Climate Change in the Northwest

Implications for Our Landscapes, Waters, and Communities

Executive Summary

Edited by:

Meghan M. Dalton

Philip W. Mote

Amy K. Snover

Full Report: www.occri.net/reports

More Information: Meghan M. Dalton

mdalton@coas.oregonstate.edu

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Executive Summary

AUTHORS
Meghan M. Dalton, Jeffrey Bethel, Susan M. Capalbo, J. E. Cuhaciyan,
Sanford D. Eigenbrode, Patty Glick, Laurie L. Houston, Jeremy S. Littell, Kathy Lynn,
Philip W. Mote, Rick R. Raymondi, W. Spencer Reeder, Sarah L. Shafer, Amy K. Snover

Chapter 1 Introduction: The Changing Northwest

The Northwest's climatic, ecological, and socioeconomic diversity set the stage for a diverse array of climate impacts, many of which will be united by their dependence on availability of water and other natural resources. (Section 1.1)

Nestled between the Pacific Ocean and the Rocky Mountains, the Northwest (NW, fig. 1.1) experiences relatively wet winters and dry summers, with locations west of the Cascade Range considerably wetter than the sometimes desert-like conditions on the east side. In addition, the thousands of miles of NW coastline support a variety of coastal environments. On the whole, the Northwest's diverse climate and landscape make it one of the most ecologically rich areas in the United States, a feature that has been integral to sustaining the region's economy, culture, and way of life. NW tribes have cultural, social,

Figure 1.1 The Northwest, comprising the states of Washington, Oregon and Idaho and including the Columbia River basin (shaded).

and spiritual traditions that are inseparable from the landscape and environmental conditions on and beyond reserved tribal lands. The region's water resources and seasonality of snow accumulation and melt shape the migration of iconic salmon and steelhead; growth and distribution of forests; and availability of water for drinking, irrigation, and hydropower production, among many other uses. Land ownership, population distribution, economic and cultural dependence on natural resources, current ecological conditions, and patterns of resource use will substantially shape the regional and local consequences of a changing climate.

Key regionally consequential risks in the Northwest include impacts of warming on watersheds where snowmelt is important, coastal consequences of sea level rise combined with other stressors, and the cumulative effects of fire, insects, and disease on forest ecosystems. (Section 1.2)

This report focuses on the major drivers of regional climate change and impacts on systems of high regional and local importance. Three key issues of concern were identified through a qualitative risk assessment that evaluated the relative likelihood and consequences of climate change impacts for the region's economy, infrastructure, natural systems, and human health. These are: impacts of warming on snow accumulation and melt and their effects on regional hydrology and related systems; coastal consequences of sea level rise combined with other drivers of change, including river flooding, coastal storms and changes in the coastal ocean, and the cumulative effects of climate change on fire, insects, and tree diseases in forest ecosystems. In addition to these three risk areas, this report focuses on three climate-sensitive sectors of regional importance: agriculture, human health, and NW tribes. Regionally-identified risks are complemented with discussion of locally-specific risks and vulnerabilities.

This assessment of climate change in the Northwest reveals a familiar story of climate impacts, but highlights new details at multiple scales considering multiple interacting drivers of change and vulnerabilities resulting from human choices throughout time. (Section 1.3.1)

The findings presented in this report largely confirm over fifteen years of research, but add new details regarding how impacts are likely to vary across the region. Analyzing climate impacts at local to regional scales and how impacts vary between natural and managed systems is essential to ensure a complete picture of projected climate impacts on the region and development of appropriate adaptive responses. Considering multiple drivers of change and their interactions is also necessary as some of the largest impacts can occur when multiple drivers align and some individual drivers of change can offset each other. Past and present human choices and actions are a large determinant of current social and ecological vulnerability to climate; understanding these causal linkages and adjusting relevant choices and actions could help reduce future climate vulnerability.

The Northwest has been a leader in applied regional climate impacts science since the 1990s, and the region's resource managers, planners, and policy makers have been early engagers in climate change issues. This report provides a solid foundation for

identifying challenges posed by climate change in order to assist adaptation efforts throughout the region. (Section 1.3.2)

Climate change adaptation focuses on adjusting existing practices in order to reduce negative consequences and take advantage of opportunities. Adaptation begins with identifying and characterizing the problem posed by climate change, a goal this report aims to serve. It then proceeds with identifying, assessing, and selecting alternative actions, and ultimately implementing, monitoring, and evaluating the selected actions. Many federal, state, local, and tribal entities in the Northwest are already engaged in various stages of climate change adaptation, including state-level climate change response strategies; however, adaptation is not yet wide-spread and few efforts have moved beyond planning to implementation.

Chapter 2 Climate: Variability and Change in the Past and the Future

Variations in solar output, volcanic eruptions, and changes in greenhouse gases all contribute to the energy balance at the top of the atmosphere, which influences global surface temperature fluctuations and changes over time. (Section 2.1)

Global surface temperature is governed by the balance at the top of the atmosphere between incoming and reflected solar radiation and outgoing infrared radiation, or heat, radiated from the Earth. Clouds and certain gases in the atmosphere (e.g., water vapor, CO_2, methane, ozone, etc.) absorb some of Earth's radiated energy reducing the amount escaping to space. Changes in these infrared–absorbing gases (or more commonly, greenhouse gases) force a change in the energy balance of the climate system, with CO_2 changes being the dominant factor. Other important factors include changes in solar output and volcanic eruptions. Variations in solar output are partially responsible for changes in the past climate, but play a small role in climate changes today. Large volcanic eruptions act to cool the Earth for a few years afterward as tiny sunlight-reflecting particles spread throughout the upper atmosphere.

Climate variability and change in the Northwest is influenced by both global and local factors, such as the El Niño-Southern Oscillation and mountain ranges. (Section 2.2)

More important than global changes in the Earth's energy balance for understanding regional and local climate variability and change are the natural variability of atmospheric and ocean circulation and effects of local topography. NW climate variability is dominated by the interaction between the atmosphere and ocean in the tropical Pacific Ocean responsible for El Niño and La Niña. During El Niño, winter and spring in the Northwest have a greater chance of being warmer and drier than normal. The complex topography of the Northwest, which includes the Coast, Cascade, and Rocky Mountain ranges, results in large changes in temperature and precipitation over relatively short distances.

During 1895–2011, the Northwest warmed approximately 0.7 °C (1.3 °F) while precipitation fluctuated with no consistent trend. (Section 2.2)

For the last 30 years, temperatures averaged over the Northwest have generally exceeded the 20th century average. During 1895–2011, the Northwest warmed by about 0.7 °C (1.3 °F). Year-to-year fluctuations in precipitation averaged over the Northwest have been slightly larger since 1970 compared with the previous 75 years, with some of the wettest and driest years occurring in the most recent 40 years. However, there has not been a clear overall increase or decrease in average precipitation over the 20th century. The observed changes in temperature include contributions from both natural climate variability and human influences. Seasonal trends in temperature, while influenced by fluctuations in atmospheric circulation patterns, are consistent with expected changes from human activities.

The frequency of extreme high nighttime minimum temperatures increased in the Northwest during 1901–2009, but observed changes in extreme precipitation are ambiguous. (Section 2.3)

Confidently detecting changes in extreme events is challenging. During 1901–2009, the number of extreme high nighttime minimum temperatures increased in the Northwest, but other extreme temperature measures showed no clear change. Observed changes in extreme precipitation are ambiguous in most areas, with some increases and some decreases, and depend on the specific type of extreme precipitation event examined. Changes are most pronounced in western Washington where most measures show increases of 10–20%.

State-of-the-art global and regional climate modeling provides a consistent basis for understanding projections of future climate and related impacts in the Northwest. (Section 2.4)

Coordinated global and regional climate modeling approaches provide a framework for understanding uncertainty associated with model projections of future climate. Three such modeling frameworks are the Coupled Model Intercomparison Project phases 3 and 5 (CMIP3/5), the North American Regional Climate Change Assessment Program (NARCCAP), and regional climateprediction.net (regCPDN) with spatial resolutions ranging from 300 to 25 km (186 to 15 mi). All three datasets are generally consistent in the broad story of projected future NW climate.

The Northwest is expected to experience an increase in temperature year-round with more warming in summer and little change in annual precipitation, with the majority of models projecting decreases for summer and increases during the other seasons. (Section 2.4.1)

Over the period from 1950–1999 to 2041–2070, CMIP5 models project NW mean annual warming of 1.1 °C to 4.7 °C (2 °F to 8.5 °F), with the lower end possible only if greenhouse gas emissions are significantly reduced (RCP4.5 scenario; fig. 2.5 *a*). All models project warming of at least 0.5 °C (0.9 °F) in every season. Projected warming is greater during the summer with increases ranging from 1.9 °C to 5.2 °C (3.4 °F to 9.4 °F) for the very high growth scenario (RCP8.5). Annual average precipitation is projected to change by about +3% with individual models ranging from –4.7% to +13.5%. For every season, some models project decreases and others increases, although for summer more models project decreases than increases, with the largest projected change of about –30%

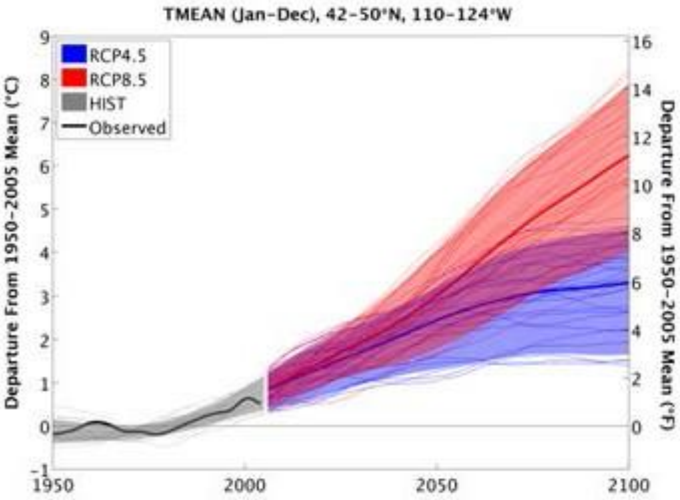

Figure 2.5. (a) Observed (1950–2011) and simulated (1950–2100) regional mean annual temperature for selected CMIP5 global models for the RCP4.5 and RCP8.5 scenarios.

by 2041–2070. In addition, the models that project the largest warming in summer also tend to project the largest precipitation decreases.

Measures of temperature and precipitation extremes are projected to increase in the Northwest. (Section 2.4.2)

Climate models are unanimous that measures of heat extremes will increase and measures of cold extremes will decrease. Averaged over the Northwest, NARCCAP results project that in the period averaged over 2041 to 2070 there will be more days above maximum temperature thresholds and fewer days below minimum temperature thresholds compared with the 1971–2000 average. For example, the number of days greater than 32 °C (90 °F) increases by 8 days (± 7), and the number of days below freezing decreases by 35 days (± 6). Future changes in precipitation extremes are more certain than changes in total seasonal precipitation. The number of days with greater than 1 in (2.5 cm) of precipitation is projected to increase by 13% (± 7%) and the 20-year and 50-year return period extreme precipitation events are projected to increase 10% (-4 to +22%) and 13% (-5 to +28%), respectively, by mid-century.

Chapter 3 Water Resources: Implications of Changes in Temperature and Precipitation

Changes in precipitation and increasing air temperatures are already having, and will continue to have, significant impacts on hydrology and water resources in the Northwest. (Section 3.1)

Such climate changes will alter streamflow magnitude and timing, water temperatures, and water quality. Hydrologic impacts will vary by watershed type. Snow-dominant watersheds are projected to shift toward mixed rain-snow conditions, resulting in earlier and reduced spring peak flow, increased winter flow, and reduced late-summer flow; mixed rain-snow watersheds are projected to shift toward rain-dominant conditions; and rain-dominant watersheds could experience higher winter streamflows if winter precipitation increases, but little change in streamflow timing (fig. 3.3). Such hydrologic impacts have important consequences for reservoir systems, hydropower production, irrigated agriculture, floodplain and municipal drinking water infrastructure, freshwater aquatic ecosystems, and water-dependent recreation.

Reduced snowpack and shifts in streamflow seasonality due to climate change pose an additional challenge to reservoir system managers as they strive both to minimize flood risk and to satisfy warm season water demands. (Section 3.2.1)

Reservoir systems in the Northwest rely heavily on the ability of snowpack to act as additional water storage. During the snowmelt season, reservoir managers face the challenge of simultaneously maximizing water storage for summer water supply and maintaining sufficient space for capturing floodwaters to minimize downstream flood risk. Earlier snowmelt and peak flow means that more water will run off when it is not needed for human uses and that less water will be available to help satisfy early summer water demand. Flood risk may decrease in some basins and will likely increase in others.

The Columbia River Basin, whose reservoir storage capacity is much smaller than its annual flow volume, is ill-equipped to handle the projected shift to earlier snowmelt and peak flow timing and will likely be forced to pass much of these earlier flows out of the system, under current operating rules. With reservoir drawdown starting earlier in the year, managers would be faced with complex tradeoffs between multiple objectives; namely, hydropower, irrigation, instream flow augmentation for fish, and flood control.

Due to earlier peak streamflow, summer hydropower generation is projected to decline, but winter hydropower generation may increase. (Section 3.3.2)

Hydropower production provides two-thirds of the region's electricity and the Northwest produces 40% of all US hydropower. The shifts in streamflow timing caused by reduced snowpack and earlier snowmelt will reduce the opportunity for hydropower generation in the late spring and summer. In one study, summer hydropower production is projected to decline by about 15% by 2040, while winter hydropower production may

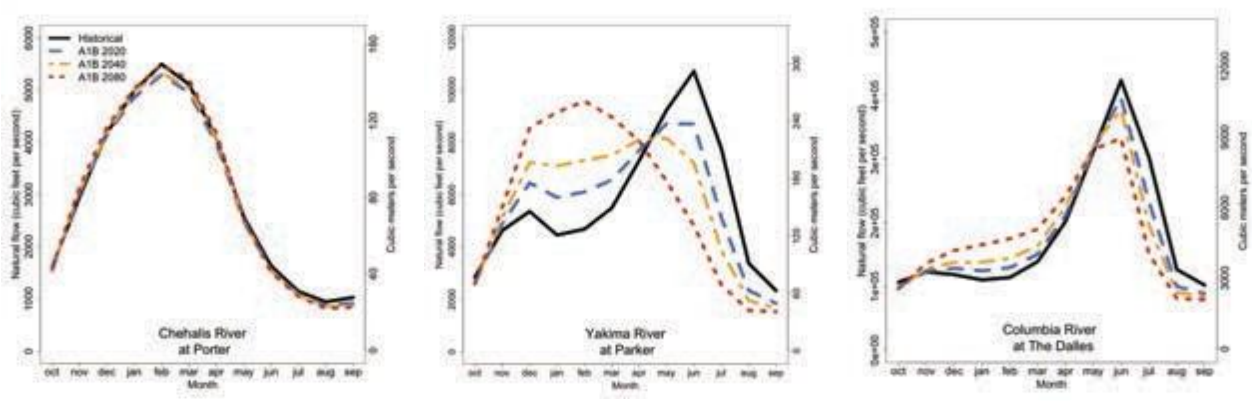

Figure 3.3. Simulated monthly streamflow hydrographs for the historical baseline (1916–2006 average, black) and the 2020s (blue), 2040s (yellow), and 2080s (red) under the SRES-A1B scenario of continued emissions growth peaking at mid-century (after Elsner et al. 2010) for three representative watershed types in the Northwest, namely rain dominant (Chehalis River at Porter, *top*), mixed rain-snow (Yakima River at Parker, *center*), and snowmelt dominant (Columbia River at The Dalles, *bottom*).

slightly increase (4%) compared to 1917–2006 levels. Further reductions in hydropower generation may also result from climate change adaptation for other competing water management objectives; for example, flood control and instream flow augmentation for fish.

Reduced water supply combined with increased water demands in the summer could lead to water shortages, reducing the proportion of irrigable cropland and the value of agricultural production. (Section 3.3.1)

Irrigated agriculture is the largest consumptive water user in the Columbia River Basin and poses the greatest demands on regional reservoir systems. Warmer, drier summers and a longer growing season may increase those demands. A case study in the Yakima River Basin projects the more frequent occurrence of conditions in which senior water right holders experience shortage. Water shortages could impact the proportion of cropland able to be irrigated during the growing season and lead to substantially reduced value of agricultural production; however, certain producer strategies may mitigate the shortage. Some evidence also suggests that increased atmospheric CO_2 concentrations may benefit water use efficiency in plants, possibly mitigating potential effects of drought.

Floodplain and municipal water supply infrastructure are vulnerable to projected increases in extreme precipitation and flood risk. (Section 3.3.3, 3.3.4)

Increases in extreme precipitation and flooding are expected, though changes in flood risk depend on the type of basin. Warmer winter temperatures and increased precipitation variability have already increased winter flood risk in mixed rain-snow basins in Washington and Oregon. Developed areas in floodplains may be particularly vulnerable to the increased flood risk, depending on flood control capacity. Water management may be stressed also by more frequent temperature extremes, warmer stream temperatures, lower summer flows, and the projected increase in municipal water demands. State and local government agencies in the Northwest are building strategies to address issues around how climate and hydrological change affects municipal water supply and use.

Changes in hydrologic flow regimes and warming stream and lake temperatures pose significant threats to aquatic ecosystems and are expected to alter key habitat conditions for salmon and other aquatic species. (Section 3.3.5)

Hydrologic changes in streamflow may harm the spawning and migration of salmon and trout species. Continued warming of stream and lake temperatures may also affect the health of and the extent of suitable habitat for many other aquatic species. Salmonids and other species that currently live in conditions near the upper range of their thermal tolerance are particularly vulnerable to higher stream temperatures, increasing susceptibility to disease and rates of mortality. Upstream migration for thermally-stressed species may be impeded by changes in channel structure from altered low-flow regimes. Reduced glacier area and volume over the long-term, which is projected for the future in the North Cascades, may challenge Pacific salmonids in those streams in which glacier melt comprises a significant portion of streamflow, although the consequences of glacial loss are not well quantified.

Water-dependent recreational activities will be affected by dry conditions, reduced snowpack, lower summer flows, impaired water quality, and reduced reservoir storage. (Section 3.3.6)

The sport fishing industry is likely to be affected by climate change effects on native fish including Pacific salmon. Mid-elevation ski resorts, located near the freezing elevation, will be the most sensitive to decreased snow, increased rain, and earlier spring snowmelt. The shortened ski-season will not only affect skiers, but the livelihood of local communities that are dependent on snow-recreation.

Chapter 4 Coasts: Complex Changes Affecting the Northwest's Diverse Shorelines

Sea level along the Northwest coast is projected to rise 4–56″ (9–143 cm) by 2100, with significant local variations. (Section 4.2)

Global mean sea level rose 0.12 in/year (3.1 mm/year) during 1993–2012, and there is high confidence that global sea level will continue to rise throughout the 21st century and beyond. Many local and regional factors modify the global trend in the Northwest. The active tectonics underlying western Oregon and Washington cause uplift in some locations, such as the Olympic Peninsula, at nearly the same rate as sea level rise resulting in little observed local sea level change, whereas subsidence in other locations leads to larger local sea level rise. End-of-the-century sea level rise projections along the NW coast range from 4 to 56 in (9–143 cm) relative to the year 2000, with variation in local factors adding to or subtracting from this range in different locations. Increasing wave heights in recent decades may have been a dominant factor in the observed increased frequency of coastal flooding along the outer coast. Regional sea levels can rise up to 12 in (30.5 cm) during an El Niño event, compounding impacts of sea level rise, but it is unknown whether and how El Niño-Southern Oscillation (ENSO) intensity and frequency may change in the future.

Increasingly acidified waters hinder the ability of some marine organisms to build shells and skeletons, which could alter key ecological processes, threatening our coastal marine ecosystems, fisheries, and aquaculture. (Sections 4.3, 4.5.3)

Anthropogenic additions of CO_2, seasonal coastal upwelling, and inputs of nutrients and organic matter combine to produce some of the most acidified marine waters worldwide along our coast; conditions in estuaries can reduce pH even further. Decreased abundance of shell forming species, many of which are highly vulnerable to ocean acidification, may alter the abundance and composition of other marine species. A simulation of ocean acidification impacts on the shelled species at the base of the marine food web resulted in a 20–80% decline of commercially important groundfish such as English sole. The rate at which mussels and oysters form shells is projected to decline by 25% and 10%, respectively, by the end of the century, and oyster larval growth rates are slower under low pH levels. Some species, such as sea grasses, may actually benefit from increased ocean acidification. Because of the serious implications of ocean acidification for marine species, several recent research initiatives have focused on identifying the impacts of ocean acidification in the Northwest.

Ocean temperatures off the Northwest coast have increased in the past and, though highly variable, are likely to increase in the future, causing shifts in distribution of marine species and contributing to more frequent harmful algal blooms. (Sections 4.4, 4.5.2)

Future increases in ocean temperature will continue to be highly variable and will affect the distribution of marine species found in NW coastal waters. Cooling of the eastern equatorial Pacific and ENSO-related changes in wind over the North Pacific may moderate warming of the northeast Pacific. Near coastal sea surface temperature (SST) varies by about 4–6 °C (7–11 °F) annually and is influenced by local coastal upwelling and downwelling and other weather and oceanographic-related factors. The range and abundance of Pacific Coast marine fish, birds, and mammals vary from year-to-year and serve as important indicators for potential fish species' responses to future climate change. For example, Pacific mackerel and hake are drawn to warmer coastal waters during El Niño events. One study found that long-term climate change, rather than climate variability, was the predominant factor in observed changes in the breeding and abundance of several seabird species in the California Current System. Blue whale and California sea lion habitats are projected to decrease over the 21st century, while northern elephant seal habitat is projected to increase. Increases in SST also contribute to more frequent and extended incidences of harmful algal blooms, increasing risks associated with paralytic shellfish toxins.

Coastal marine ecosystems in the Northwest provide important habitat for a diverse range of species. Coastal changes, such as sea level rise, erosion, and saltwater intrusion, could lead to loss or decline of some habitats, with impacts varying along the coast. (Section 4.5.1, Fig. 4.2.b)

Coastal wetlands, tidal flats, and beaches in low-lying areas with limited opportunity to move upslope (either by migrating inland or directly upwards by accumulating sediment) are highly vulnerable to sea level rise and coastal erosion, threatening the loss of key habitats and supported species. Significant beach erosion has occurred in north-central Oregon, where local sea levels have been rising, whereas southern Oregon beaches, where local sea levels have not risen, are relatively stable. Beach erosion increasingly exposes upland habitat to extreme tides and storm surges, affecting, for example, haul-out sites used by harbor seals for resting, breeding, and rearing pups. Coastal freshwater marsh and swamp habitats are projected to convert to salt or transitional marsh due to increasing saltwater inundation, reducing the extent of tidal flats and estuarine and outer coast beaches and affecting associated species, such as shorebirds and forage fish. Sea level rise could reduce the extent of certain coastal marshes and riparian habitat used by juvenile Chinook salmon as they transition between freshwater and ocean life stages. Potential increases in surface and groundwater salinity, due to sea level rise, may affect coastal plant and animal species unable to tolerate such increases. Some coastal habitats may be able to accommodate moderate rates of sea level rise by migrating inland, provided that there are no barriers such as dikes and seawalls.

Sea level rise and flooding will affect Northwest coastal transportation infrastructure, though the degree of potential impacts will vary. (Section 4.6.1)

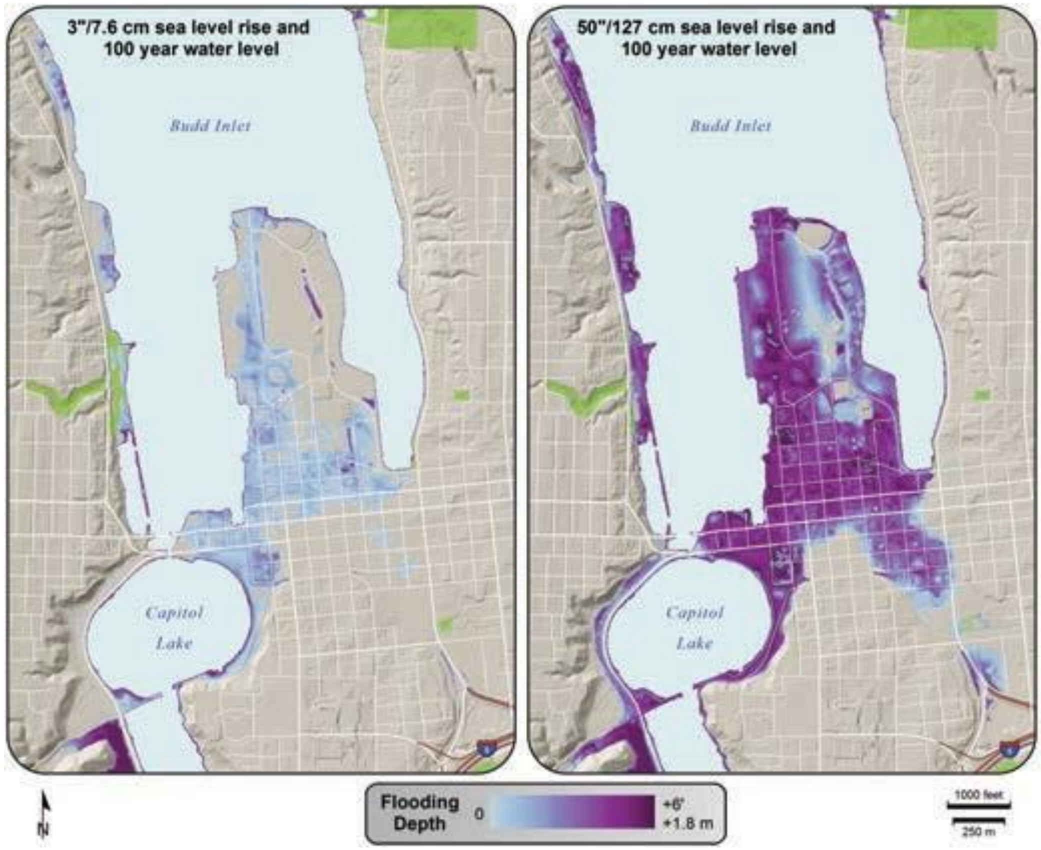

Figure 4.6 Projected flooding of downtown Olympia with a 100-year water level and 127 cm (50 in) of sea level rise. Redrawn from Coast and Harbor Engineering (2011).

About 2800 miles of roads in Washington and Oregon coastal counties are in the 100-year floodplain. The Washington State Department of Transportation assessed the climate change vulnerability of state-owned transportation infrastructure, identifying some outer coast and low-lying highways near Puget Sound that may face long-term inundation from 2 ft (0.6 m) of sea level rise. Most major state highways in Washington are situated high enough to experience only temporary closures. Highways near the mouth of the Columbia River near Astoria, Oregon, are also at risk. Inundation of low-lying secondary transportation routes in many coastal areas of the Northwest will very likely worsen and has the potential to temporarily cut off access to some communities during high tide and storm events.

Northwest coastal cities face multiple climate impacts and risks, including sea level rise, erosion, and flooding. Some local governments are evaluating and preparing for climate-related risks and vulnerabilities. (Section 4.6.2, Box 4.1)

The City of Seattle is assessing the vulnerability of its infrastructure to sea level rise and storm surge and is developing adaptation options. The City of Olympia is similarly examining areas of future exposure to inundation in the downtown core under various sea level rise and creek flooding scenarios (fig. 4.6), examining engineering and regulatory responses, and incorporating sea level rise response in their comprehensive planning process. The City of Anacortes has examined risks to their water treatment facility from projected increases in river flooding and resultant increases in sediment loading. The Swinomish Indian Tribal Community has examined a wide range of climate vulnerabilities and corresponding adaptation strategies and is incorporating assessment findings into ongoing regulatory and economic development efforts.

Climate driven changes in ocean conditions may have important economic impacts on marine fisheries, including shellfish aquaculture and fish landings. (Section 4.7.1)

Marine and coastal resources, particularly marine fisheries, provide communities in the Northwest with numerous economic benefits. The response of fish species to climate change will vary, so there may be both positive and negative economic impacts on commercial and recreational fisheries. Shellfish aquaculture, which provides many jobs and 49% and 72% of the commercial fishing landing value in Oregon and Washington, respectively, is threatened by ocean acidification. Climate–driven changes in the distribution, abundance, and productivity of key commercial species in Oregon and Washington could impact landings and revenues, which averaged around $275 million per year from 2000 to 2009.

Chapter 5 Forest Ecosystems: Vegetation, Disturbance, and Economics

The spatial distribution of suitable climate for many important Northwest tree species and vegetation types may change considerably by the end of the 21st century, and some vegetation types, such as subalpine forests, will probably become extremely limited. (Section 5.2)

Climate change is likely to affect the distribution, growth, and function of NW forests. Tree growth responses to future climate change will vary both within the region and in time with climate variability, but some locations are likely to experience higher growth (e.g., higher elevations) whereas other areas are likely to experience reduced growth (e.g., the lower elevation eastern parts of the Cascade Range). Forests limited by water availability will likely experience longer, more severe water-limitation under projected warming and reduced warm-season precipitation, resulting in decreased tree growth. Forests limited by energy or temperature will likely experience increased growth, depending on water availability. Area climatically favorable for Douglas-fir is projected to decrease by 32% by the 2060s in Washington in one study, but another study suggests that Douglas-fir may be able to balance loss of climate suitability at lower elevations with increases at higher elevations. Sub-alpine tree species are projected to decline and have limited potential to migrate upslope, resulting in potential loss of these high-elevation habitats, affecting associated wildlife and biodiversity. Vulnerability to disturbances is expected to increase in most forests.

Grasslands in some areas may expand under warmer and drier conditions, while sagebrush steppe habitat may transition to other vegetation (woodland or even forest)

depending on the amount and seasonality of precipitation change. Increased fire activity and expansion of invasive species will also determine the response of these systems to climate change. (Box 5.1)

Grassland and shrubland systems have already declined through land use and management changes, and the effect of future climate change will vary. Grass-dominated prairies and oak savannas in western parts of the Northwest are adapted to periodic drought and may expand under future warmer and drier conditions. Sagebrush steppe systems and associated species are sensitive to altered precipitation patterns and may decline, being replaced by woodland and forest vegetation. Expansion of new and current invasive species, both native (e.g., western juniper) and non-native (e.g., yellow starthistle), will influence the response of grassland and shrubland systems to climate change. Many grassland and shrubland systems are adapted to frequent fires, but projected increases in future fire activity threaten fire intolerant shrubs and the greater sage-grouse that depend on them for feeding, nesting, and protection.

The cumulative effects of climate change on disturbances (fire, insects, tree disease), and the interactions between them, will dominate changes in forest landscapes over the coming decades. (Sections 5.3, 5.3.4)

Large areas have been affected by disturbances in recent years (fig. 5.7), and climate change is expected to increase the probability of disturbance. The interaction between multiple disturbances (insect or disease outbreaks and wildfires) will heighten impacts on forests. The forests that establish after disturbance will depend on disturbance, climate, and other conditions that affect forest processes, though cumulative effects will vary. At least in the first half of the 21st century, climate change impacts on plant productivity, life history, and distribution are likely to be secondary to disturbance in terms of the area affected and risk presented to human values via altered forest ecosystem services.

Fire activity in the Northwest is projected to increase in the future in response to warmer and drier summers that reduce the moisture of existing fuels, facilitating fire. One study estimated that the regional area burned per year will increase by roughly 900 sq. mi. by the 2040s. (Section 5.3.1)

Climate influences both vegetation growth prior to the fire season and short-term vegetation moisture during the fire season, which influence fire-season activity. Fire activity in most NW forests tends to increase with higher summer temperature and lower summer precipitation. In one study, regional area burned is projected to increase by 0.3, 0.6, and 1.5 million acres by the 2020s, 2040s, and 2080s, respectively. Years with abnormally high area burned may become more frequent in the future: the chance of a given year being what was historically a "high" fire year is projected to increase by up to 30% for non-forested systems, 19% for the western Cascade Range, and 76% for the eastern Cascade Range. Greater fire severity is expected as increases in extreme events, particularly droughts and heat waves, will likely increase fire activity in the Northwest.

Recent mountain pine beetle and other insect outbreaks were facilitated by higher-than-average temperatures and drought stress, and the frequency and area of such

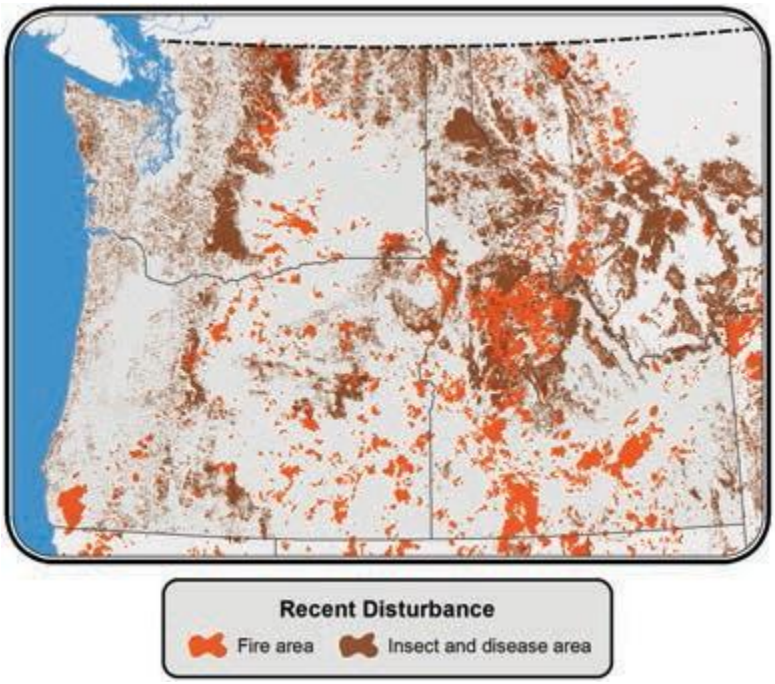

Figure 5.7. Areas of recent fire and insect disturbance in the Northwest.

outbreaks is expected to increase, particularly in high-elevation forests. Certain forest diseases, such as Swiss needle cast in Douglas-fir, are also expected to increase in the future. (Sections 5.3.2, 5.3.3)

Insect life-stage development and mortality rates are influenced by temperature, and drought can cause host trees to be more vulnerable to insects, leading to higher tree mortality. The frequency and area of mountain pine and spruce beetle outbreaks is expected to increase with future warming in the Northwest, particularly in high-elevation forests that are typically too cold to support the insect. Climate also influences the range and survival of forest pathogens, but the climate-disease relationship is unclear for many diseases and depends on pathogen-host interaction. Higher average temperatures and increased spring precipitation in the Oregon Coast Range have contributed to an increase in severity and distribution of Swiss needle cast in Douglas-fir, which is projected to have a greater impact in the future.

While the Northwest's forest economy is sensitive to climate changes, federal and state policies governing management and harvest have and will continue to impact the net returns to this sector, and the magnitudes of the impacts from policy changes and from climate change are difficult to separate. (Section 5.4.1)

The sustainability, net returns, and long-term future of the forest economy depend on the interaction of climate factors and management practices and policies. In the Northwest, while yields may increase due to a more favorable set of climate changes, leading to increased timber production, timber markets may be adversely impacted because of declining global prices and reduced net returns to timber producers. Timber yield losses due to regional insect and disease outbreaks and wildfires could also offset any potential economic benefit from increased growth in the Northwest. Furthermore, increasing severity and intensity of Swiss needle cast affecting the commercially and culturally important Douglas-fir could pose a threat to the NW timber industry west of the Cascade Range; the dominant commercial species east of the Cascade Range, ponderosa pine, is increasingly affected by mountain pine beetle and other insect and disease attacks, decreasing growth and yield.

Tourism and recreation on publicly owned lands (about two-thirds of Northwest forests) are important economically and socially in the region and may be affected by climate change. (Section 5.4.1.3)

Although no specific studies have been conducted on the NW economy, national scale estimates suggest forest recreation revenue losses of $650 million by 2060. Given the extent of forested and recreational land in the Northwest, along with projected increased risk of wildfire and decreased snowpack, impacts on the NW recreational economy will likely be negative. In the short-term, summer recreational opportunities in publicly owned forest land could increase due to lengthening of the high-use summer season, while winter recreational opportunities may decline. The local economies in drier regions of the Northwest could experience economic losses because of forest closures from wildfires.

Forest ecosystem services, such as flood protection or water purification, and goods, such as species habitat or forest products, add wealth to society and will be affected by climate change. (Section 5.4.1.4)

Valuing changes in these ecosystem goods and services is based on demand for these services. Changes in the demand of these services is influenced by many factors including land development, water demands, and air pollution, which all interact with climate change, making it difficult to isolate the impact of climate change on the value of ecosystem goods and services. However, values of some ecosystem goods and services in the Northwest have been estimated: water purification function of forests ($3.2 million per year); erosion control in the Willamette Valley ($5.5 million per year); cultural and aesthetic uses ($144 per household per year); and endangered species habitat ($95 per household per year).

Northwest forest ecosystems that will be affected by climate change support many species of fish and wildlife whose abundance and distribution may also be affected. (Section 5.4.2)

Wolverines and pika are particularly vulnerable to projected loss of alpine and subalpine habitat provided by snow cover and high-elevation tree species. Changes in fire regime could negatively impact old-growth habitat species, such as marbled murrelets and northern spotted owls, and affect stream temperatures and riparian vegetation important for spawning and juvenile bull trout. Some species, such as the northern flicker and hairy woodpecker, may thrive with more frequent fires. The effects of climate change may exacerbate existing stressors to natural systems.

Chapter 6 Agriculture: Impacts, Adaptation, and Mitigation

Agriculture is important to the Northwest's economy, environment, and culture. Our region's diverse crops depend on adequate water supplies and temperature ranges, which are projected to change during the 21st century. (Sections 6.1, 6.2, 6.3)

Agriculture contributes 3% of the Northwest's gross domestic product, crop and pastureland comprise about one-quarter of NW land area, and farming and ranching have been a way of life for generations. Wheat, potatoes, tree fruit, vineyards, and over 300 minor crops, as well as livestock grazing and confined animal feeding operations such as beef and dairy, depend on adequate supply of water and temperature ranges. Higher temperatures and altered precipitation patterns throughout the 21st century may benefit some cropping systems, but challenge others. Vulnerabilities differ among agricultural sectors, cropping systems (fig. 6.3), and location. Climate changes could alter pressure from pests, diseases, and invasive species. Available studies specifically examining climate change and NW agriculture are limited, and have focused on major commodities.

Projected climate changes will have mixed implications for dryland crops. Warmer, drier summers increase risks of heat and drought stress. At the same time, warmer winters could be advantageous for winter wheat and other winter crops, and increases in atmospheric CO_2 can improve yields at least until mid-century (Section 6.4.1.1)

Dryland cereal-based cropping systems occur mainly in the semiarid portion of central Washington and the Columbia Plateau of northeastern Oregon and northern Idaho. Winter wheat may benefit from warmer winters, but drier summers may delay fall planting of this crop. Increased winter precipitation could hamper spring wheat planting, but could also mitigate projected reductions in summer precipitation. Taking into account the beneficial effects of atmospheric CO_2, winter wheat yields are projected to increase 13–25% while spring wheat yields are projected to change by –7% to +2% by mid-21st century across several locations in Washington.

Irrigated crops are vulnerable to higher temperatures and projected water shortages from increasing demands and reduced supplies; potato yields are generally projected to increase with increasing atmospheric CO_2 to mid-century and decline to levels similar to or substantially below current yields by end of century. (Section 6.4.1.2)

The rivers of the Columbia and Klamath Basins provide irrigation water for surrounding agricultural areas that receive low summer and annual precipitation. Irrigation demands are expected to increase in the summertime with warmer temperatures, while water supplies are likely to be reduced, which could exacerbate water shortages in some areas, potentially reducing yields of irrigated wheat, potatoes, sugarbeets, forages, corn, tree fruit, and vegetable crops. Potatoes, grown under irrigation primarily in central Washington and the Snake River valleys of Idaho, are projected to experience yield losses from higher temperature, but when considering CO_2 fertilization, losses may only be 2–3% by the end of the century. Some studies project higher losses of up to 40% in Boise, Idaho.

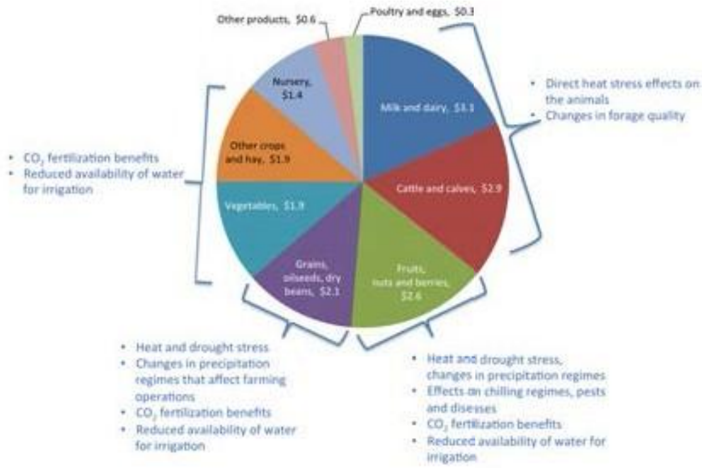

Figure 6.3. Northwest agricultural commodities with market values shown in $ (billion) in 2007. Potential effects of climate change on these sectors, if any have been projected, are shown.

Warmer winters could adversely affect tree fruits dependent on chilling for fruit set and quality. Tree fruits, most of which are produced with irrigation, are vulnerable to projected reduction in water supplies. Increased CO_2 may offset these effects; irrigated apple production is projected to increase 9% by the 2040s. (Section 6.4.2.1)

Payette County, Idaho, the Willamette Valley in Oregon, and central Washington are home to major tree-fruit production that requires irrigation and adequate chilling periods. Projected warmer temperatures that disrupt chilling requirements could hamper production of some existing tree fruits while allowing new cold-sensitive varieties to be grown. Under warming, irrigated apple production is projected to decrease by 3% in the 2040s, but increase by 9% when CO_2 fertilization is included. In addition, early budding from warmer spring temperatures could put trees more at risk to damage by frost. Tree fruits are water-intensive crops, making them vulnerable to projected reduced water supplies in some locations.

Northwest wine regions are already seeing an increase in the length of the frost-free period and warmer temperatures, which could adversely impact this growing industry. (Section 6.4.2.2)

Wine grapes are primarily grown in western Oregon and the Columbia River Basin. Each wine grape varietal has an optimal growing-season temperature range. Warmer temperatures could shift which varieties are produced in specific locations and alter wine quality. While some varietals, such as Pinot Noir and Pinot Gris (dominant grapes grown in Oregon), may experience temperatures in excess of optimal thresholds by mid-century, other varietals may become viable or more favorable in Oregon and Washington, although the cost of replacing long-lived vines must be considered.

Warming may reduce the productivity and nutritional value of forage in rangelands and pastures, though alfalfa production may increase as long as water is available. Higher temperatures can affect animal health, hampering milk production and beef cattle growth. (Section 6.4.3)

Grazing lands provide important ecosystem services. A warming climate may reduce productivity and nutritional value in rangelands located in warmer, drier climates while benefiting those in wetter environments. As long as water is not limiting, alfalfa production may increase in the Northwest under warmer temperatures and higher CO_2 concentrations. Climate change in rangeland systems may alter pressure from invasive species leading to degradation. Decreased availability, nutritional quality, and digestibility of forages, projected under higher CO_2 concentrations, may adversely affect livestock. Increased temperatures and extreme heat days can also affect animal health. Warmer temperatures can reduce milk production and decrease the rate of beef cattle growth, reducing the economic value of these products.

Agriculture is both impacted by and contributes to climate change. There are opportunities to reduce Northwest agriculture's contribution to climate change. (Box 6.1)

Opportunities to mitigate emissions in the Northwest include reducing tillage (which increases carbon storage in the soil), improving nitrogen fertilization efficiency to limit nitrous oxide production and release to the atmosphere (nitrous oxide is a greenhouse gas), and capturing methane emissions from manure. Mitigation strategies may have co-benefits that help with adaptation, sustainability and profitability of farming.

Northwest agriculture may be well positioned to adapt autonomously to climate changes due to the flexible nature of agriculture in responding to variable weather conditions and the relatively moderate projected impacts for the Northwest region. (Section 6.5)

Inherent adaptability varies by cropping system, with diversified systems potentially more adaptable than semi-arid inland wheat production and rangeland grazing. Agriculture's adaptive capacity is constrained by availability and time required for transitioning to new varieties, risk aversion among farmers, water availability in irrigation-dependent regions, and some economic, environmental, and energy policies. Partnerships and investments between public and private sectors have helped ensure agriculture remained strong in the preceding century and will be essential in the future.

Chapter 7 Human Health: Impacts and Adaptation

While the potential health impact of climate change is low for the Northwest relative to others parts of the United States, key climate-related risks facing our region include heat waves, changes in infectious disease epidemiology, river flooding, and wildfires. (Section 7.1)

Climate change in the Northwest will have implications for all aspects of society, including human health. Communities in the Northwest will experience the effects of climate change differently depending on existing climate and varying exposure to climate-related risks. While vulnerability remains relatively low in the Northwest, the negative impacts of climate change outweigh any positive ones. Increasing temperatures, changing precipitation patterns, and the possibility of more extreme weather could increase morbidity and mortality due to heat-related illness, extreme weather hazards, air pollution and allergenic disease exacerbation, and emergence of infectious diseases.

Average temperatures and heat events are projected to increase in the Northwest with an expected increase in incidence of heat-related illness and death (Section 7.2.1)

Heat-related deaths in the US have increased over the past few decades. In Oregon, the hottest days in the 2000s had about three times the rate of heat-related illness compared with days 10 °F (5.6 °C) cooler. Warmer temperatures and more extreme heat events are expected to increase the incidence of heat-related illnesses (e.g., heat rash, heat stroke) and deaths. One study projected up to 266 excess deaths among persons 65 and older in 2085 in the greater Seattle area compared to 1980–2006. Outdoor workers are especially vulnerable to heat-related illnesses.

People in the Northwest are threatened by projected increases in the risk of extreme climate-related hazards such as winter flooding and drought. (Section 7.2.2)

Wintertime flood-risk is likely to increase in mixed rain-snow basins in Washington and Oregon due to increased temperatures and, potentially, increased winter precipitation. Decreased summer precipitation and temperature-driven loss of snowpack can lead to more frequent drought conditions in the Northwest, leading to human health impacts due to food insecurity and associated wildfires. Drought can reduce global food supply and increase food prices, threatening food insecurity, especially for the poor and those living in rural areas of the Northwest. The 2012 US drought, one of the most extensive in 25 years with an estimated loss of up to $7–$20 billion, resulted in disaster declarations across the country, including counties in Oregon and Idaho.

Climate change can have a negative impact on respiratory disorders due to longer and more potent pollen seasons, increases in ground-level ozone, and more wildfire particulate matter (Section 7.2.3, 7.2.2)

Extended growing periods due to increased temperature can lengthen the pollen season and increase pollen production. Greater CO_2 concentrations can also heighten the potency of some pollens such as ragweed, found throughout the Northwest. A relatively small increase in ozone is expected for the Northwest (fig. 7.2) compared to other regions of the US, but increased ground-level ozone, or air pollution, can exacerbate asthma symptoms and lead to a higher risk of cardio-pulmonary death. Excess deaths due to ground-level ozone between 1997–2006 and mid-21st century are projected to increase from 69 to 132 and 37 to 74, respectively, in King and Spokane counties in Washington under a scenario of continued emissions growth (SRES-A2). The Northwest is expected to experience more burned acres during the wildfire season, releasing more particulate matter into the air. Wildfire risk is greatest east of the Cascade Range, but all population centers in the region are at risk of poor air quality from drifting smoke plumes, which could exacerbate respiratory disease.

Changes in climate can potentially impact the spread of vector-borne, water-borne, and fungal diseases, raising the risk of exposure to infectious diseases. (Section 7.2.4)

Longer, drier, warmer summers in the Northwest may have a significant impact on the incidence of arboviruses, such as West Nile virus. Higher ocean and estuarine temperatures in the Northwest have the potential to increase the number of *Vibrio parahaemolyticus* infections from eating raw oysters or other shellfish. Anticipated increases in

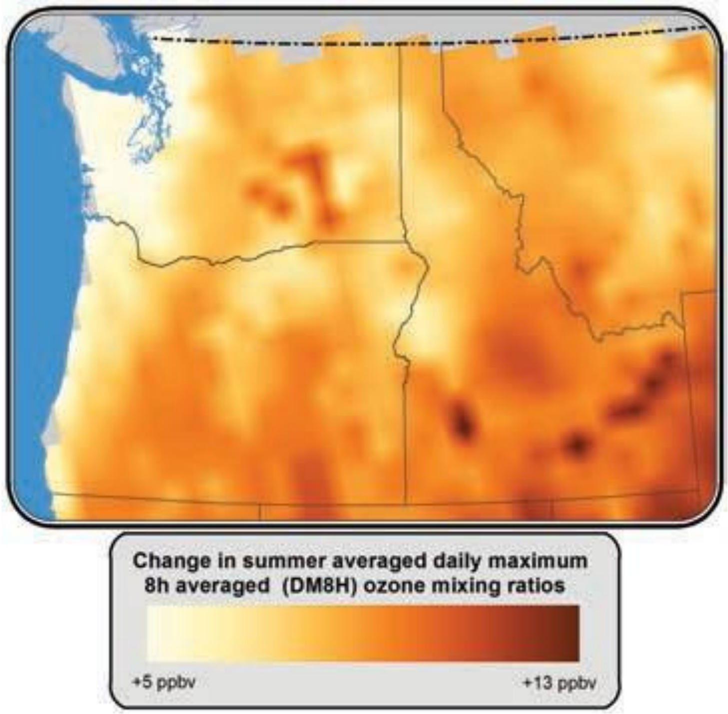

Figure 7.2. Change in summer averaged daily maximum 8-hr ozone mixing ratios (ppbv) between a future case (2045–2054) and base case (1990–1999) based on future climate from a model forced with the continued growth emissions scenario (SRES-A2). Changes in ground-level ozone are due to global and local emissions, changes in environmental conditions and urbanization, and increasing summer temperatures. Adapted from Chen et al. (2009).

precipitation and subsequent flooding have the potential to wash animal intestinal pathogens into drinking water reservoirs and recreational waters, potentially increasing the risk of *Cryptosporidium* outbreaks. The emergence of the fungus *Cryptococcus gattii* in the Northwest in the early 2000s may have some relationship to climate change.

Longer harmful algal blooms increase the risk of paralytic shellfish and domoic acid poisoning in humans. (Section 7.2.5)

The frequency, intensity, and duration of harmful algal blooms appear to be increasing globally, but the exact relationship to climate change is unknown. In the Puget Sound, rising water temperatures promote earlier and longer lasting harmful algal blooms, which can cause paralytic shellfish and domoic acid poisoning in humans who consume infected shellfish.

Climate change may affect mental health and well-being. (Section 7.2.6)

Like physical health impacts, there are direct and indirect mental health impacts of climate change. Extreme weather events can cause mental distress, and even the threat of a climate event, the uncertainty of the future, or the loss of control over a situation can result in feelings of depression or helplessness.

Public health practitioners and researchers in the Northwest are actively engaging local communities regarding adaptation measures for climate change. Additional efforts

are needed to engage a greater number of communities and build our understanding of how climate change will affect human health. (Sections 7.3, 7.4)

Public health officials, universities, and state agencies in the Northwest are engaged in numerous adaptation activities to address the potential impact of climate change on human health by developing public health adaptation resources, integrating planning at various government levels, and creating programs to monitor and respond to public health issues. Even some local health departments are creating their own climate change adaptation plans. In order to better understand the full impact of climate change on human health and for communities to effectively adapt, several needs must be addressed including accurate surveillance data on climate-sensitive health and environmental indicators.

Chapter 8 Northwest Tribes: Cultural Impacts and Adaptation Responses

Northwest tribes are intimately connected to the land's resources, and are tied to their homelands by law as well as by culture. The impacts of climate change will not recognize geographic or political boundaries. (Sections 8.1, 8.2)

Climate change will have complex and profound effects on tribal resources, cultures, and economies. In ceding lands and resources to the US, tribes were guaranteed the rights to hunt, fish, and gather on their usual and accustomed places both on and off reservation lands (fig. 8.2). Climate change could potentially affect these treaty-protected rights. For example, treaty-protected fish and shellfish populations may become threatened or less accessible to tribes due to climate change. Treaty water rights could also be affected by climate change through changes to water quantity and quality that affect salmon and other fisheries.

Reduced snowpack and shifts in timing and magnitude of precipitation and runoff could significantly affect culturally and economically important aquatic species, such as salmon. (Section 8.3.1, Box 8.1)

Salmon are culturally and economically significant to inland and coastal tribes throughout the Northwest. Spring Chinook salmon that spawn in the Nooksack River watershed, for example, are especially important to the Nooksack Indian Tribe for ceremonial, commercial, and subsistence uses. Past land-use practices have resulted in loss of fish habitat in the Nooksack watershed; observed changes in climate, such as decreased summer flows, increased stream temperatures, and higher peak winter flows, exacerbate the existing stressors that affect the migration and spawning of Chinook and other Pacific salmonids. Continued climate change will further challenge salmonid survival, highlighting the need for effective restoration strategies that consider both existing stressors and those added by climate change.

Increasing ocean acidification, hypoxia, and warmer air and water temperatures threaten many species of fish and shellfish widely used by tribes. (Section 8.3.2)

In the Puget Sound, fish and shellfish harvests are primary sources of income for tribal members. The health of these fisheries depends on how they are managed and the

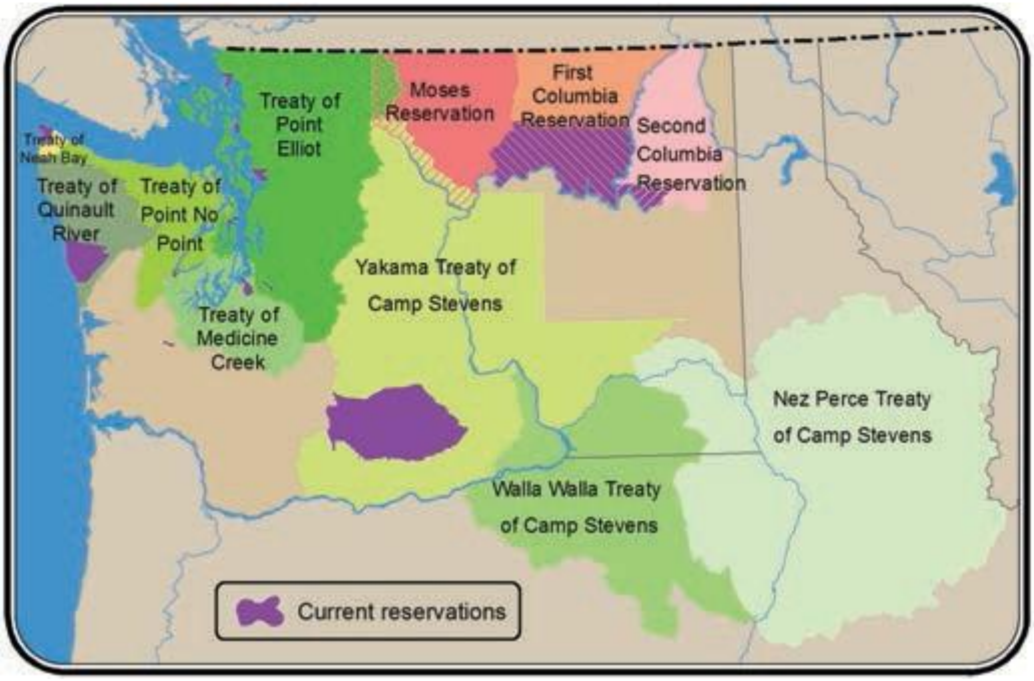

Figure 8.2. Treaty Ceded Lands. Washington State Historic Tribal Lands (Tribal Areas of Interest. Washington Department of Ecology)

health of the waters and ecosystems they inhabit. Decreasing pH is already associated with observed declines in the abundance and mean size of mussels from Tatoosh Island on the Makah Reservation in Washington. Warmer air temperatures have led to a decrease in the vertical extent of the California mussel in the Strait of Juan de Fuca.

Tribal coastal infrastructure and ecosystems are threatened by sea level rise, storm surge, and increasing wave heights. (Section 8.3.3)

Rising seas threaten culturally important areas of coastal tribes' homelands, such as burial grounds and traditional fishing and shellfish gathering areas, as well as infrastructure in low-lying areas. Small coastal reservations may face tension between allowing coastal habitat to shift inland (to limit habitat loss from sea level rise) and maintaining space for land-based needs and infrastructure.

Changes in forest ecosystems and disturbances will affect important tribal resources. (Section 8.3.4)

Projected changes in large-scale tree distribution across the Northwest, including those already occurring such as northward and elevational migration of temperate forests, will affect resources and habitats that are important for the cultural, medicinal, economic, and community health of tribes. Compounding impacts from forest disturbances, including wildfires and insect outbreaks, also pose a threat to traditional foods, plants, and wildlife that tribes depend on.

There are numerous tribes in the region pro-actively addressing climate change and bridging opportunities with non-tribal entities to engage in climate change research, assessments, plans, and policies. (Section 8.4)

There are many tribes in the Northwest pro-actively addressing climate change through a myriad of efforts. The Swinomish Indian Tribal Community showed early innovation in developing a tribal climate change impacts assessment and adaptation plan. The Tulalip Tribes are taking an ecosystem-based approach to understand and address interrelated changes in local ecosystems due to climate change. The Suquamish Tribe is engaged in federal, state, and academic research partnerships to study the effects of pH on crab larvae and is creating an online database to direct teachers to high quality climate change education materials. Other tribes in the region have initiated efforts to reduce greenhouse gas emissions through energy efficiency, renewable energy sources, and carbon sequestration.

Tribes in the Northwest have identified climate change needs and opportunities, including understanding the role of traditional ecological knowledge in climate initiatives and improving the government-to-government relationship. (Section 8.5)

Vulnerability to climate change and tribal adaptation strategies require explicit attention because of the unique social, legal, and regulatory context for tribes. It will be important for future climate research and policies to consider how reserved rights, treaty rights, and tribal access to cultural resources will be affected by climate change, potential species and habitat migration, and implementation of adaptation and mitigation strategies. Traditional knowledge can inform tribal and non-tribal understanding of how climate change may impact tribal resources and traditional ways of life. Strengthening government-to-government relationships is important in order to protect tribal rights and resources in the face of climate change, as is effective communication, collaboration, and federal-tribal partnerships.