timber harvests and land use changes to natural disturbances such as wildfires, insect outbreaks, and diseases over recent decades (Cohen *et al.*, 2016).

Insect and pathogen driven mortality is pervasive throughout Oregon but remains generally at low levels. Wildfires are less common but result in partial- to stand-replacing disturbances with higher mortality levels (Reilly and Spies, 2016). Stand replacing fires open up the canopy and facilitate vegetation shift. Under climate change, the tree species that grow back after a fire may be different from those that previously existed (Sheehan *et al.*, 2015). Some models suggest that forests west of the Cascade Range may shift from conifer to a mixed conifer forest in the future due to increased wildfires driven by climate change (Sheehan *et al.*, 2015) (fig. 5.6). The strong linkage between climate-related disturbances and ecosystem changes in the Pacific Northwest poses great challenges to land managers planning for the future (Oliver *et al.*, 2016).

Sub-alpine forests are particularly vulnerable to climate change (Peterson *et al.*, 2014) due to their limited ability to migrate upslope or across unfavorable landscapes. This vulnerability may result in the loss of these high-elevation habitats, affecting associated wildlife and biodiversity (Littell *et al.*, 2013). High-elevation energy-limited forests may experience increased tree growth under future warmer conditions and elevated atmospheric CO_2 concentrations. However, the extent of sub-alpine forests is ultimately expected to decline (Peterson *et al.*, 2014). Dynamic global vegetation models consistently project the contraction of sub-alpine forests and the expansion of temperate forests (Littell *et al.*, 2013; Peterson *et al.*, 2014; Shafer *et al.*, 2015; Sheehan *et al.*, 2015). Increasing forest disturbances may accelerate high-elevation vegetation changes

(Littell *et al.*, 2013). Some of the most vulnerable tree species in western North America are high-elevation species, such as subalpine larch (*Larix lyallii*) and whitebark pine (*Pinus albicaulis*) (Case and Lawler, 2016) (fig. 5.5). A key strategy will be to “monitor and detect change in seedling survival, species composition, and mortality of mature trees in subalpine forests” (Halofsky and Peterson, 2016) in order to develop coping strategies and better manage for the future.

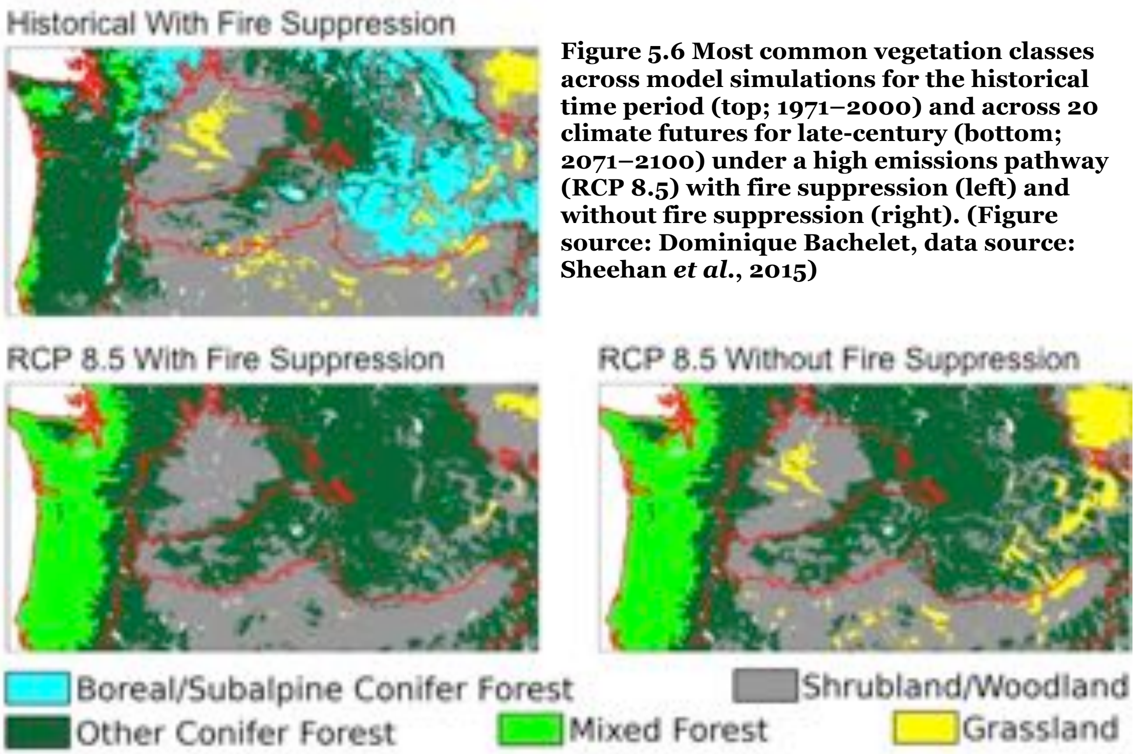


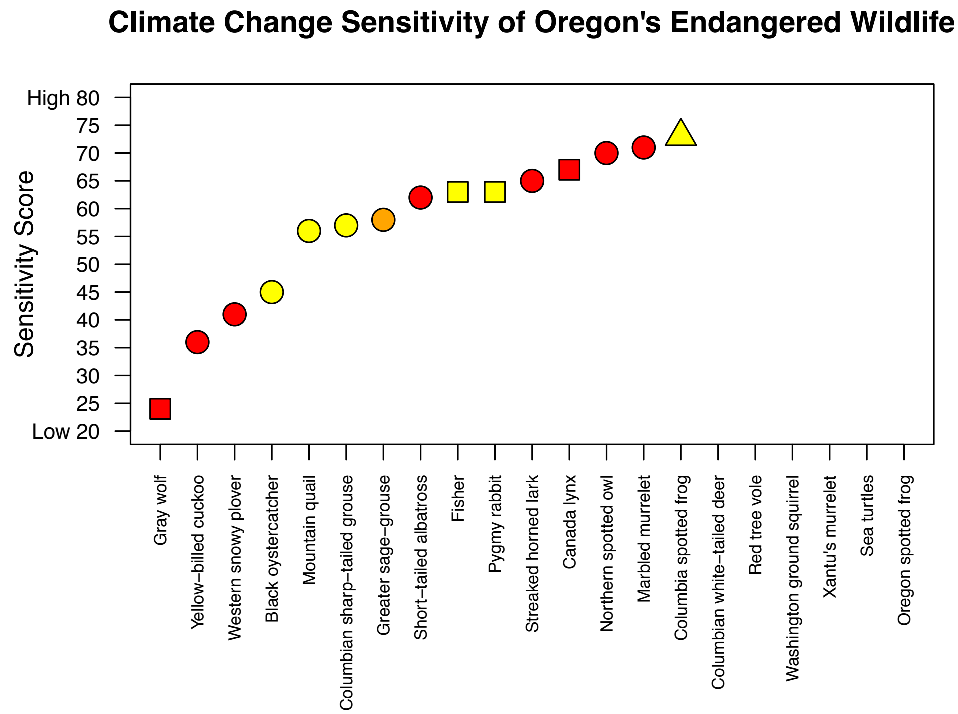
Figure 5.6 Most common vegetation classes across model simulations for the historical time period (top; 1971–2000) and across 20 climate futures for late-century (bottom; 2071–2100) under a high emissions pathway (RCP 8.5) with fire suppression (left) and without fire suppression (right). (Figure source: Dominique Bachelet, data source: Sheehan *et al.*, 2015)

Wildlife

Climate change will affect Oregon’s wildlife in a variety of ways; some species will be more sensitive to climate change than others (fig. 5.7) (Case *et al.*, 2015). At-risk species generally have higher sensitivity scores than those species without Endangered Species Act designations (Case *et al.*, 2015). Dependence on climate-sensitive habitats (such as seasonal streams, wetlands and vernal pools, seeps and springs, alpine and subalpine areas, grasslands and balds) is a large driver of species sensitivity (Case *et al.*, 2015).

Large mammals, those with fixed nighttime or daytime activity times, and species with higher latitude or elevation ranges, are more likely to be affected by climate change (McCain and King, 2014). One salient example is the American pika (*Ochotona princeps*). Although a relatively small mammal, the pika is active during the day but is intolerant of high temperatures (McCain and King, 2014). The pika is considered highly sensitive to climate change due in large part to its dependence on subalpine habitat and snow cover, which is also projected to decline (Case *et al.*, 2015). In the Great Basin, American pika distribution has changed during the 2000s, primarily at the edges of its range, owing largely to decreases in maximum snowpack and growing season precipitation (Beever *et al.*, 2013). As American pika shift to more climatically suitable habitat, they may be impeded by topographic relief, water features, and high heat exposure of west-facing slopes, as found in a study at Crater Lake (Castillo *et al.*, 2014).

Figure 5.7 Climate change sensitivity scores for endangered mammals, birds, and amphibians in Oregon. Red=listed; Orange=Candidate; Yellow=Species of Concern. Square=Mammal; Circle=Bird; Triangle=Amphibian. (Figure source: Meghan Dalton; data sources: Case et al. 2015 and https://www.fws.gov/oregonfwo/promo.cfm?id=177175701



Local climate and habitat characteristics are important for predicting pika range shifts. For example, at Crater Lake National Park, the most important for pika migration was found to be winter snowpack, but different climate and non-climate factors were more important for other National Park areas (Schwalm *et al.*, 2016). Adaptive behaviors may be key for American pika survival. In addition to migrating to higher elevations, some pika could persist at low-elevation sites, provided that they make some adjustments. For example, by altering their diet and spending more time under forest canopies to avoid high heat periods, American pika have managed to persist in an atypical low-elevation habitat in the Columbia River Gorge (Varner *et al.*, 2016; Varner and Dearing, 2014).

The distribution of some western North American bird populations appear to have already shifted in response to warmer winters and changes in precipitation (Illán *et al.*, 2014). In West Coast lowlands and mountains, including western and central Oregon, breeding distributions shifted by about 0.3 and 0.5 miles per year, respectively, between 1950 and 2011. In the temperate desert and steppe mountains, including eastern Oregon, breeding distributions shifted 0.7 and 0.9 miles per year, respectively, during the same period (Bateman *et al.*, 2016). Predicting future changes is extremely challenging as there are both climate and local non-climate factors that affect distribution change

(Bateman *et al.*, 2016). One study projects that more than half of North American bird species will lose at least half of their current range; for about two-fifths of those species, ranges will not expand to other areas by the 2080s under a medium-high emission pathway (SRES A2) (Langham *et al.*, 2015). For Oregon, that would mean breeding range losses for 28 species and breeding range gains for 13 species, on average (Langham *et al.*, 2015).

The northern spotted owl (*Strix occidentalis caurina*) and marbled murrelet (*Brachyramphus marmoratus*) are considered highly sensitive to climate (fig. 5.7) due to their vulnerability to increasing wildfire activity and dependency on old-growth habitat (Case *et al.*, 2015). The northern spotted owl is considered "climate endangered", with projected terrestrial range contractions greater than 50% without future net gains (Langham *et al.*, 2015). The marbled murrelet, on the other hand, is considered "climate stable", meaning that less than 50% of its current terrestrial range would contract under future climate scenarios (Langham *et al.*, 2015) However, changes to the marbled murrelet's marine habitat could negatively affect the population in the future (Lorenz *et al.*, 2016).

In the sagebrush-steppe ecosystem in southeastern Oregon, wildlife may be affected by numerous climate change-related stressors including invasive grasses, encroaching woody vegetation, fire, and land use (Creutzburg *et al.*, 2015). The greater sage grouse (*Centrocercus urophasianus*) is a threatened species with medium sensitivity to climate change largely because of the fact that increasing fire frequency, due to the expansion of invasive grasses caused by human activities, would reduce the shrub habitat they use for feeding, nesting, and shelter (Case *et al.*, 2015; Littell *et al.*, 2013). The greater sage grouse is also considered "climate endangered", with net range contraction expected (Langham *et al.*, 2015). In southeastern Oregon, shrub-steppe vegetation simulated by a dynamic vegetation model is projected to contract under future climate conditions and to be replaced by grassland or open woodland vegetation (Shafer *et al.*, 2015). However, in a vegetation and habitat state-and-transition model run under a range of climate and management scenarios, sage-grouse habitat declined in the first few decades due to expansion of exotic grasses, woody vegetation encroachment, and climatic unsuitability, but increased later in the century due to expanding moist shrub steppe (Creutzburg *et al.*, 2015).

Forest management in the face of climate change

"Land managers planning for a future without climate change may be assuming a future that is unlikely to exist" (Halofsky *et al.*, 2014). Forest vulnerabilities to climate change are similar across biogeographically diverse regions of the Pacific Northwest, as are many of the current adaptation options (Halofsky and Peterson, 2016). Increasing temperatures and changes in precipitation and the hydrologic cycle are expected to lead to temperature and drought stress for many tree species, making forests more susceptible to wildfire and insect attacks and leading to widespread climate-induced forest die-offs, shifts in ecosystem structure and function, a concomitant loss of habitat for plants and animals, and the loss of large carbon stores. Recent science-management partnerships have generated an extensive list of adaptation strategies and tactics, primarily focusing on increasing resilience to disturbance and reducing existing stressors; the list is being used to inform sustainable resource management in large part by adjusting existing management strategies (Halofsky and Peterson, 2016) that already have broad support and accomplish multiple goals (Kemp *et al.*, 2015).

Management principles to foster resilience to disturbance while conserving ecosystem services include: 1) managing dynamically and experimentally through a sustained commitment to adaptive management, 2) managing for ecological processes and functional characteristics instead of specific structures and species compositions, 3) considering trade-offs and conflicts that include ecological and socioeconomic sensitivities, 4) prioritizing choices that are likely to work within a range of possible futures and in crucial areas that are most exposed to changing disturbance regimes, 5) managing for realistic outcomes by focusing on a broader set of ecosystem services, and 6) treating disturbance as a management opportunity for applying adaptation strategies (Seidl *et al.*, 2016).

Tribal Considerations

Changes in forest ecosystems and disturbances will affect resources and habitats that are important for the cultural, medicinal, economic, and community health of tribes (Lynn *et al.*, 2013). In Oregon, 62% of tribal reservation land is forested, and the US government has a trust responsibility toward such forests (Indian Forest Management Assessment Team, 2013). American Indian and Alaska Native tribes that depend on forest ecosystems, whether on or off reservations, are among the first to experience the impacts that climate change is having on forests, such as the expansion of invasive species, insects, diseases, and wildfires (Norton-Smith *et al.*, 2016). Invasive species that displace native species can negatively affect tribal subsistence and ceremonial practices, although there is little knowledge about on how climate change will interact with invasive species (Norton-Smith *et al.*, 2016). Increasing wildfire, insects, and diseases have jeopardized the economic and ecological sustainability of tribally managed forests and important tribal resources (Indian Forest Management Assessment Team, 2013; Norton-Smith *et al.*, 2016). Collaborative adaptive forest management that integrates tribal traditional ecological knowledge can support socio-ecological resilience to climate change (Armatas *et al.*, 2016).

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Chapter 6: Agriculture

Summary

Agriculture, one of Oregon's largest industries, will experience both positive and negative outcomes as the climate continues to change. The impacts will vary across crops and regions. Over the next decade or two, warming winters, expanding growing seasons, and carbon dioxide enrichment may boost yields for some Oregon crops and create opportunities to grow new crops and varieties. For other crops such as tree fruits, warming winters may prevent adequate chilling hours needed for a healthy crop yield. Any benefits hinge on having adequate water supply, which is projected to dwindle during parts of the year with particular impacts on areas that rely on snowpack. Over the long term, increased heat and drought stress, water shortage, and pressure from pests and diseases may supersede the positive benefits of increased crop yield. Improved irrigation and efficient water management strategies will be necessary to resiliently handle heat and drought stress and longer growing seasons. Consideration of alternative crops and varieties and farm management strategies will be important to maintain reliable and profitable operations under a changing climate. Additionally, cost-benefit tools and analyses are needed to aid farmers' decisions.

Introduction

Agriculture in Oregon is diverse and is one of the state's largest industries. Farmland covers more than a quarter of Oregon's land, and the industry generated nearly $4.9 billion in gross agricultural products in 2012 (National Agricultural Statistics Service, 2014)—about 13% of all Oregon sales—and is linked to nearly 14% of Oregon jobs (Sorte and Rahe, 2015).

Climate change—warming temperatures, altered precipitation patterns, reduced water availability, and increasing carbon dioxide—is likely to affect crop planting schedules, pest management strategies, crop growth, crop yields, livestock health, soil retention, and more (Eigenbrode *et al.*, 2013). In the near term, climate change may benefit some Oregon crops by boosting crop yields through carbon dioxide fertilization, by enhancing productivity during warmer winters and a longer growing season, and by creating opportunities to grow new varieties and crops (Eigenbrode *et al.*, 2013). Such benefits hinge on having adequate water supply, which is projected to dwindle in irrigated areas that rely on snowpack (see Chapter 3).

Over the long term, increased heat and drought stress, water shortage, and pressure from pests and diseases may supersede the positive benefits of any increased yields. The impacts will be crop and region dependent. People in the Pacific Northwest are generally aware of the higher risk of food shortages and crop failure due to climate change (Bernacchi *et al.*, 2015). Keeping Oregon's agriculture industry resilient in the face of a changing climate will require flexibility in crop choices and crop management (Creighton *et al.*, 2015).

This chapter restates key findings from the agriculture chapter of the previous Oregon climate assessment (Eigenbrode *et al.*, 2013) and a recent synthesis on climate impacts to agriculture sectors done by the Northwest Regional Climate Hub (Creighton *et al.*, 2015) while incorporating recent publications. For more in depth coverage on a topic, the reader is referred to relevant sections in those reports.

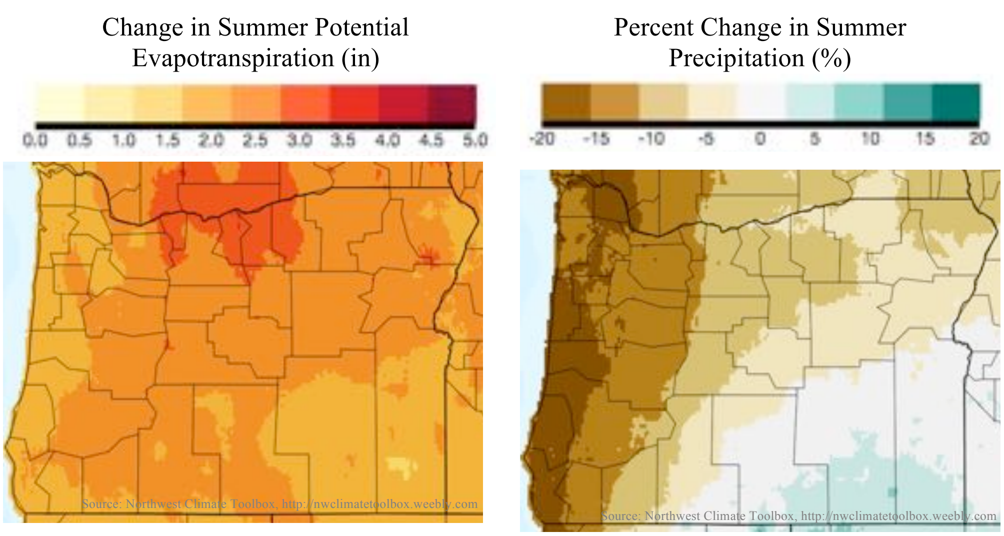
Water Availability & Drought Stress

Adequate water supply is paramount for agriculture. About 42% of Oregon farms use irrigation and about 10% of Oregon's total farm acres are irrigated (National Agricultural Statistics Service, 2014). Irrigated areas that rely on dwindling mountain snowpack (Mote and Sharp, 2015) to supply increasing summer water demands (Abatzoglou *et al.*, 2014) are particularly vulnerable to water scarcity. Irrigated areas in rain dominant watersheds and rain-fed cropping systems are less vulnerable, but may still experience increased drought stress due to projected decreases in summer precipitation, soil moisture, and increased evapotranspiration (fig. 6.1) (Eigenbrode *et al.*, 2013).

Increased winter precipitation projected for the Pacific Northwest may improve soil moisture conditions for establishing spring crops, but wetter soils in spring could impede spring planting operations in some systems (Eigenbrode *et al.*, 2013).

Improved management strategies for irrigation water may be necessary to handle heat and drought stress and longer growing seasons (Creighton *et al.*, 2015). Already, irrigation decisions made by producers are influenced by water scarcity, climate and extreme heat and drought (Olen *et al.*, 2016). Farmers surveyed in the Colorado River Basin are most concerned about water, drought, and climate change, and most are already prioritizing and enacting water conservation strategies (Greenberg *et al.*, 2016). Oregon farmers are also implementing water conservation strategies. For example, producers in eastern Oregon are replacing open irrigation ditches with closed buried pipes to reduce evaporation (Stevenson, 2016) (see Chapter 2).

Figure 6.1 Multi-model mean projected change in summer (Jun-Jul-Aug) potential evapotranspiration (left) and precipitation (right) between a high emissions pathway (RCP 8.5) for the 2040–2069 average and historical baseline 1971–2000 average. (Figure source: Northwest Climate Toolbox, http://nwclimatetoolbox.weebly.com)



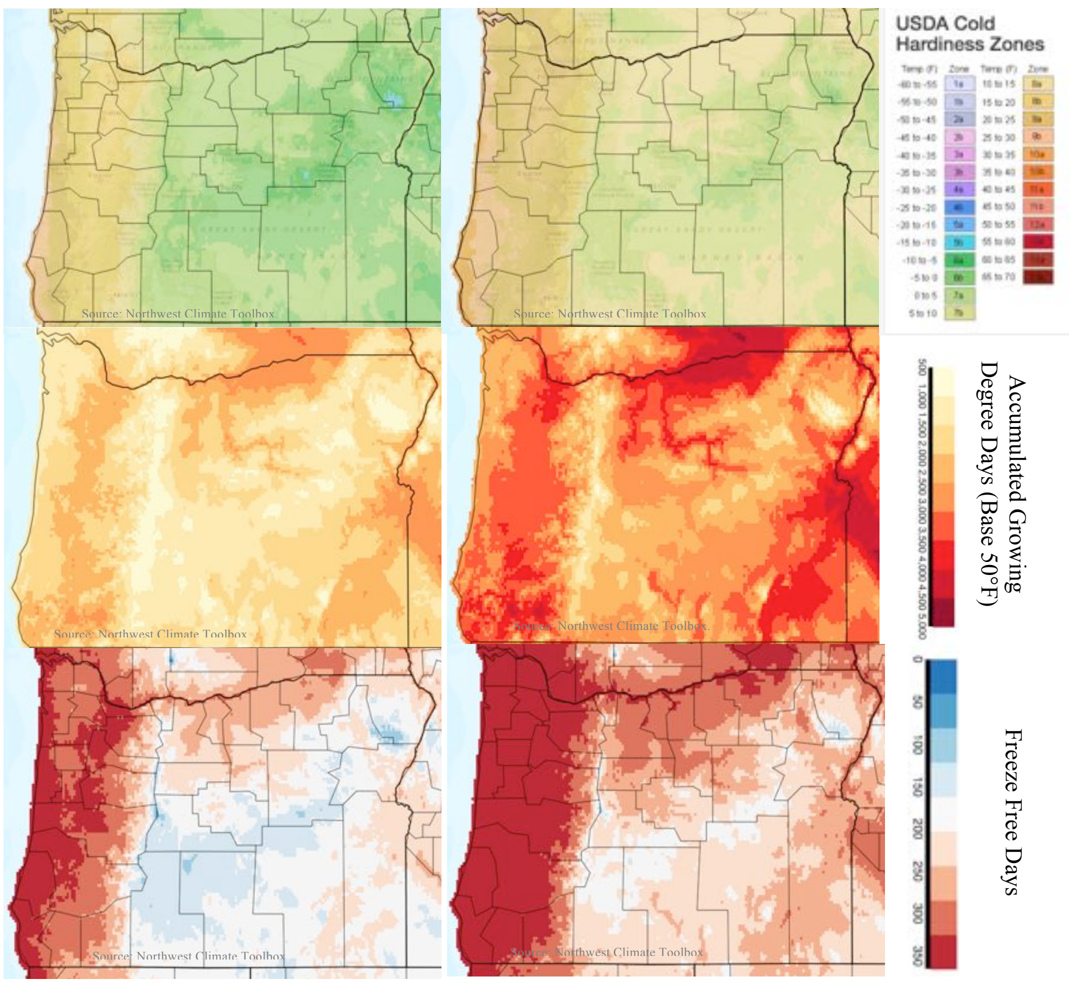
Heat Stress & Longer Growing Season

Climate change will result in year-round warming and more heat extremes, leading to greater risk of heat stress, reducing yields and yield stability for many crops and livestock (Eigenbrode et al., 2013). On the other hand, warmer winters could boost productivity and survival of winter crops and cold-sensitive perennials (Eigenbrode et al., 2013).

Longer growing seasons and greater accumulation of growing degree days (fig. 6.2) would create opportunities for selecting alternative crops and varieties (Eigenbrode et al., 2013). The freeze-free season lengthened by about two weeks in the Pacific Northwest during 1901–2012 (Abatzoglou et al., 2014).

Spring plant growth, coaxed earlier from the soils by warmer temperatures, could be vulnerable to subsequent spring freezes called “false springs.” However, observations have shown fewer false springs consistent with expectations in a warming climate (Peterson and Abatzoglou, 2014). The last spring freeze has occurred about a week earlier across the Pacific Northwest (Abatzoglou *et al.*, 2014).

Figure 6.2 (top) Cold hardiness zones, (middle) accumulated growing degree-days (base 50°F), and (bottom) growing season length (freeze-free days) for the historical period 1971–2000 and future period 2040–2069 under the high emissions pathway (RCP 8.5) for the multi-model mean. (Figure source: Northwest Climate Toolbox, http://nwclimatetoolbox.weebly.com)



Carbon Dioxide Enrichment

Increasing atmospheric carbon dioxide (CO_2) may boost crop growth and increase drought tolerance through increasing water use efficiency of some crops, but this benefit is largely constrained to the next several decades (Eigenbrode *et al.*, 2013). Higher CO_2 in the air can also lower the nutritional value of some staple foods, such as wheat, by reducing protein and essential mineral concentrations (Ziska *et al.*, 2016).

Pests & Pathogens

Crop pests and pathogens may continue to migrate poleward under global warming as has been observed globally for several types since the 1960s (Bebber *et al.*, 2013). Much remains to be learned about which pests and pathogens are most likely to affect certain crops as the climate changes, and about which management strategies will be most effective.

Soil Erosion

Climate change has the potential to impact soil health and productivity through altered topsoil erosion patterns by wind and water. Soil erosion is a key climate-related concern particularly for dryland farmers in the Columbia Plateau (Farrell *et al.*, 2015). In a Columbia Plateau winter wheat–summer fallow crop rotation, erosion by wind is projected to decline 25–84% largely due to increased biomass from CO_2 enrichment and warmer temperatures by mid-century under a low emissions pathway (RCP 4.5) (Sharratt *et al.*, 2015). In a wetter region of the Plateau (the Palouse in Washington), 4°F of warming resulted in a nearly three-fold increase in soil loss largely during winter due to reduced snow on the ground and increases in rain and snowmelt (Farrell *et al.*, 2015). Higher soil retention was achieved both in wind and water erosion modeling studies under conservation tillage compared with conventional tillage (Farrell *et al.*, 2015; Sharratt *et al.*, 2015).

Climate Change Impacts on Selected Commodities

The impacts of climate change on agriculture will depend on crop and region. This section discusses impacts to select US Department of Agriculture commodity groups. Climate change may require reconsideration of crop systems and farming operations; cost and benefit analyses of alternative choices is a major need to assist farmers in adapting to climate change (Creighton *et al.*, 2015).

Grains, oilseeds, dried beans, and dried peas

Grains, oilseeds, dried beans, and dried peas production in Oregon generated $570 million in sales in 2012 (National Agricultural Statistics Service, 2014). The semi-arid climate in the northeastern Oregon Columbia plateau supports dryland cereal-based cropping systems, which are particularly important as a source of revenue to the Confederated Tribes of the Umatilla Indian Reservation (Confederated Tribes of the Umatilla Indian Reservation, 2015). Parts of the cooler, wetter Willamette Valley also support dryland cropping. Warmer and drier summers in these areas would increase risks of heat and drought stress and soil erosion, whereas warmer winters may benefit winter wheat yields (Eigenbrode *et al.*, 2013).

Warming temperatures alone are expected to reduce wheat production globally and in the Pacific Northwest (Asseng *et al.*, 2015; Eigenbrode *et al.*, 2013). However, CO_2

fertilization may offset any projected yield declines (Eigenbrode *et al.*, 2013). In the Columbia Plateau, which includes northeastern Oregon, climate change is expected to increase relative yields of winter wheat under a range of future climates scenarios by mid- to late-century assuming conventional tillage (Antle *et al.*, 2015b). However, some areas may experience lower yields. For example, by mid-century under a high emissions pathway (RCP 8.5), winter wheat average net returns for farms in the Columbia Plateau are projected to increase by 3%–24%; however, 19%–44% of farms are vulnerable to economic losses (Antle *et al.*, 2015a). These results assume current economic conditions, which are unlikely to prevail in the future. Relative yield for spring peas in the annual cropping system is projected to decline under climate change scenarios (Antle *et al.*, 2015b).

A warming climate may support greater spread of plant diseases, pests, and invasive weeds (Eigenbrode *et al.*, 2013). The cereal leaf beetle is one such pest that has caused 20% losses in spring wheat yield in Oregon. Favorable climatic conditions for pests and diseases are projected to increase under climate change. This could require greater need for successive spray controls; however, biological control would likely still be effective, although costs might increase (Eigenbrode *et al.*, 2014). Downy brome is an invasive weed that can reduce winter wheat yields. The early flowering type is expected to expand its range as winters and springs warm and bloom dates occur earlier requiring changes in timing of management control inputs (Burke *et al.*, 2014).

Irrigated grain cropping systems are vulnerable to decreased water available for irrigation (Eigenbrode *et al.*, 2013) which would require adjusting the timing of farm operations (Creighton *et al.*, 2015). Increased heat stress would increase water demands, requiring improved irrigation efficiency (Creighton *et al.*, 2015). Changes in precipitation regimes would also affect farm operations: drier summers may delay fall planting of winter wheat, while wetter winters could hamper spring wheat planting (Eigenbrode *et al.*, 2013). Advanced growing degree days may require earlier applications of fertilizers, different pest controls, earlier harvest, and changed crops and rotations (Creighton *et al.*, 2015).

Fruits, tree nuts, and berries

Fruit, tree nut, and berry production in Oregon, largely in the Willamette Valley, generated more than $517 million in sales in 2012 (National Agricultural Statistics Service, 2014). These crops are expected to be affected by increased heat and drought stress, changes in precipitation and chilling regimes, altered pest and disease pressure, reduced water available for irrigation, and increased CO_2 fertilization (Eigenbrode *et al.*, 2013). Warmer winters may result in unmet chilling requirements for certain specialty tree fruit crops, which can hamper crop yield, but warming may also allow new varieties to be grown (Eigenbrode *et al.*, 2013; Houston *et al.*, (n.d.)).

Fruit and nut trees require intensive irrigation, making them vulnerable to reduced water availability, particularly as warmer temperatures increase water demands. Assuming sufficient water and CO_2 fertilization, yields for tree fruits are expected to increase under climate change scenarios (Creighton *et al.*, 2015; Eigenbrode *et al.*, 2013). Warming and increasing precipitation is expected to increase pressures from some fruit tree pests and fungal diseases (Eigenbrode *et al.*, 2013). Increased pest pressure would require more monitoring and reporting of outbreaks, and increased fungal diseases would require more spraying or use of different tree varieties (Creighton *et al.*, 2015).

Some tree fruits and grape vines grown in Oregon's Willamette Valley, Southern Oregon, and Columbia River Basin require cold temperatures to produce the best yield and quality (Creighton *et al.*, 2015). As winters warm, the chilling requirement for certain specialty tree fruit crops may not be met, which can hamper crop yield (Houston *et al.*, (n.d.)). The coldest day of the year, used to define cold hardiness zones, is projected to shift northward and toward higher elevations as the climate warms (fig. 6.2) (Parker and Abatzoglou, 2016).

Climate change may prompt grape growers to move north or into higher elevations, although this may be costly and lead to wildlife conservation conflicts (Ashenfelter and Storchmann, 2016). Already, the growing-season temperature in Salem, Oregon, exceeds the price-maximizing temperature for pinot noir (72°F), potentially decreasing the profitability of pinot noir as temperatures continue to rise (Ashenfelter and Storchmann, 2016). However, adaptation strategies, such as planting warmer climate varieties, drought resistant varieties, harvesting earlier, and expanding vineyards northward, may prevent economic losses for wine grape growers (Ashenfelter and Storchmann, 2016).

Vegetables, melons, potatoes, and sweet potatoes

Vegetable, melon, potato, and sweet potato production in Oregon generated more than $492 million in sales in 2012 (National Agricultural Statistics Service, 2014). Rivers of the Columbia and Klamath basins provide the necessary irrigation water for the surrounding annual cropping agricultural areas that receive low summer and annual precipitation (Eigenbrode *et al.*, 2013). These areas are highly vulnerable to diminishing snowpack, increasing water demand, and reductions in water availability (Eigenbrode *et al.*, 2013). Significant yield declines are projected for potato crops as warmer temperatures accelerate development, thereby shortening the growing season and reducing the growth and quality of potatoes (Eigenbrode *et al.*, 2013). However, CO_2 fertilization may at least partially offset future yield losses at least until the middle of the century (Eigenbrode *et al.*, 2013). Developing and using a later-maturing potato variety may prove to be an effective adaptation strategy (Creighton *et al.*, 2015).

Beef and Dairy Cattle

Calf and cattle ranching comprises nearly a third of all Oregon farms and generated more than $894 million in sales in 2012 (National Agricultural Statistics Service, 2014). Dairy farm operations in Oregon generated more than $519 million in milk sales in 2012 (National Agricultural Statistics Service, 2014). Dairy cows and beef cattle are vulnerable to increased heat stress which can decrease fertility, increase infections, decrease growth and decrease milk production (Creighton *et al.*, 2015; Eigenbrode *et al.*, 2013). In Oregon, dairy cow milk production is projected to decrease by less than 1% on average by the end of the 21st century under a medium emissions pathway (SRES A1B) due to increasing temperature and humidity (Mauger *et al.*, 2015). This is a small projected loss compared to US average projected losses of 6.3% (Mauger *et al.*, 2015). In Tillamook County, for example, heat-related milk production losses were projected at –1.1 and –1.8 ounces per day per cow by the 2050s and 2080s, respectively, resulting in economic losses of $100,000 and $200,000 per year assuming present milk prices and livestock data (Mauger *et al.*, 2015). The previous Oregon climate assessment reported on projected economic losses of climate change-related reductions in beef production in Oregon: $11 million and $67 million by the 2040s and 2080s, respectively, under a high emissions pathway (SRES A1FI) (Eigenbrode *et al.*, 2013). It is important to note that future economic projections of commodity markets are highly uncertain as they rely on a suite of factors, climate being only one. Adaptation strategies to reduce vulnerability to heat-stress include breeding for more heat-tolerant livestock, providing heat abatement strategies, as well as adjusting the timing of livestock grazing rotation (Creighton *et al.*, 2015).

Warmer temperatures, changes in precipitation amount and timing, increasing CO_2, and expansion of invasive weeds will likely bring about changes in forage availability and quality on grazing lands, affecting cattle and calf production (Creighton *et al.*, 2015; Eigenbrode *et al.*, 2013). A longer growing season may boost productivity in rangelands in cooler, moister climates of the Pacific Northwest, but may decrease productivity and exacerbate drought stress in rangelands in warmer, drier climates (Creighton *et al.*, 2015; Eigenbrode *et al.*, 2013). More CO_2 could also boost forage production but decrease forage quality (Creighton *et al.*, 2015; Eigenbrode *et al.*, 2013).

Net primary productivity in rangelands is projected by vegetation modeling to increase in northerly US rangelands, including eastern Oregon, during the 21st century under a range of emissions pathways, but notable changes would only be detectable after about 2030. Temperature and CO_2 concentration were the bioclimatic drivers most strongly influencing projected net primary production trends in eastern Oregon (Reeves *et al.*, 2014).

A recent study estimated the climate change vulnerability of cattle production on US rangelands; by combining climate and vegetation modeling, the study projected changes in forage amount, vegetation type, heat stress, and forage variability (Reeves and Bagne, 2016). In rangelands of the Intermountain West, forage quantity is projected to increase while forage dependability is projected to decrease, and exposure to heat stress is projected to increase. Combining all factors and averaging across low to high emissions pathways, the vulnerability score for rangelands in eastern Oregon was moderately negative, suggesting that there may be reductions in cattle stocking densities on rangelands (Reeves and Bagne, 2016). Some important factors not considered in the study include forage quality, water availability, pests, diseases, and biodiversity.

To take advantage of projected increases in forage quantity in the Intermountain West, adaptation options include flexible stocking and rotation and forage harvest. Adaptations to projected decreases in forage dependability could include increasing flexibility or reducing stocking rates, carrying over of cattle yearlings, and using climate forecasting (Reeves and Bagne, 2016).

Rangeland forage can be affected by droughts. Decreased precipitation would reduce forage and water availability for livestock grazing. In turn, reduced vegetative cover can enable wind and water erosion (Vose *et al.*, 2016). Adjusted forage management practices to reduce soil erosion and maintain adequate water supply may be required to sustain feeding health of dairy cows and other grazing livestock (Creighton *et al.*, 2015).

In addition, more frequent rangeland droughts could facilitate invasion of non-native weeds as native vegetation succumbs to drought or wildfire cycles, leaving bare ground (Vose *et al.*, 2016). Cheatgrass (*Bromus tectorum L.*), a lower nutritional quality forage grass, facilitates more frequent fires, which reduces the capacity of shrub steppe ecosystem to provide livestock forage and critical wildlife habitat (Boyte *et al.*, 2016). Cheatgrass is a highly invasive species in the rangelands in the West that is projected to expand northward (Creighton *et al.*, 2015) and remain stable or increase in cover in most parts of the Great Basin (Boyte *et al.*, 2016) under climate change. Adjusting grazing management timing and locations may be required as plant communities shift (Creighton *et al.*, 2015).

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Chapter 7: Human Health

Summary

Climate change threatens the health of Oregonians. More frequent heat waves are expected to increase heat-related illness and death. More frequent wildfires and poor air quality are expected to increase respiratory illnesses. Warmer temperatures and extreme precipitation are expected to increase the risk of exposure to some vector- and water-borne diseases. Access to sufficient, safe, and nutritious food may be jeopardized by climate change. Extreme climate or weather events, or even the threat of one, can lead to adverse, and sometimes lasting, mental health outcomes. Certain populations, including the elderly, the young, pregnant women, the poor, persons with chronic medical conditions, persons with disabilities, outdoor workers, immigrants and limited English proficiency groups, and Indigenous peoples will be disproportionately affected by such climate-related health impacts. However, adaptation strategies may reduce the projected adverse health outcomes.

Introduction

Climate change threatens the health of people in the United States and around the world (Crimmins *et al.*, 2016; IPCC, 2014). The previous Oregon Climate Assessment found that the potential health impact of climate change is lower for the Pacific Northwest than for other areas in the United States; however, extreme heat events, wildfires, changes in infectious disease dynamics, and flooding are key climate-related hazards facing people of the Pacific Northwest (Dalton *et al.*, 2013). Many potential health impacts from climate change can be avoided by preparedness actions (Crimmins *et al.*, 2016). With funding from the Centers for Disease Control and Prevention, Oregon has become a leader in assessing and planning for the health impacts of climate change (Haggerty, 2015; Haggerty *et al.*, 2014). Oregon has evaluated climate change vulnerabilities and recently released a statewide climate and health resilience plan (Haggerty *et al.*, 2014). This chapter describes updated information on the climate-related health impacts that are relevant to Oregon, and largely follows the findings of a recent synthesis of human health impacts of climate change in the United States (Crimmins *et al.*, 2016).

Temperature-Related Death & Illness

Increases both in average and extreme temperatures are expected to increase the number of heat-related deaths and to decrease the number of cold-related deaths (Sarofim *et al.*, 2016). Even small increases in the average summer temperature can result in increased heat-related deaths (Sarofim *et al.*, 2016). In some areas across the globe, this trend is already apparent (IPCC, 2014). Mid-century climate in Portland, Oregon, under a medium emissions pathway (RCP 6.0) is projected to result in 81–118 more heat-related premature deaths than the present-day baseline, although this figure does not account for future population growth or possible adaptations (Schwartz *et al.*, 2015). The number of cold-related premature deaths is projected to decrease but by a smaller margin than heat-related premature deaths would increase (Schwartz *et al.*, 2015). Projections for changes in the number of heat-related premature deaths are listed in Table 7.1 for Portland, Eugene, Medford, and Klamath Falls.

Table 7.1 Projected increase in heat-attributable premature deaths for four cities in Oregon for 2030, 2050, and 2100 relative to the 1990 baseline for each model. The range is based on climate projections from two global climate models forced with a medium emissions pathway (RCP 6.0). Numbers are rounded to the nearest integer. (Schwartz *et al.*, 2015)

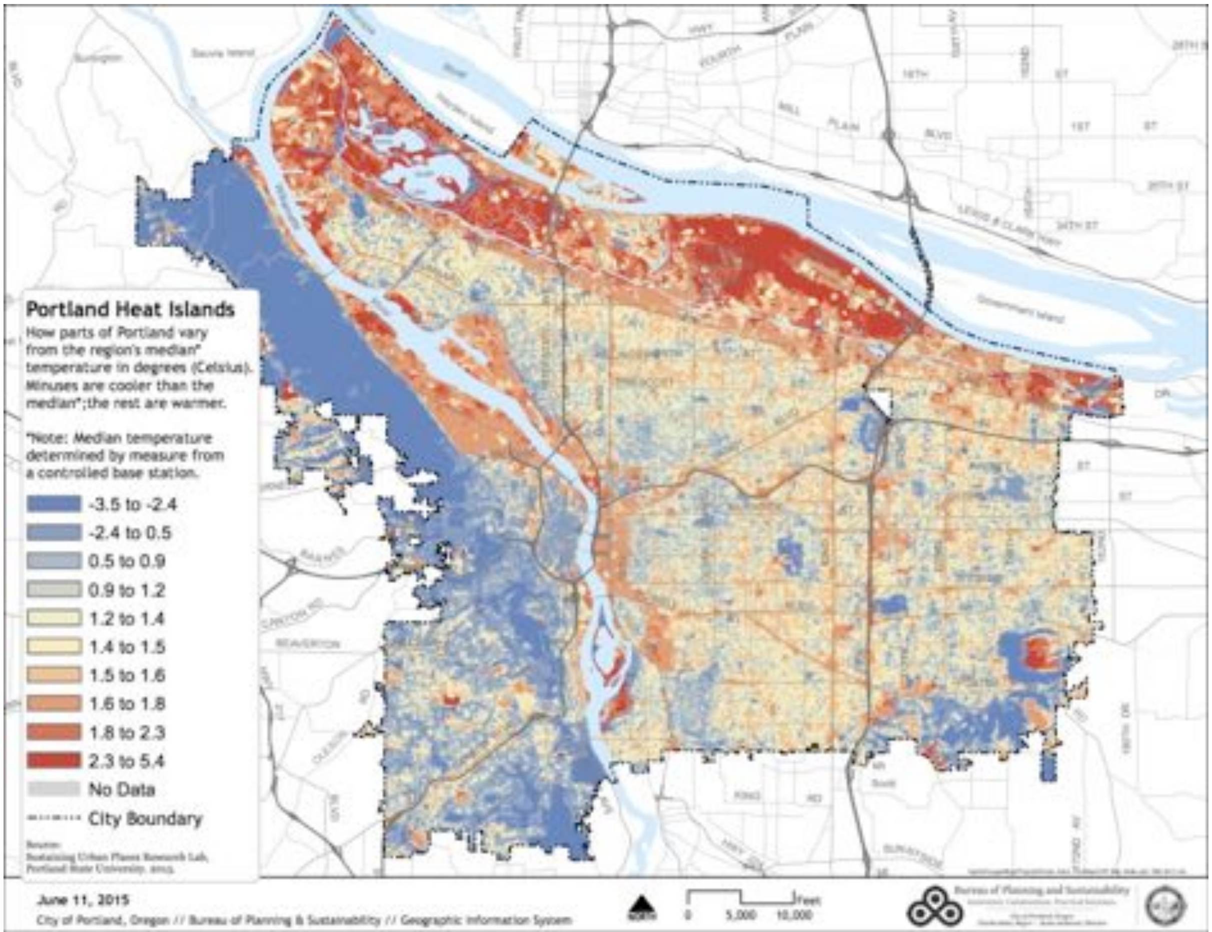
City	2030	2050	2100
Portland	59–78	81–118	153–234
Eugene	8–13	12–22	27–49
Klamath Falls	1–2	2–2	3–6
Medford	6–8	9–13	17–27

Adaptation, such as increased use of air conditioning, improved social and behavioral responses, and physiological acclimatization, may reduce the projected increase in heat-related illnesses and deaths (Sarofim *et al.*, 2016). The relative risk of heat mortality in the United States decreased during 1985–2006 and this trend likely reflects the increasing penetration of air conditioning and public health interventions, despite an aging population (Gasparrini *et al.*, 2015). About half of Oregonian households have air conditioning, with greater penetration in southwest Oregon (NEEA, 2014). Future population growth, broad shifts in population distribution (Jones *et al.*, 2015) and adaptation measures (Petkova *et al.*, 2016) are significant components that should be included in projections of future extreme heat risk and mortality.

More frequent heat waves are expected to increase the burden of heat-related illnesses including heat rash and heat stroke in addition to exacerbating chronic conditions such as cardiovascular and kidney disease (Bethel *et al.*, 2013). Frequent heat exposure during physical exertion without drinking enough water can lead to a form of kidney disease distinct from other causes; it is suggested that heat-stress kidney disease may be one of the first climate change epidemics (Glaser *et al.*, 2016). Recent studies in King County, Washington, found that the risk of heat-related hospital admissions and deaths were 2% and 10% higher, respectively, during extreme heat events of the last few decades (Isaksen *et al.*, 2015, 2016). Extreme heat events increased the relative risk of hospitalizations due to kidney disease, kidney failure, and natural heat exposure (e.g., heat stroke) for all ages.

The elderly (85+) are particularly vulnerable to heat (Sarofim *et al.*, 2016), but age groups 45+ also experienced significant increased risk of hospitalization due to heat in King County (Isaksen *et al.*, 2015). Children are also at higher risk of heat-related illness as they are less able to regulate their internal temperature (Sarofim *et al.*, 2016). New evidence from New York City suggests that extreme heat experienced during pregnancy could modestly reduce birth weight (Ngo and Horton, 2016). Other groups especially vulnerable to extreme heat include outdoor workers, the socially isolated and economically disadvantaged, and those with chronic illnesses (Sarofim *et al.*, 2016). Urban dwellers may be more exposed to heat waves when they occur due to the urban heat island effect which raises the temperature even more in certain areas within the built environment (Stanforth and Johnson, 2016) shows the City of Portland's heat islands, or areas that experience higher temperatures during heat waves.

Figure 7.1 Portland, Oregon's urban heat islands, the parts of the city that see hotter temperatures in heat waves (Figure source: Shandas, V. and J. Voelkel, Sustaining Urban Places Research (SURP) Lab, Portland State University, 2016.)



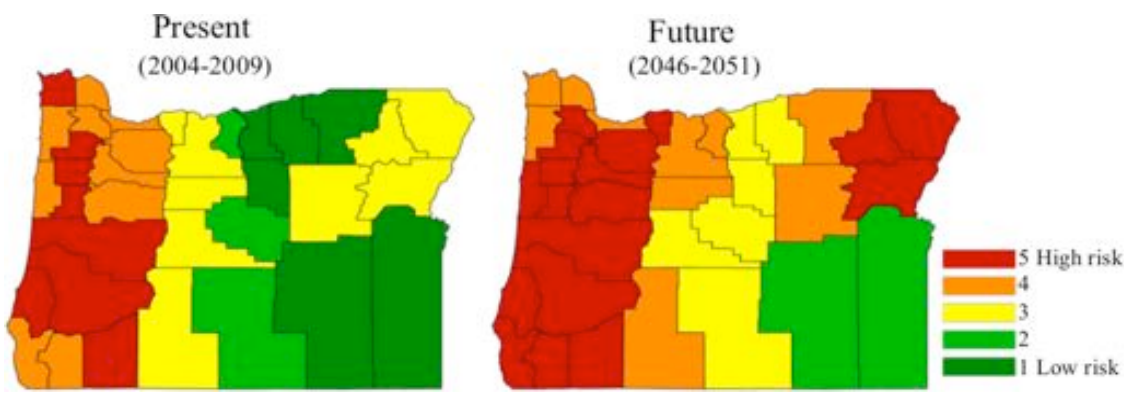
Air Quality Impacts

Climate change is expected to worsen outdoor air quality. Warmer temperatures may increase ground level ozone pollution, more wildfires may increase smoke and particulate matter, and longer, more potent pollen seasons may increase aeroallergens (Fann *et al.*, 2016). Such poor air quality is expected to exacerbate allergy and asthma conditions and increase respiratory and cardiovascular illnesses and death (Fann *et al.*, 2016).

Climate warming is expected to increase the formation of ground level ozone pollution thereby increasing the risk of ozone-related respiratory illness and death, though the impact in the Pacific Northwest would be small compared to other regions of the United States (Fann *et al.*, 2016).

Fine particulate matter ($PM_{2.5}$) concentrations from climate, emissions, and land use changes are generally projected to decrease in the western United States by mid-century under both low (RCP 4.5) and high (RCP 8.5) emissions pathways, largely owing to declining emissions of air pollutants and more stringent air quality standards over time embedded in the RCPs (Val Martin *et al.*, 2015). However, wildfire-specific $PM_{2.5}$ is projected to increase over the western United States, resulting in overall greater concentrations in the future (Val Martin *et al.*, 2015; Yue *et al.*, 2013). Climate change is expected to result in a longer wildfire season with more frequent wildfires and greater area burned (Sheehan *et al.*, 2015). Wildfires are primarily responsible for days when air quality standards for $PM_{2.5}$ are exceeded in western Oregon and parts of eastern Oregon (Liu *et al.*, 2016), although woodstove smoke and diesel emissions are also main contributors (Oregon DEQ, 2016). Across the western United States, $PM_{2.5}$ levels from wildfires are projected to increase 160% by mid-century under a medium emissions pathway (SRES A1B) (Liu *et al.*, 2016). This translates to a greater risk of wildfire smoke exposure through increasing frequency, length, and intensity of "smoke waves"—that is, two or more consecutive days with high levels of $PM_{2.5}$ from wildfires (Liu *et al.*, 2016) (fig. 7.2). Such smoke waves during 2004–2009 were associated with a 7.2% increase in respiratory hospital admissions among adults aged 65 and older in the western United States (Liu *et al.*, 2017). Similarly, correlations were found between wildfire-specific $PM_{2.5}$ and emergency department visits for asthma and chronic obstructive pulmonary disease during the 2012 wildfire season in Colorado (Alman *et al.*, 2016) and the 2008 season in northern California (Reid *et al.*, 2016).

Figure 7.2 Fire Smoke Risk Index during fire seasons (May–October) for (left) present day (2004–2009) and (right) future (2046–2051) under a medium emissions pathway (SRES A1B) (Figure source: Linnia Hawkins; data source: Liu *et al.*, 2016a, http://khanotations.github.io/smoke-map/)



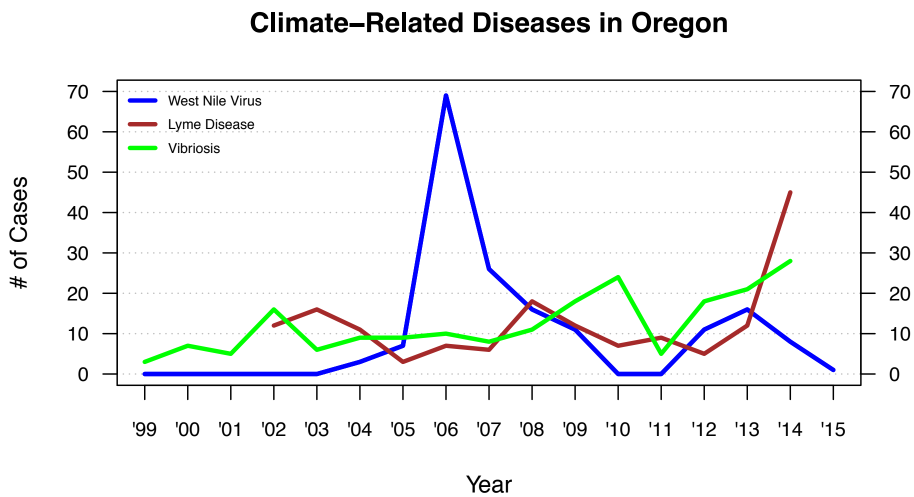
Vector-Borne Diseases

Climate change is expected to result in increased incidence of vector-borne diseases by altering geographic and seasonal distribution of vectors (e.g., mosquitoes, ticks) and the diseases they carry. However, adaptive capacity measures such as controlling vectors and protecting oneself can limit disease incidence (Beard *et al.*, 2016).

Since appearing in Oregon in 2004, 168 human cases of West Nile virus (WNV) have been reported through 2015 (fig. 7.3). Warmer than average temperatures were associated with the emergence of WNV in the western United States in the early 2000s, and prior drought may have factored into the initial outbreak (Bethel *et al.*, 2013). Warming temperatures, changes in precipitation, and more extreme weather may affect the number and location of WNV-carrying mosquitoes by altering their habitat and their rate of reproduction, thereby altering the disease risk for people (Beard *et al.*, 2016). One study projected WNV incidence under a medium emissions pathway (SRES A1B) to increase in northern US states, including Oregon, by at least 10% by mid-21st century due to increasing temperature (Harrigan *et al.*, 2014).

Lyme disease incidence may also increase with climate change. Between 2002 and 2014, 163 cases of Lyme disease were reported in Oregon (fig. 7.3). In response to warming temperatures associated with climate change, ticks capable of transmitting Lyme disease will emerge earlier in the season and their range will expand northward (Beard *et al.*, 2016). However, climate change's effect on Lyme disease incidence remains uncertain (Beard *et al.*, 2016).

Figure 7.3 Occurrences of climate-related diseases in Oregon from 1999–2015. (Figure source: Meghan Dalton; data sources: West Nile Virus, http://www.cdc.gov/westnile/statsmaps/index.html; Lyme disease, http://www.cdc.gov/lyme/stats/tables.html; Vibriosis, https://www.cdc.gov/vibrio/surveillance.html)



Water-Related Illness

The risk of exposure to waterborne pathogens and algal toxins is expected to increase under climate change (Trtanj *et al.*, 2016). Warming waters are expected to alter the seasonal windows of growth and the geographic range of suitable habitat for freshwater and marine toxin-producing harmful algae and certain naturally occurring *Vibrio* bacteria (Trtanj *et al.*, 2016). In the Puget Sound, under a medium emissions pathway (SRES A1B), local atmospheric heating of surface waters is projected to result in thirty more days a year that are favorable to algal blooms and an increased rate of bloom growth (Moore *et al.*, 2015). Toxins from such harmful algal blooms accumulate in filter-feeding shellfish, leading to illnesses for those who eat them (Bethel *et al.*, 2013). In 2015, during the largest harmful algal bloom ever observed off the West Coast from California to Alaska, high levels of domoic acid led to the closure of shellfish harvesting from the Columbia River to Tillamook Head, and high levels of paralytic shellfish toxins led to the closure of mussel harvesting along the Oregon coast north of Gold Beach (Milstein, 2015).

Vibrio parahaemolyticus is a common culprit behind seafood-associated gastroenteritis worldwide, and some of the most virulent strains are found in coastal waters of the Pacific Northwest (Martinez-Urtaza *et al.*, 2013). *Vibrio* concentrations increase seasonally as waters warm in spring and summer and higher ocean, and estuarine temperatures associated with climate change could increase the risk of infection from eating compromised shellfish (Bethel *et al.*, 2013). From 1999 to 2014, nearly 200 cases of *Vibrio* infection have been reported in Oregon (fig. 7.3).

More frequent and intense extreme precipitation events projected under climate change could increase the risk of exposure to water-related illnesses as the runoff introduces pathogens, such as *Cryptosporidium*, into recreational and drinking water (Trtanj *et al.*, 2016). Extreme precipitation events may also lead to more combined sewer overflows, thereby compromising the sources of drinking water and increasing the risk of gastrointestinal illness (Jagai *et al.*, 2015). Approximately 23% of Oregon's population relies on private wells for drinking water and may be more at risk of water contamination (Haggerty et al. 2014). Extreme precipitation runoff can also influence the prevalence of toxic algal blooms and human exposure to compromised harvested shellfish (Trtanj *et al.*, 2016).

The projected increase in flooding related to extreme precipitation, and combined with sea level rise on the coast, may also threaten to disrupt the infrastructure that is essential to safeguarding physical safety and human health. For example, infrastructure that becomes compromised by mold and mildew can lead to respiratory illnesses (Haggerty et al. 2014). Flooding may disproportionately affect some populations including people with disabilities, older adults, pregnant women and children, low-income populations, and some occupational groups (Bell *et al.*, 2016).

Food Security

Climate change may jeopardize food security—"permanent access to a sufficient, safe, and nutritious food supply needed to maintain an active and healthy lifestyle" (Brown *et al.*, 2015; Ziska *et al.*, 2016). Warmer temperatures and changes in extreme events could increase food's exposure to pathogens and toxins, increasing risk of foodborne illness. However, this risk may be reduced by food safeguarding practices (Ziska *et al.*, 2016). A heightened risk of salmonella infection was associated with extreme temperature and precipitation events in Maryland, with coastal communities disproportionately affected (Jiang *et al.*, 2015). Climate change may also require more pesticide and drug use in food in response to greater pressure from agricultural pests and diseases, thereby increasing human exposure to chemical contaminants (Ziska *et al.*, 2016). More frequent flooding may increase the risk of introducing contaminants into the food chain (Ziska *et al.*, 2016). Warming oceans may result in higher mercury concentrations in seafood and more frequent high toxin levels in shellfish that are affected by harmful algal blooms (Trtanj *et al.*, 2016; Ziska *et al.*, 2016). The nutritional value of wheat, rice, and other crops may be reduced by higher atmospheric carbon dioxide concentrations (Ziska *et al.*, 2016). Finally, more extreme weather events could disrupt food distribution, potentially limiting access to safe and affordable food (Ziska *et al.*, 2016). Low-income people, children, and Indigenous populations are more vulnerable to climate impacts on food safety, nutrition, distribution and access (Ziska *et al.*, 2016).

Mental Health & Well-Being

Extreme weather events can affect mental health, with impacts ranging from general anxiety disorder to post-traumatic stress disorder (Bethel *et al.*, 2013; Dodgen *et al.*, 2016). Most people recover from mental illness after a weather-related disaster, but trauma can have long-term effects, and some people develop chronic psychological dysfunction (Dodgen *et al.*, 2016). The elderly, pregnant and post-partum women, children, those with pre-existing mental illness, the economically disadvantaged, the homeless, and first responders are at higher risk of experiencing adverse mental health outcomes from climate or weather-related events (Dodgen *et al.*, 2016). In addition, people living in areas with greater exposure to climate change events and long-term climate disruptions, and people whose livelihood and sustenance depends upon the natural environment, are at higher risk (Dodgen *et al.*, 2016). Even the threat of climate change can increase stress and adversely affect mental health outcomes (Bethel *et al.*, 2013; Dodgen *et al.*, 2016).

Populations of Concern

Previous Oregon climate assessments noted that certain groups, such as the elderly, young children, pregnant women, low-income individuals, persons with chronic medical conditions, and outdoor workers are particularly vulnerable to extreme heat events (Bethel *et al.*, 2013). In addition, other groups are of particular concern, including immigrants, people with limited English proficiency, Indigenous peoples, and persons with disabilities. As is described in a chapter focused on populations of concern (Gamble *et al.*, 2016), different degrees of vulnerability result from variations in levels of exposure to climate change, in inherent sensitivities, and in the ability to respond to climate-related health threats of people across locations, communities, and individuals throughout the lifespan.

Low-income groups, people with limited English proficiency, and undocumented immigrants are particularly vulnerable due to high exposure and low adaptive capacity (Gamble *et al.*, 2016). In Oregon, 12% of the population is Hispanic or Latino, 15.5% is below the poverty level, 6% report speaking English less than very well, and 10% was born abroad (Haggerty *et al.*, 2014). These people are more likely to live in areas that are prone to experience climate events. Their ability to deal with climate-related health risks is limited by income, education, and transportation, as well as limited access to and use of health and social services due to language barriers or citizenship status. In addition, chronic medical conditions are more common in these groups (Gamble *et al.*, 2016).

Indigenous populations, especially those whose sustenance depends on the environment or those who live in isolated or impoverished communities, face greater exposure and lower resilience to health effects of climate change (Gamble *et al.*, 2016). In Oregon, American Indians comprise 1.8% of the population (Haggerty *et al.*, 2014). Some may lack adequate systems for safe water supply. Climate impacts on traditional foods, such as salmon, shellfish, and berries, which are integral to Indigenous culture and subsistence, may lead to poorer nutrition and higher prevalence of obesity and diabetes (Donatuto *et al.*, 2014; Gamble *et al.*, 2016). Indigenous communities are also at risk of losing part of their cultural identity through climate-related changes in the availability and timing of culturally relevant plant and animal species (Chisholm Hatfield and Mote, 2015; Donatuto *et al.*, 2014). Health indicators specific to Indigenous peoples are important for assessing climate change sensitivity and creating adaptation plans for Indigenous communities, but key community health concerns are often omitted from local, regional and national climate assessments (Donatuto *et al.*, 2014).

Children—from within their mother's womb through their teenage years—are particularly vulnerable (Gamble *et al.*, 2016). Children under the age of 18 comprise 23% of Oregon's population, and 6% of Oregon's population is younger than five-years-old (Haggerty *et al.*, 2014). Some incidences of low birth weight and preterm birth are associated with mothers being affected by extreme heat events, airborne particulate matter, and floods. Infants' and toddlers' developing bodies and immune systems, and their propensity to play on the ground and stick fingers in their mouths, increases their risk to a multitude of exposures that could result in negative health outcomes such as asthma, diarrhea, and heat-related illness. Older children's behaviors and activities risk higher exposure to heat-related illness, vector-borne and waterborne disease, and respiratory effects from air pollution and allergens (Gamble *et al.*, 2016).

Older adults—those age 65 years and older—will occupy a growing percentage of the population over the next several decades and are particularly vulnerable to heat waves, floods, droughts, wildfires, poor air quality, and exposure to infectious disease (Gamble *et al.*, 2016). About 14% of Oregonians are age 65 and older; in rural areas, older adults comprise a greater percentage of the population (Haggerty *et al.*, 2014). Older adults are already among those most affected by heat waves and they are at higher risk of becoming sick from contaminated waters. Vulnerability among older adults depends not only upon physiological factors, but also upon mobility and cognitive impairments: nearly half of older adults have some form of disability (Gamble *et al.*, 2016).

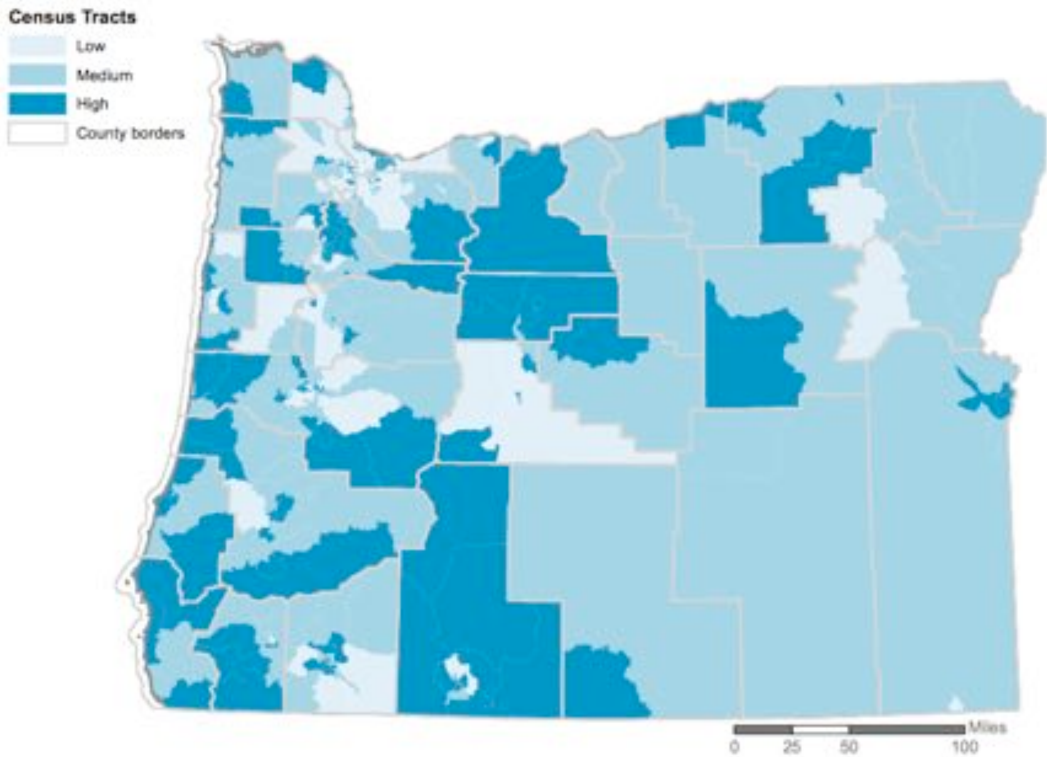
Outdoors workers are especially exposed to extreme heat events and are at higher risk of heat-related illness; indoor workers that lack an air-conditioned environment are also at risk. Emergency responders, including firefighters, are at increased risk due to their occupational direct exposure to floods and wildfires. As wildfires increase in frequency and extent across the western United States due to climate change, more firefighters will be exposed to dangerous job conditions (Gamble *et al.*, 2016). In Oregon, 3.4% of the workforce is employed in outdoor industries (Haggerty *et al.*, 2014).

People with disabilities often also experience lower income and education levels leading to poorer health outcomes during extreme events or climate-related emergencies. Disabilities include limitations to hearing, speech, vision, cognition, and mobility (Gamble *et al.*, 2016). In Oregon, 27% of adults and 37% of 8th and 11th graders report having a disability (Haggerty *et al.*, 2014). People with disabilities are often "invisible" to decision-makers and planners who may overlook the need to make emergency response plans that specifically address the functional needs of disabled people (Gamble *et al.*, 2016).

People with chronic medical conditions, such as cardiovascular and respiratory diseases, diabetes, asthma, obesity, and mental health challenges face higher risk of complications from heat waves (Gamble *et al.*, 2016). For example, 11% of adults and 8% of children in Oregon have asthma (Haggerty *et al.*, 2014). Certain medications may inhibit a person's ability to regulate body temperature during a heat wave. Extreme climate-related events may interrupt ongoing medical treatment (Gamble *et al.*, 2016).

The Oregon Health Authority assessed social vulnerability (Haggerty, 2015) by combining several indicators based on demographics, socioeconomic status, and health to understand Oregonians' vulnerability to climate impacts across the state (fig. 7.4). High social vulnerability tracts "are distributed in many parts of the state, and largely overlap with broad indicators of socioeconomic status such as educational attainment" (Haggerty, 2015).

Figure 7.4 Oregon's social vulnerability composite index by census tract. This index is a combination of eleven indicators of social vulnerability including measures of demographics, socioeconomic status, and health. (Haggerty, 2015)



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Chapter 8

Regional Risks

Introduction

Oregon's diverse landscape, from coastal beaches and lowland valleys to mountain peaks and high desert, faces regionally varied concerns around climate change. On the coast, sea level rise and increasing waves may increase the risk of coastal erosion and flooding; ocean acidification and hypoxia threaten the coastal marine ecosystems; and wildfire may become more frequent under warmer and drier conditions. In the Willamette Valley, warmer temperatures may enhance agricultural productivity; but increasing heat events would increase the risk of heat-related illnesses among its large population centers. Forests of the Cascade Range and the Blue Mountains will face an increasing risk of forest transformation from wildfire, insects and diseases, as well as range shifts and species composition changes. In the eastern and southern part of the state where snowpack reserves water for the summer season, water resources will likely become scarce; altered precipitation patterns will influence rangeland vegetation; and agriculture may see greater production so long as water is available.

This chapter provides an overview of the main climate change risks and highlights some recent regional case studies or results for four broad regions in Oregon including the Oregon Coast, the Willamette Valley, the Cascade Range, and eastern Oregon.

Oregon Coast

The Oregon Coast, from its estuaries to the Coast Range, will experience greater risks of estuarine habitat degradation, coastal erosion and flooding, forest disturbance and transformation, and challenges to salmon.

Estuarine habitat degradation

Oregon's estuaries are crucial habitat for many species, including juvenile salmon and shellfish larvae. Climate change is expected to alter estuarine habitat through changes in sea level, ocean acidification, water temperature, upwelling, freshwater runoff, and sedimentation. Sea level rise and ocean acidification and how they will affect conservation of tidal wetland habitat and threatened species are the main concerns of West Coast estuarine managers (Thorne *et al.*, 2016).

In the Tillamook Estuary changes in relative sea level, wind, waves, and freshwater input by 2041–2060 under a medium-high emissions pathway (SRES A2) compared to 1979–1998 are projected to result in 39%–46% higher extreme total water levels in winter, with some areas more exposed than others (Cheng *et al.*, 2015).

In the Yaquina Estuary, a 5.4°F increase in air temperature is projected to result in 1.3°–2.9°F warming in the estuarine waters, with the upper portion experiencing up to 40 more days not meeting water temperature criteria for the protection of rearing and migrating salmonids (Brown *et al.*, 2016).

Coastal erosion and flooding

Sea level rise and increasing wave heights will likely increase the risk of coastal erosion and flooding.

In Tillamook County, accounting for a range of sea level rise and wave height scenarios, the number of structures in Rockaway Beach potentially exposed to the annual flooding event is projected to more than double between 2009 and 2050 to more than 500 and nearly 1,000 by 2100. The smaller communities of Neskowin and Sand Lake have fewer exposed structures, but they may experience more significant losses overall (Baron *et al.*, 2014).

In Clatsop County, 19 inches of local sea level rise by 2100, consistent with a high emissions pathway (RCP 8.5), is projected to result in a 70% risk of at least one flood per year reaching 4 feet above the current high tide line. This would expose more than 3,400 people, over 1,500 homes, and 60 miles of roads to flooding (Strauss *et al.*, 2014).

Forest disturbance and transformation

Future warmer and drier conditions in the Coast Range may result in vegetation shifting from conifer forests to more drought-tolerant mixed forests. In addition, wildfires are expected to become more commonplace (Sheehan *et al.*, 2015) Swiss needle cast, a fungal disease that stunts Douglas-fir growth, is increasingly affecting Coast Range forests where the disease severity is expected to increase with warmer winters (Ritóková *et al.*, 2016).

Challenges to near-shore fisheries

Oregon's near-shore coastal fisheries, including salmon, groundfish, crab, and shellfish, will likely be affected by multiple changes to the coastal ocean environment such as warming waters, ocean acidification, and sea level rise.

Coastal salmon populations, such as the threatened Coho salmon (*Oncorhynchus kisutch*), are vulnerable to reduced estuarine rearing habitat from sea level rise, and to increasing thermal stress, to susceptibility to disease, and to predation due to warmer waters (Wainwright and Weitkamp, 2013). High exposure to warmer stream temperatures and changes in streamflow, particularly along the southern Oregon coast, will also affect coastal salmon populations such as the Oregon coast steelhead population (*Oncorhynchus mykiss*), a "species of concern" (Wade *et al.*, 2013).

Ocean acidification is already negatively affecting Oregon coastal shellfish production. For example, overall production at the Whisky Creek Shellfish Hatchery in Netarts Bay, Oregon, was 25% of normal in 2008 when coastal waters were anomalously acidic and lacking in oxygen (Barton *et al.*, 2015).

Willamette Valley

The Willamette Valley, the most densely populated and fastest-growing region in Oregon, nestled between the Coast and Cascade Ranges, is expected to experience greater risks of extreme heat events, summer water scarcity, declining oak savanna habitat, and poor air quality.

Extreme heat events

Heat waves are expected to become longer, more common, and more intense, exposing Oregonians to greater risk of heat-related illnesses. Extreme heat events are considered the top climate risk facing public health in Multnomah and Benton counties (OHA, 2013). By 2050 relative to 1990, the number of premature deaths attributed to heat exposure is projected to increase by 81–118 in the city of Portland (Schwartz *et al.*, 2015).

Summer water scarcity

Because of the Willamette Valley's wet winters and dry summers, a series of dams and reservoirs in the Willamette Basin serve balanced purposes of maximizing water storage for the dry season demands while minimizing flood risk during the wet season. Declining snowpack and earlier snowmelt in the headwaters combined with greater summer season water demand is expected to result in greater summer season water scarcity (Jaeger *et al.*, 2014). Adjusting reservoir operating rules to balance flood risk and summer water supply in a warmer climate could be done by starting reservoir refill earlier, but at a slower rate.(Moore, 2015) In the Santiam River basin, spring and summer runoff is expected to decrease, particularly for mixed rain-snow catchments with little groundwater influence (Surfleet and Tullos, 2013). Agricultural and urban water demand in the lower reaches of the basin has the strongest influence on sensitivity to water scarcity (Mateus *et al.*, 2015).

Declining oak savanna habitat

Urban and agricultural development over the past century and a half has altered the Willamette Valley's natural oak woodland, savanna, grassland, and wetland habitats (*Oregon Conservation Strategy*, 2016). The Oregon white oak (*Quercus garryana*), which occupies some of the driest low woodland and savanna sites from British

Columbia to California, is highly vulnerable to climate change and depends on disturbances, such as periodic, low intensity fires (Case and Lawler, 2016). Model simulations incorporating future climate in the Willamette Valley without disturbances project a decline in oak savanna and woodland vegetation, but future disturbance scenarios may mediate such a decline (Yospin *et al.*, 2015).

Poor air quality

In the Willamette Basin, fire activity is expected to increase, with a projected three to nine fold increase in annual area burned by 2100 (Turner *et al.*, 2015). Degraded air quality from more frequent wildfires is one of the top public health risks for Multnomah and Benton counties (OHA, 2013). Between 2050 and present day, the average intensity on days with high wildfire-specific particulate matter is projected to increase by 58%–173% across Willamette Basin counties (Liu *et al.*, 2016).

Cascade Range

The Cascade Range, including the Klamath Mountains, will likely experience greater risks of shifting streamflow seasonality and forest transformation and disturbance.

Shifting streamflow seasonality

As winters warm, mountain precipitation will fall less as snow and more as rain, resulting in a shift of much of the Cascade Range's snow-dominant areas to a mixed rain-snow regime and the Klamath Mountains becoming almost entirely rain-dominant (Klos *et al*., 2014). This represents a fundamental shift in hydrology that would affect the timing and amount of water resources, resulting in a greater risk of water scarcity for multiple water uses including drinking water, irrigation water, and in-stream flows for fish.

Snowpack in the McKenzie River Basin, for example, is projected to decrease by 56% and peak 12 days earlier under 3.6°F of warming (Sproles *et al*., 2013). Elevations between about 3300 and 6600 feet are most sensitive to warming-induced snowpack declines (Sproles *et al*., 2013). With diminishing snowpack and a greater proportion of rain versus snow, streamflow is expected to peak earlier in the year, peak flow events are expected to be larger, and low summer flows are expected to be lower. Groundwater processes at high elevations may provide a buffer against the projected higher high and lower low flows.

In the Santiam River basin, increases in fall and winter runoff and decreases in spring and summer runoff are expected, particularly for mixed rain-snow catchments with little groundwater influence (Surfleet and Tullos, 2013).

In the Hood River basin, spring runoff is projected to peak earlier in the season, resulting in more frequent shortages of minimum flow requirements, particularly in the summer (Frans *et al*., 2016).

Forest transformation and disturbance

Forests of the Cascade Range are expected to undergo transformation driven by changes in climate and by disturbances such as wildfires, drought, insects, and diseases, and the interaction between them. Climate change is expected to result in greater wildfire activity.

From the Cascade Range to the coast, the number of years between fires is projected to decrease by about 42% between the 21st and 20th centuries under a low emissions pathway (RCP 4.5) and effective fire suppression management (Sheehan *et al.*, 2015). The time between fires would decrease further under the high emissions pathway (RCP 8.5) and under no fire suppression (Sheehan *et al.*, 2015).

The risk of increased incidence of respiratory illness from wildfire smoke is a top public health risk in Jackson County (OHA, 2013) where the average intensity on days with high wildfire-specific particulate matter is projected to increase by 81% by 2050 under a medium emissions pathway (SRES A1B) relative to present-day (Liu *et al.*, 2016).

Due to future changes in climate and increased wildfires, some models suggest that forests of the Cascade Range and westward may shift from predominantly conifer to mixed-conifer forests, with only remnant conifer forests in the higher elevations (Sheehan *et al.*, 2015). Furthermore, cool, moist mixed-conifer forest are projected to decrease in favor of warm, dry mixed-conifer forests (Halofsky *et al.*, 2014; Sheehan *et al.*, 2015).

Warming and more frequent drought and wildfires will likely lead to a greater susceptibility of trees to insects and pathogens and a greater risk of extensive forest insect and disease outbreaks (Halofsky and Peterson, 2016b). Mountain pine beetle and western spruce budworm are the most common native forest insect pests in Oregon and have caused substantial tree mortality and defoliation over the past several decades, with the budworm more prevalent in the northern Oregon Cascade Range and the pine beetle more prevalent in the eastern Cascade Range in central Oregon (Meigs *et al.*, 2015).

Eastern Oregon

Eastern Oregon, including the Blue Mountains and Columbia Plateau in the north and the Great Basin in the south, is expected to see greater risks of shifting streamflow seasonality, forest transformation and disturbance, challenges to salmon, and altered rangeland and sagebrush habitat.

Shifting streamflow seasonality

In eastern Oregon, snowpack retains water for the summer season. As winters warm, mountain precipitation will fall more as rain and less as snow, resulting in a shift of much of the Blue Mountains' snow-dominant areas to a mixed rain-snow regime (Klos *et al.*, 2014). This represents a fundamental shift in hydrology, and declining snowpack will likely result in changes in the timing of water resources and greater water scarcity for multiple water uses, particularly for irrigation and in-stream flows for fish. Already, earlier spring peak streamflow and more frequent low summer flows are occurring in parts of northeast Oregon (Dittmer, 2013).

Having no man-made water storage, people in the John Day River basin in northeast Oregon are particularly vulnerable to declining snowpack (Halofsky and Peterson, 2016a; Leibowitz *et al.*, 2014).

In Wasco, Sherman, Gilliam, and Crook counties, drought is considered to be a top public health risk (OHA, 2013).

Forest transformation and disturbance

Forests of the Blue Mountains are expected to undergo transformation driven by changes in climate and by disturbances such as wildfires, drought, insects, and diseases, and the interaction between them. Climate change is expected to result in greater wildfire activity (Sheehan *et al.*, 2015). Western spruce budworm and mountain pine beetle are expected to continue causing forest mortality in the Blue Mountains (Halofsky and Peterson, 2016a; Meigs *et al.*, 2015).

Between the 2050s and present day, the counties of Baker, Wallowa, Union, and Umatilla are projected to experience more than 20 more days in six years of high wildfire-smoke particulate matter affecting public health (Liu *et al.*, 2016).

Challenges to fish

In the John Day River basin, steelhead, bull trout (*Salvelinus confluentus*), and Chinook salmon (*Oncorhynchus tshawytscha*) are expected to experience range contractions as stream temperatures warm in the future (Halofsky and Peterson, 2016a). Climate change will interact with existing stressors, such as riparian corridor degradation and the introduction of non-native predators, potentially threatening the persistence of Oregon's salmonid species. For example, stream temperature increases resulted in more overlap between juvenile Chinook salmon and potentially predatory bass—limited by cold upper watershed temperatures—in early summer in the John Day River basin. Combined with a highly modified riparian zone, a near total loss of Chinook salmon rearing habitat and complete invasion by bass was projected; however, riparian restoration could prevent extirpation of Chinook salmon and restrict bass from the upper reaches of salmon-rearing habitat (Lawrence *et al.*, 2014).

Altered rangeland and sagebrush habitat

In the Northern Basin and Range of southeast Oregon, climate change could facilitate invasion by non-native weeds. Cheatgrass (*Bromus tectorum L.*), a highly invasive species in Oregon's rangelands that is projected to expand, facilitates more frequent fires, which reduces the capacity of the shrub steppe ecosystem to provide nutritious livestock forage and critical wildlife habitat (Boyte *et al.*, 2016). The greater sage grouse (*Centrocercus urophasianus*) relies on shrub-steppe vegetation for feeding, nesting, and shelter, and that habitat in southeast Oregon is projected to contract over the next several decades (Creutzburg *et al.*, 2015).

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