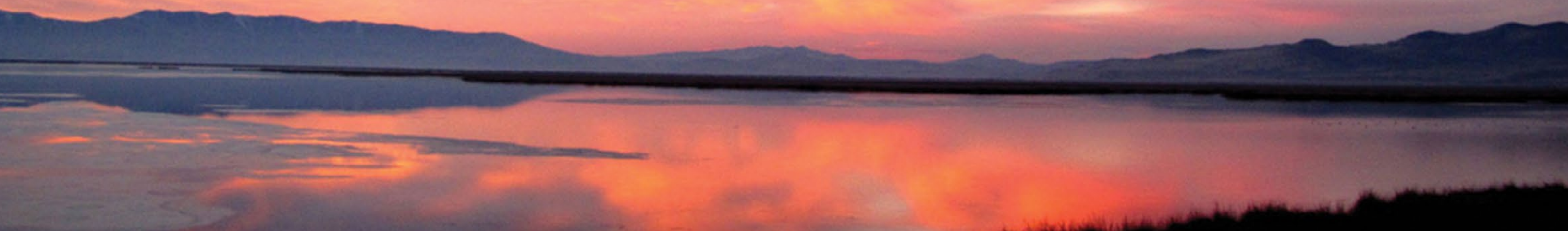

Climate Change Impacts in the United States

CHAPTER 21 NORTHWEST

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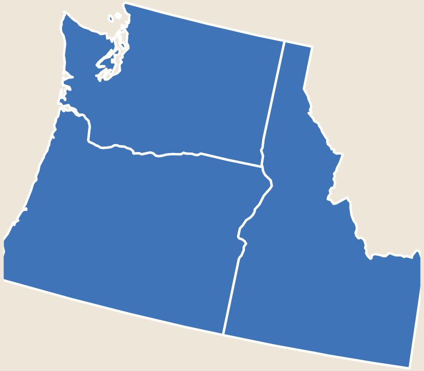

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21 NORTHWEST

Key Messages

1. **Changes in the timing of streamflow related to changing snowmelt are already observed and will continue, reducing the supply of water for many competing demands and causing far-reaching ecological and socioeconomic consequences.**
2. **In the coastal zone, the effects of sea level rise, erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.**
3. **The combined impacts of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Under higher emissions scenarios, extensive conversion of subalpine forests to other forest types is projected by the 2080s.**
4. **While the agriculture sector's technical ability to adapt to changing conditions can offset some adverse impacts of a changing climate, there remain critical concerns for agriculture with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.**

With craggy shorelines, volcanic mountains, and high sage deserts, the Northwest's complex and varied topography contributes to the region's rich climatic, geographic, social, and ecologic diversity. Abundant natural resources – timber, fisheries, productive soils, and plentiful water – remain important to the region's economy.

Snow accumulates in mountains, melting in spring to power both the region's rivers and economy, creating enough hydropower (40% of national total)[1] to export 2 to 6 million megawatt hours per month.[2] Snowmelt waters crops in the dry interior, helping the region produce tree fruit (number one in the world) and almost $17 billion worth of agricultural commodities, including 55% of potato, 15% of wheat, and 11% of milk production in the United States.[3]

Seasonal water patterns shape the life cycles of the region's flora and fauna, including iconic salmon and steelhead, and forested ecosystems, which cover 47% of the landscape.[4] Along more than 4,400 miles of coastline, regional economic centers are juxtaposed with diverse habitats and ecosystems that support thousands of species of fish and wildlife, including commercial fish and shellfish resources valued at $480 million in 2011.[5]

Adding to the influence of climate, human activities have altered natural habitats, threatened species, and extracted so much water that there are already conflicts among multiple users in dry years. More recently, efforts have multiplied to balance environmental restoration and economic growth while evaluating climate risks. As conflicts and tradeoffs increase, the region's population continues to grow, and the regional consequences of climate change continue to unfold. The need to seek solutions to these conflicts is becoming increasingly urgent.

The Northwest's economy, infrastructure, natural systems, public health, and vitally important agriculture sector all face important climate change related risks. Those risks – and possible adaptive responses – will vary significantly across the region.[6] Impacts on infrastructure, natural systems, human health, and economic sectors, combined with issues of social and ecological vulnerability, will play out quite differently in largely natural areas, like the Cascade Range or Crater Lake National Park, than in urban areas like Seattle and Portland (Ch. 11: Urban),[7] or among the region's many Native American tribes, like the Umatilla or the Quinault (Ch. 12: Indigenous Peoples).[8]

As climatic conditions diverge from those that determined patterns of development and resource use in the last century, and as demographic, economic, and technological changes also stress local systems, efforts to cope with climate change would benefit from an evolving, iterative risk management approach.[9]

Observed Climate Change

Temperatures increased across the region from 1895 to 2011, with a regionally averaged warming of about 1.3°F.[10] While precipitation has generally increased, trends are small as compared to natural variability. Both increasing and decreasing trends are observed among various locations, seasons, and time periods of analysis (Ch. 2: Our Changing Climate, Figure 2.12). Studies of observed changes in extreme precipitation use different time periods and definitions of "extreme," but none find statistically significant changes in the Northwest.[11] These and other climate trends include contributions from both human influences (chiefly heat-trapping gas emissions) and natural climate variability, and consequently are not projected to be uniform or smooth across the country or over time (Ch. 2: Our Changing Climate, Key Message 3). They are also consistent with expected changes due to human activities (Ch. 2: Our Changing Climate, Key Message 1).

Projected Climate Change

An increase in average annual temperature of 3.3°F to 9.7°F is projected by 2070 to 2099 (compared to the period 1970 to 1999), depending largely on total global emissions of heat-trapping gases. The increases are projected to be largest in summer. This chapter examines a range of scenarios, including ones where emissions increase and then decline, leading to lower (B1 and RCP 4.5) and medium (A1B) total emissions, and scenarios where emissions continue to rise with higher totals (A2, A1FI, and RCP 8.5 scenarios). Change in annual average precipitation in the Northwest is projected to be within a range of an 11% decrease to a 12% increase for 2030 to 2059 and a 10% decrease to an 18% increase for 2070 to 2099[12] for the B1, A1B, and A2 scenarios (Ch. 2: Our Changing Climate). For every season, some models project decreases and some project increases (Ch. 2: Our Changing Climate, Key Message 5),[10,12] yet one aspect of seasonal changes in precipitation is largely consistent across climate models: for scenarios of continued growth in global heat-trapping gas emissions, summer precipitation is projected to decrease by as much as 30% by the end of the century (Ch. 2: Our Changing Climate).[10,12] Northwest summers are already dry and although a 10% reduction (the average projected change for summer) is a small amount of precipitation, unusually dry summers have many noticeable consequences, including low streamflow west of the Cascades[13] and greater extent of wildfires throughout the region.[14] Note that while projected temperature increases are large relative to natural variability, the relatively small projected changes in precipitation are likely to be masked by natural variability for much of the century.[15]

Ongoing research on the implications of these and other changes largely confirms projections and analyses made over the last decade, while providing more information about how climate impacts are likely to vary from place to place within the region. In addition, new areas of concern, such as ocean acidification, have arisen.

Key Message 1: Water-related Challenges

Changes in the timing of streamflow related to changing snowmelt have been observed and will continue, reducing the supply of water for many competing demands and causing far-reaching ecological and socioeconomic consequences.

Description of Observed and Projected Changes

Observed regional warming has been linked to changes in the timing and amount of water availability in basins with significant snowmelt contributions to streamflow. Since around 1950, area-averaged snowpack on April 1 in the Cascade Mountains decreased about 20%,[16] spring snowmelt occurred 0 to 30 days earlier depending on location,[17] late winter/early spring streamflow increases ranged from 0% to greater than 20% as a fraction of annual flow,[18,19] and summer flow decreased 0% to 15% as a fraction of annual flow,[17] with exceptions in smaller areas and shorter time periods.[20]

Hydrologic response to climate change will depend upon the dominant form of precipitation in a particular watershed, as well as other local characteristics including elevation, aspect, geology, vegetation, and changing land use.[22] The largest responses are expected to occur in basins with significant snow accumulation, where warming increases winter flows and advances the timing of spring melt.[18,23] By 2050, snowmelt is pro-

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jected to shift three to four weeks earlier than the 20th century average, and summer flows are projected to be substantially lower, even for an emissions scenario that assumes substantial emissions reductions (B1).[24] In some North Cascade rivers, a significant fraction (10% to 30%) of late summer flow originates as glacier melt;[25] the consequences of eventual glacial disappearance are not well quantified. Basins with a significant groundwater component may be less responsive to climate change than indicated here.[26]

Changes in river-related flood risk depends on many factors, but warming is projected to increase flood risk the most in mixed basins (those with both winter rainfall and late spring snowmelt-related runoff peaks) and remain largely unchanged in snow-dominant basins.[27] Regional climate models project increases of 0% to 20% in extreme daily precipitation, depending on location and definition of "extreme" (for example, annual wettest day).

Observed Shifts in Streamflow Timing

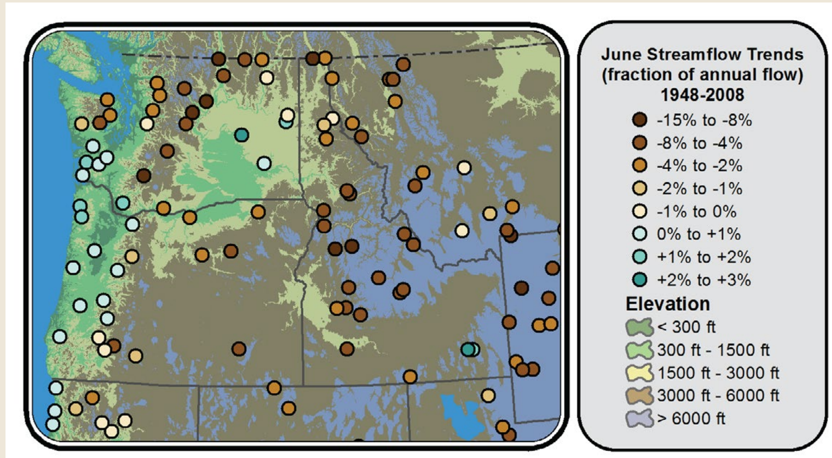

Figure 21.1. Reduced June flows in many Northwest snow-fed rivers is a signature of warming in basins that have a significant snowmelt contribution. The fraction of annual flow occurring in June increased slightly in rain-dominated coastal basins and decreased in mixed rain-snow basins and snowmelt-dominated basins over the period 1948 to 2008.[21] The high flow period is in June for most Northwest river basins; decreases in summer flows can make it more difficult to meet a variety of competing human and natural demands for water. (Figure source: adapted from Fritze et al. 2011[21]).

Future Shift in Timing of Stream Flows

Reduced Summer Flows

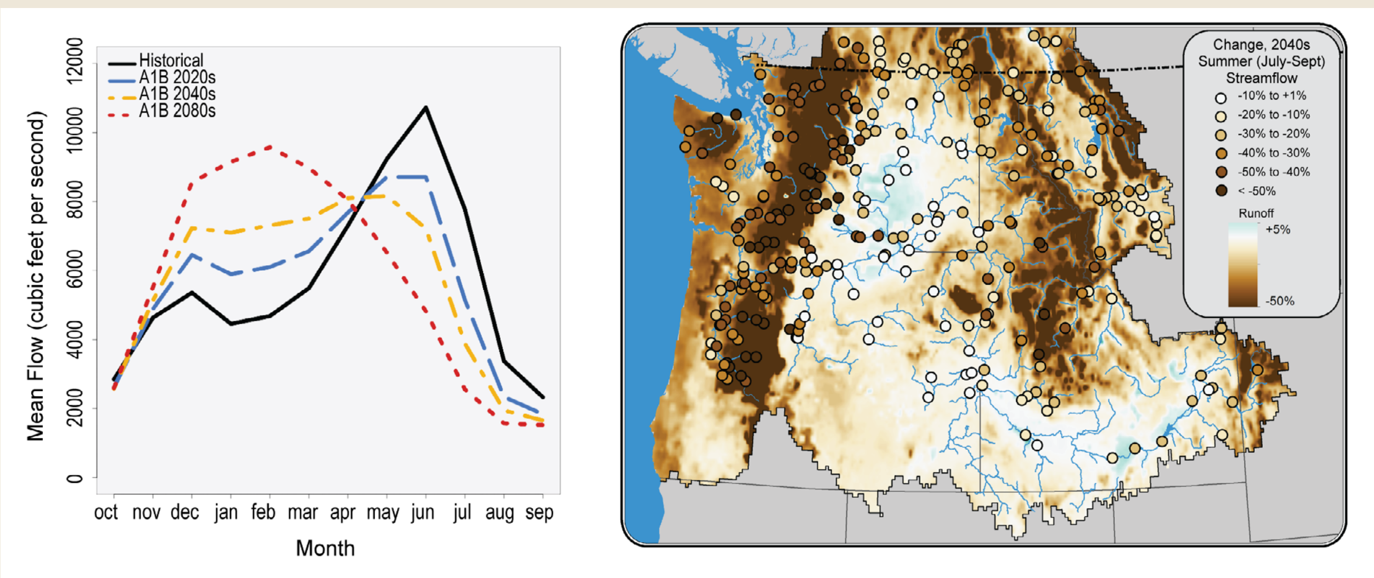

Figure 21.2. (Left) Projected increased winter flows and decreased summer flows in many Northwest rivers will cause widespread impacts. Mixed rain-snow watersheds, such as the Yakima River basin, an important agricultural area in eastern Washington, will see increased winter flows, earlier spring peak flows, and decreased summer flows in a warming climate. Changes in average monthly streamflow by the 2020s, 2040s, and 2080s (as compared to the period 1916 to 2006) indicate that the Yakima River basin could change from a snow-dominant to a rain-dominant basin by the 2080s under the A1B emissions scenario (with eventual reductions from current rising emissions trends). (Figure source: adapted from Elsner et al. 2010)[24].

(Right) Natural surface water availability during the already dry late summer period is projected to decrease across most of the Northwest. The map shows projected changes in local runoff (shading) and streamflow (colored circles) for the 2040s (compared to the period 1915 to 2006) under the same scenario as the left figure (A1B).[29] Streamflow reductions such as these would stress freshwater fish species (for instance, endangered salmon and bull trout) and necessitate increasing tradeoffs among conflicting uses of summer water. Watersheds with significant groundwater contributions to summer streamflow may be less responsive to climate change than indicated here.[26]

Averaged over the region, the number of days with more than one inch of precipitation is projected to increase 13% in 2041 to 2070 compared with 1971 to 2000 under a scenario that assumes a continuation of current rising emissions trends (A2),[10] though these projections are not consistent across models.[28] This increase in heavy downpours could increase flood risk in mixed rain-snow and rain-dominant basins, and could also increase stormwater management challenges in urban areas.

Consequences and Likelihoods of Changes

Reservoir systems have multiple objectives, including irrigation, municipal and industrial use, hydropower production, flood control, and preservation of habitat for aquatic species. Modeling studies indicate, with near 100% likelihood and for all emissions scenarios, that reductions in summer flow will occur by 2050 in basins with significant snowmelt (for example, Elsner et al. 2010[24]). These reduced flows will require more tradeoffs among objectives of the whole system of reservoirs,[30] especially with the added challenges of summer increases in electric power demand for cooling[31] and additional water consumption by crops and forests.[10,32] For example, reductions in hydropower production of as much as 20% by the 2080s could be required to preserve in-stream flow targets for fish in the Columbia River basin.[33] Springtime irrigation diversions increased between 1970 and 2007 in the Snake River basin, as earlier snowmelt led to reduced spring soil moisture.[34] In the absence of human adaptation, annual hydropower production is much more likely to decrease than to increase in the Columbia River basin; economic impacts of hydropower changes could be hundreds of millions of dollars per year.[35]

Region-wide summer temperature increases and, in certain basins, increased river flooding and winter flows and decreased summer flows, will threaten many freshwater species, particularly salmon, steelhead, and trout.[27] Rising temperatures will increase disease and/or mortality in several iconic salmon species, especially for spring/summer Chinook and sockeye in the interior Columbia and Snake River basins.[36] Some Northwest streams[30] and lakes have already warmed over the past three decades, contributing to changes such as earlier Columbia River sockeye salmon migration[37] and earlier blooms of algae in Lake Washington.[38] Relative to the rest of the United States, Northwest streams dominated by snowmelt runoff appear to be less sensitive, in the short term, to warming due to the temperature buffering provided by snowmelt and groundwater contributions to those streams.[39] However, as snowpack declines, the future sensitivity to warming is likely to increase in these areas.[40] By the 2080s, suitable habitat for the four trout species of the interior western U.S. is projected to decline 47% on average, compared to the period 1978-1997.[41] As species respond to climate change in diverse ways, there is potential for ecological mismatches to occur – such as in the timing of the emergence of predators and their prey.[38]

Adaptive Capacity and Implications for Vulnerability

The ability to adapt to climate changes is strengthened by extensive water resources infrastructure, diversity of institutional arrangements,[42] and management agencies that are responsive to scientific input. However, over-allocation of existing water supply, conflicting objectives, limited management flexibility caused by rigid water allocation and operating rules, and other institutional barriers to changing operations continue to limit progress towards adaptation in many parts of the Columbia River basin.[43,44] Vulnerability to projected changes in snowmelt timing is probably highest in basins with the largest hydrologic response to warming and lowest management flexibility – that is, fully allocated, mid-elevation, temperature-sensitive, mixed rain-snow watersheds with existing conflicts among users of summer water. Regional power planners have expressed concerns over the existing hydroelectric system's potential inability to provide adequate summer electricity given the combination of climate change, demand growth, and operating constraints.[1] Vulnerability is probably lowest where hydrologic change is likely to be smallest (in rain-dominant basins) and where institutional arrangements are simple and current natural and human demands rarely exceed current water availability.[43,45,46]

The adaptive capacity of freshwater ecosystems also varies and, in managed basins, will depend on the degree to which the need to maintain streamflows and water quality for fish and wildlife is balanced with human uses of water resources. In highly managed rivers, release of deeper, colder water from reservoirs could offer one of the few direct strategies to lower water temperatures downstream.[47] Actions to improve stream habitat, including planting trees for shade, are being tested. Some species may be able to change behavior or take advantage of cold-water refuges.[48]

Key Message 2: Coastal Vulnerabilities

In the coastal zone, the effects of sea level rise, erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.

With diverse landforms (such as beaches, rocky shorelines, bluffs, and estuaries), coastal and marine ecosystems, and human uses (such as rural communities, dense urban areas, international ports, and transportation), the Northwest coast will experience a wide range of climate impacts.

Description of Observed and Projected Changes

Global sea levels have risen about 8 inches since 1880 and are projected to rise another 1 to 4 feet by 2100 (Ch. 2: Our Changing Climate, Key Message 10). Many local and regional factors can modify the global trend, including vertical land movement, oceanic winds and circulation, sediment compaction, subterranean fluid withdrawal (such as groundwater and natural gas), and other geophysical factors such as the gravitational effects of major ice sheets and glaciers on regional ocean levels.

Much of the Northwest coastline is rising due to a geophysical force known as "tectonic uplift," which raises the land surface. Because of this, apparent sea level rise is less than the currently observed global average. However, a major earthquake along the Cascadia subduction zone, expected within the next few hundred years, would immediately reverse centuries of uplift and, based on historical evidence, increase relative sea level 40 inches or more.[49,50] On the other hand, some Puget Sound locations are currently experiencing subsidence (where land is sinking or settling) and could see the reverse effect, witnessing immediate uplift during a major earthquake and lowered relative sea levels.[51,52]

Taking into account many of these factors and considering a wider range of emissions scenarios than are used in this assessment (Appendix 5: Scenarios and Models), a recent

Projected Relative Sea Level Rise for the Latitude of Newport, Oregon

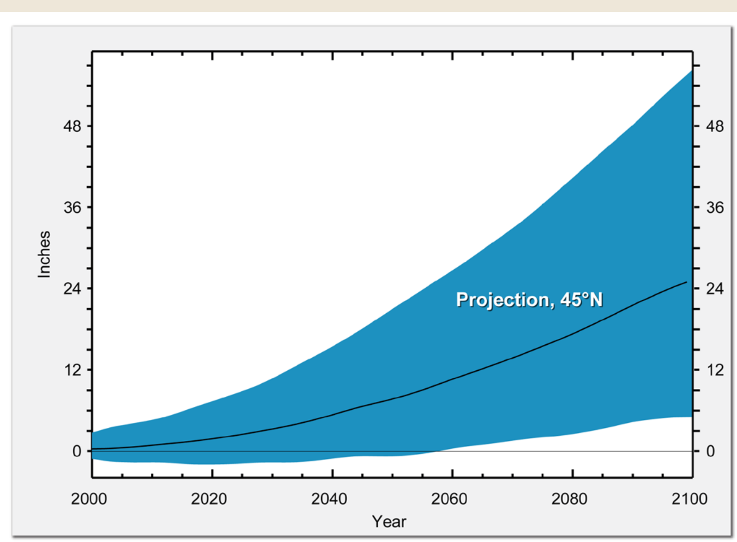

Figure 21.3. Projected relative sea level rise for the latitude of Newport, Oregon (relative to the year 2000) is based on a broader suite of emissions scenarios (ranging from B1 to A1FI) and a more detailed and regionally-focused calculation than those generally used in this assessment (see Ch. 2: Our Changing Climate).[50] The blue area shows the range of relative sea level rise, and the black line shows the projection, which incorporates global and regional effects of warming oceans, melting land ice, and vertical land movements.[50] Given the difficulty of assigning likelihood to any one possible trajectory of sea level rise at this time, a reasonable risk assessment would consider multiple scenarios within the full range of possible outcomes shown, in conjunction with long- and short-term compounding effects, such as El Niño-related variability and storm surge. (Data from NRC 2012[50]).

evaluation calculated projected sea level rise and ranges for the years 2030, 2050, and 2100 (relative to 2000) based on latitude for Washington, Oregon, and California (see Figure 21.3).[50] In addition to long-term climate-driven changes in sea level projected for the Northwest, shorter-term El Niño conditions can increase regional sea level by about 4 to 12 inches for periods of many months.[50,53]

Northwest coastal waters, some of the most productive on the West Coast,[54] have highly variable physical and ecological conditions as a result of seasonal and year-to-year changes in upwelling of deeper marine water that make longer-term changes difficult to detect. Coastal sea surface temperatures have increased[55] and summertime fog has declined between 1900 and the early 2000s, both of which could be consequences of weaker upwelling winds.[56] Projected changes include increasing but highly variable acidity,[57,58,59] increasing surface water temperature (2.2°F from the period 1970 to 1999 to the period 2030 to 2059),[60] and possibly changing storminess.[61] Climate models show inconsistent projections for the future of Northwest coastal upwelling.[12,62]

Consequences and Likelihoods of Changes

In Washington and Oregon, more than 140,000 acres of coastal lands lie within 3.3 feet in elevation of high tide.[63] As sea levels continue to rise, these areas will be inundated more frequently. Many coastal wetlands, tidal flats, and beaches will probably decline in quality and extent as a result of sea level rise, particularly where habitats cannot shift inland because of topographical limitations or physical barriers resulting from human development. Species such as shorebirds and forage fish (small fish eaten by larger fish, birds, or mammals) would be harmed, and coastal infrastructure and communities would be at greater risk from coastal storms.[64]

Ocean acidification threatens culturally and commercially significant marine species directly affected by changes in ocean chemistry (such as oysters) and those affected by changes in the marine food web (such as Pacific salmon[65]). Northwest coastal waters are among the most acidified worldwide, especially in spring and summer with coastal upwelling[58,59,66] combined with local factors in estuaries.[57,58]

Increasing coastal water temperatures and changing ecological conditions may alter the ranges, types, and abundances of marine species.[67,68] Recent warm periods in the coastal ocean, for example, saw the arrival of subtropical and offshore marine species from zooplankton to top predators such as striped marlin, tuna, and yellowtail more common to the Baja area.[69] Warmer water in regional estuaries (such as Puget Sound) may contribute to a higher incidence of harmful blooms of algae linked to paralytic shellfish poisoning,[70] and may result in adverse economic impacts from beach closures affecting recreational harvesting of shellfish such as razor clams.[71] Toxicity of some harmful algae appears to be increased by acidification.[72]

Rising Sea Levels
and Changing Flood Risks in Seattle

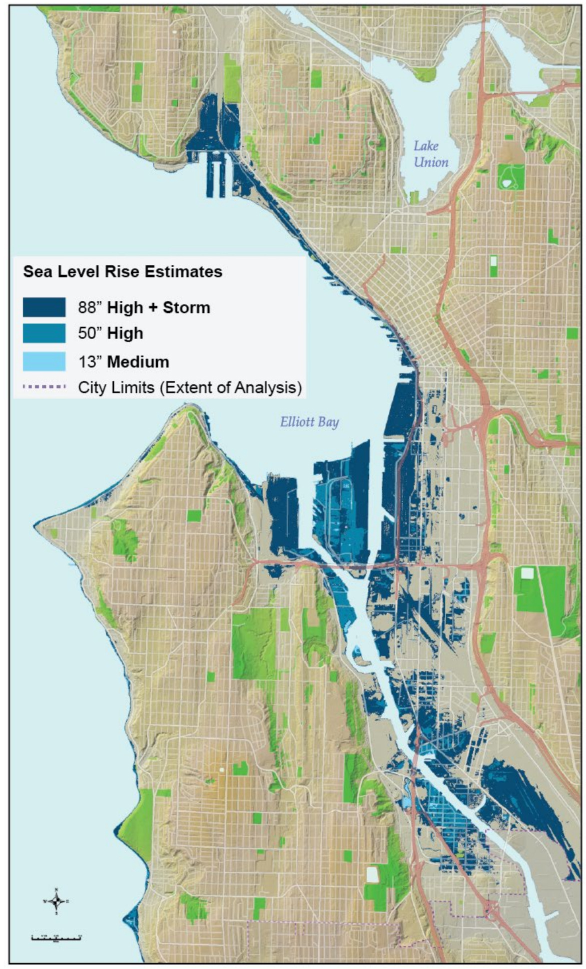

Figure 21.4. Areas of Seattle projected by Seattle Public Utilities to be below sea level during high tide (Mean Higher High Water) and therefore at risk of flooding or inundation are shaded in blue under three levels of sea level rise,[78] assuming no adaptation. (High [50 inches] and medium [13 inches] levels are within the range projected for the Northwest by 2100; the highest level [88 inches] includes the compounding effect of storm surge, derived from the highest observed historical tide in Seattle[79]). Unconnected inland areas shown to be below sea level may not be inundated, but could experience problems due to areas of standing water caused by a rise in the water table and drainage pipes backed up with seawater. (Figure source: Seattle Public Utilities[80]).

Many human uses of the coast – for living, working, and recreating – will also be negatively affected by the physical and ecological consequences of climate change. Erosion, inundation, and flooding will threaten public and private property along the coast; infrastructure, including wastewater treatment plants;[7,73] stormwater outfalls;[74,75] ferry terminals;[76] and coastal road and rail transportation, especially in Puget Sound.[77] Municipalities from Seattle[74] and Olympia,[75] Washington, to Neskowin, Oregon, have mapped risks from the combined effects of sea level rise and other factors.

Adaptive Capacity and Implications for Vulnerability

Human activities have increased the vulnerability of many coastal ecosystems, by degrading and eliminating habitat[81] and by building structures that, along with natural bluffs, thwart inland movement of many remaining habitats. In Puget Sound, for example, seawalls, bulkheads, and other structures have modified an estimated one-third of the shoreline,[82] though some restoration has occurred. Human responses to erosion and sea level rise, especially shoreline armoring, will largely determine the viability of many shallow-water and estuarine ecosystems.[68,82,83] In communities with few alternatives to existing coastal transportation networks, such as on parts of Highway 101 in Oregon, sea level rise and storm surges will pose an increasing threat to local commerce and livelihoods. Finally, there are few proven options for ameliorating projected ocean acidification.[84]

Adapting the Nisqually River Delta to Sea Level Rise

Figure 21.5. In Washington's Nisqually River Delta, estuary restoration on a large scale to assist salmon and wildlife recovery provides an example of adaptation to climate change and sea level rise. After a century of isolation behind dikes (left), much of the Nisqually National Wildlife Refuge was reconnected with tidal flow in 2009 by removal of a major dike and restoration of 762 acres (right), with the assistance of Ducks Unlimited and the Nisqually Indian Tribe. This reconnected more than 21 miles of historical tidal channels and floodplains with Puget Sound.[85] A new exterior dike was constructed to protect freshwater wetland habitat for migratory birds from tidal inundation and future sea level rise. Combined with expansion of the authorized Refuge boundary, ongoing acquisition efforts to expand the Refuge will enhance the ability to provide diverse estuary and freshwater habitats despite rising sea level, increasing river floods, and loss of estuarine habitat elsewhere in Puget Sound. This project is considered a major step in increasing estuary habitat and recovering the greater Puget Sound estuary. (Photo credits: (left) Jesse Barham, U.S. Fish and Wildlife Service; (right) Jean Takekawa, U.S. Fish and Wildlife Service).

Key Message 3: Impacts on Forests

The combined impacts of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Under higher emissions scenarios, extensive conversion of subalpine forests to other forest types is projected by the 2080s.

Evergreen coniferous forests are a prominent feature of Northwest landscapes, particularly in mountainous areas. Forests support diverse fish and wildlife species, promote clean air and water, stabilize soils, and store carbon. They support local economies and traditional tribal uses and provide recreational opportunities.

Description of Observed and Projected Changes

Climate change will alter Northwest forests by increasing wildfire risk and insect and tree disease outbreaks, and by forcing longer-term shifts in forest types and species (see Ch 7: Forests). Many impacts will be driven by water deficits, which increase tree stress and mortality, tree vulnerability to insects, and fuel flammability. The cumulative effects of disturbance – and possibly interactions between insects and fires – will cause the greatest changes in Northwest forests.[86,87] A similar outlook is expected for the Southwest region (see Ch. 20: Southwest, Key Message 3).

Forest Mortality

Figure 21.6. Forest mortality due to fire and insect activity is already evident in the Northwest. Continued changes in climate in coming decades are expected to increase these effects. Trees killed by a fire (left side of watershed) and trees killed by mountain pine beetle and spruce beetle infestations (orange and gray patches, right side of watershed) in subalpine forest in the Pasayten Wilderness, Okanogan Wenatchee National Forest, Washington, illustrates how cumulative disturbances can affect forests. (Photo credit: Jeremy Littell, USGS).

Although wildfires are a natural part of most Northwest forest ecosystems, warmer and drier conditions have helped increase the number and extent of wildfires in western U.S. forests since the 1970s.[14,87,88,89] This trend is expected to continue under future climate conditions. By the 2080s, the median annual area burned in the Northwest would quadruple relative to the 1916 to 2007 period to 2 million acres (range of 0.2 to 9.8 million acres) under the A1B scenario. Averaged over the region, this would increase the probability that 2.2 million acres would burn in a year from 5% to nearly 50%.[14] Within the region, this probability will vary substantially with sensitivity of fuels to climatic conditions and local variability in fuel type and amount, which are in turn a product of forest type, effectiveness of fire suppression, and land use. For example, in the Western Cascades, the year-to-year variability in area burned is difficult to attribute to climate conditions, while fire in the eastern Cascades and other specific vegetation zones is responsive to climate.[14] How individual fires behave in the future and what impacts they have will depend on factors we cannot yet project, such as extreme daily weather and forest fuel conditions.

Higher temperatures and drought stress are contributing to outbreaks of mountain pine beetles that are increasing pine mortality in drier Northwest forests.[90,91] This trend is projected to continue with ongoing warming.[14,92,93,94] Between now and the end of this century, the elevation of suitable beetle habitat is projected to increase as temperature increases, exposing higher-elevation forests to the pine beetle, but ultimately limiting available area as temperatures exceed the beetles' optimal temperatures.[14,92,93] As a result, the proportion of Northwest pine forests where mountain pine beetles are most likely to survive is projected to first increase (27% higher in 2001 to 2030 compared to 1961 to 1990) and then decrease (about 49% to 58% lower by 2071 to 2100).[92] For many tree species, the most climatically suited areas will shift from their current locations, increasing vulnerability to insects, disease, and fire in areas that become unsuitable. Eighty-five percent of the current range of three species that are host to pine beetles is projected to be climatically unsuitable for one or more of those species by the 2060s,[14,95] while 21 to 38 currently existing plant species may no longer find climatically appropriate habitat in the Northwest by late this century.[96]

Consequences and Likelihoods of Changes

The likelihood of increased disturbance (fire, insects, diseases, and other sources of mortality) and altered forest distribution are very high in areas dominated by natural vegetation, and the resultant changes in habitat would affect native species and ecosystems. Subalpine forests and alpine ecosystems are especially at risk and may undergo almost complete conversion to other vegetation types by the 2080s (A2 and B1;[104] A2;[105] Ensemble A2, B1, B2;[106]). While increased area burned can be statistically estimated from climate projections, changes in the risk of very large, high-intensity, stand-replacing fires cannot yet be predicted, but such events could have enormous impacts for forest-dependent species.[88] Increased wildfire could exacerbate respiratory and cardiovascular illnesses in nearby populations due to smoke and particulate pollution (Ch. 9: Human Health).[107,108]

These projected forest changes will have moderate economic impacts for the region as a whole, but could significantly affect local timber revenues and bioenergy markets.[109]

Insects and Fire in Northwest Forests

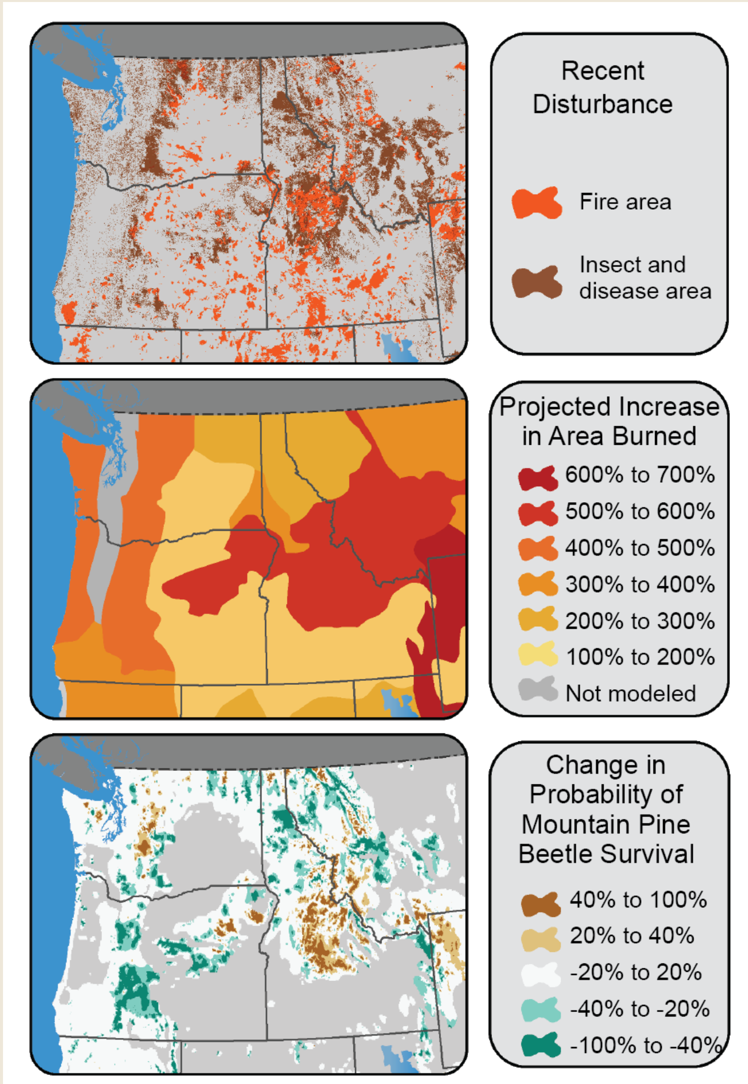

Figure 21.7.

(Top) Insects and fire have cumulatively affected large areas of the Northwest and are projected to be the dominant drivers of forest change in the near future. Map shows areas recently burned (1984 to 2008)[97,98] or affected by insects or disease (1997 to 2008).[99]

(Middle) Map indicates the increases in area burned that would result from the regional temperature and precipitation changes associated with a 2.2°F global warming[100] across areas that share broad climatic and vegetation characteristics.[101] Local impacts will vary greatly within these broad areas with sensitivity of fuels to climate.[14]

(Bottom) Projected changes in the probability of climatic suitability for mountain pine beetles for the period 2001 to 2030 (relative to 1961 to 1990), where brown indicates areas where pine beetles are projected to increase in the future and green indicates areas where pine beetles are expected to decrease in the future. Changes in probability of survival are based on climate-dependent factors important in beetle population success, including cold tolerance,[102] spring precipitation,[103] and seasonal heat accumulation.[91,92]

Adaptive Capacity and Implications for Vulnerability

Ability to prepare for these changes varies with land ownership and management priorities. Adaptation actions that decrease forest vulnerability exist, but none is appropriate across all of the Northwest's diverse climate threats, land-use histories, and management objectives.[86,110] Surface and canopy thinning can reduce the occurrence and effects of high severity fire in currently low severity fire systems, like drier eastern Cascades forests,[111] but may be ineffective in historically high-severity-fire forests, like the western Cascades, Olympics, and some subalpine forests. It is possible to use thinning to reduce tree mortality from insect outbreaks,[86,112] but not on the scale of the current outbreaks in much of the West.

Key Message 4: Adapting Agriculture

While the agriculture sector's technical ability to adapt to changing conditions can offset some adverse impacts of a changing climate, there remain critical concerns for agriculture with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.

Agriculture provides the economic and cultural foundation for Northwest rural populations and contributes substantively to the overall economy. Agricultural commodities and food production systems contributed 3% and 11% of the region's gross domestic product, respectively, in 2009.[113] Although the overall consequences of climate change will probably be lower in the Northwest than in certain other regions, sustainability of some Northwest agricultural sectors is threatened by soil erosion[114] and water supply uncertainty, both of which could be exacerbated by climate change.

Description of Observed and Projected Changes

Northwest agriculture's sensitivity to climate change stems from its dependence on irrigation water, a specific range of temperatures, precipitation, and growing seasons, and the sensitivity of crops to temperature extremes. Projected warming will reduce the availability of irrigation water in snowmelt-fed basins and increase the probability of heat stress to field crops and tree fruit. Some crops will benefit from a longer growing season[115] and/or higher atmospheric carbon dioxide, at least for a few decades.[115,116] Longer-term consequences are less certain. Changes in plant diseases, pests, and weeds present additional potential risks. Higher average temperatures generally can exacerbate pest pressure through expanded geographic ranges, earlier emergence or arrival, and increased numbers of pest generations (for example, Ch. 6: Agriculture).[117] Specifics differ among pathogen and pest species and depend upon multiple interactions (Ch. 6: Agriculture)[118] preventing region-wide generalizations. Research is needed to project changes in vulnerabilities to pest, disease, and weed complexes for specific cropping systems in the Northwest.

Consequences of Changes

Because much of the Northwest has low annual precipitation, many crops require irrigation. Reduction in summer flows in snow-fed rivers (see Figure 21.2), coupled with warming that could increase agricultural and other demands, potentially produces irrigation water shortages.[108] The risk of a water-short year – when Yakima basin junior water rights holders are allowed only 75% of their water right amount – is projected to increase from 14% in the late 20th century to 32% by 2020 and 77% by 2080, assuming no adaptation and under the A1B scenario.[46]

Assuming adequate nutrients and excluding effects of pests, weeds, and diseases, projected increases in average temperature and hot weather episodes and decreases in summer soil moisture would reduce yields of spring and winter wheat in rain-fed production zones of Washington State by the end of this century by as much as 25% relative to 1975 to 2005. However, carbon dioxide fertilization should offset these effects, producing net yield increases as great as 33% by 2080.[115] Similarly, for irrigated potatoes in Washington State, carbon dioxide fertilization is projected to mostly offset direct climate change related yield losses, although yields are still projected to decline by 2% to 3% under the A1B emissions scenario.[115] Higher temperatures could also reduce potato tuber quality.[119]

Irrigated apple production is projected to increase in Washington State by 6% in the 2020s, 9% in the 2040s, and 16% in the 2080s (relative to 1975 to 2005) when offsetting effects of carbon dioxide fertilization are included.[115] However, because tree fruit requires chilling to ensure uniform flowering and fruit set and wine grape varieties have specific chilling requirements for maturation,[120] warming could adversely affect currently grown varieties of these commodities. Most published projections of climate change impacts on Northwest agriculture are limited to Washington State and have focused on major commodities, although more than 300 crops are grown in the region. More studies are needed to identify the implications of climate change for additional cropping systems and locations within the region. The economic consequences for Northwest agriculture will be influenced by input and output prices driven by global economic conditions as well as by regional and local changes in productivity.

Adaptive Capacity and Implications for Vulnerability

Of the four areas of concern discussed here, agriculture is perhaps best positioned to adapt to climate trends without explicit planning and policy, because it already responds to annual climate variations and exploits a wide range of existing climates across the landscape.[121] Some projected changes in climate, including warmer winters, longer annual frost-free periods, and relatively unchanged or increased winter precipitation, could be beneficial to some agriculture systems. Nonetheless, rapid climate change could present difficulties. Adaptation could occur slowly if substantial investments or significant changes in farm operations and equipment are required. Shifts to new varieties of wine grapes and tree fruit, if indicated, and even if ultimately more profitable, are necessarily slow and expensive. Breeding for drought- and heat-resistance requires long-term effort. Irrigation water shortages that necessitate shifts away from more profitable commodities could exact economic penalties.[108]

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages
The authors and several dozen collaborators undertook a risk evaluation of the impacts of climate change in the Northwest that informed the development of the four key messages in this chapter (see also Ch. 26: Decision Support). This process considered the combination of impact likelihood and the consequences for the region's economy, infrastructure, natural systems, human health, and the economically-important and climate sensitive regional agriculture sector (see Dalton et al. 2013[6] for details). The qualitative comparative risk assessment underlying the key messages in the Northwest chapter was informed by the Northwest Regional Climate Risk Framing workshop (December 2, 2011, in Portland, OR). The workshop brought together stakeholders and scientists from a cross-section of sectors and jurisdictions within the region to discuss and rank the likelihood and consequences for key climate risks facing the Northwest region and previously identified in the Oregon Climate Change Adaptation Framework.[122] The approach consisted of an initial qualitative likelihood assessment based on expert judgment and consequence ratings based on the conclusions of a group of experts and assessed for four categories: human health, economy, infrastructure, and natural systems.[123]

This initial risk exercise was continued by the lead author team of the Northwest chapter, resulting in several white papers that were 1) condensed and synthesized into the Northwest chapter, and 2) expanded into a book-length report on Northwest impacts.[6] The NCA Northwest chapter author team engaged in multiple technical discussions via regular teleconferences and two all-day meetings. These included careful review of the foundational technical input report[123] and approximately 80 additional technical inputs provided to the NCA by the public, as well additional published literature. They also drew heavily from two state climate assessment reports.[124]

The author team identified potential regional impacts by 1) working forward from drivers of regional climate impacts (for example, changes in temperature, precipitation, sea level, ocean chemistry, and storms), and 2) working backward from affected regional sectors (for example, agriculture, natural systems, and energy). The team identified and ranked the relative consequences of each impact for the region's economy, infrastructure, natural systems, and the health of Northwest residents. The likelihood of each impact was also qualitatively ranked, allowing identification of the impacts posing the highest risk, that is, likelihood × consequence, to the region as a whole. The key regionally consequential risks thus identified are those deriving from projected changes in streamflow timing (in particular, warming-related impacts in watersheds where snowmelt is an important contributor to flow); coastal consequences of the combined impact of sea level rise and other climate-related drivers; and changes in Northwest forest ecosystems. The Northwest chapter therefore focuses on the implications of these risks for Northwest water resources, key aquatic species, coastal systems, and forest ecosystems, as well as climate impacts on the regionally important, climate-sensitive agricultural sector.

Each author produced a white paper synthesizing the findings in his/her sectoral area, and a number of key messages pertaining to climate impacts in that area. These syntheses were followed by expert deliberation of draft key messages by the authors wherein each key message was defended before the entire author team before this key message was selected for inclusion in the report. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities," including likelihood of climate change and relative magnitude of its consequences for the region as a whole, including consequences for the region's economy, human health, ecosystems, and infrastructure.[123]

Though the risks evaluated were aggregated over the whole region, it was recognized that impacts, risks, and appropriate adaptive responses vary significantly in local settings. For all sectors, the focus on risks of importance to the region's overall economy, ecology, built environment, and health is complemented, where space allows, by discussion of the local specificity of climate impacts, vulnerabilities and adaptive responses that results from the heterogeneity of Northwest physical conditions, ecosystems, human institutions and patterns of resource use.

Key message #1 Traceable Account

Changes in the timing of streamflow related to changing snowmelt are already observed and will continue, reducing the supply of water for many

competing demands and causing far-reaching ecological and socioeconomic consequences.

Description of evidence base

This message was selected because of the centrality of the water cycle to many important human and natural systems of the Northwest: hydropower production and the users of this relatively inexpensive electricity; agriculture and the communities and economies dependent thereon, and; coldwater fish, including several species of threatened and endangered salmon, the tribal and fishing communities and ecosystems that depend on them, and the adjustments in human activities and efforts necessary to restore and protect them. Impacts of water-cycle changes on these systems, and any societal adjustments to them, will have far-reaching ecological and socioeconomic consequences.

Evidence that winter snow accumulation will decline under projected climate change is based on 20th century observations and theoretical studies of the sensitivity of Northwest snowpack to changes in precipitation and temperature. There is good agreement on the physical role of climate in snowpack development, and projections of the sign of future trends are consistent (many studies). However, climate variability creates disagreement over the magnitude of current and near-term future trends.

Evidence that projected climate change would shift the timing and amount of streamflow deriving from snowmelt is based on 20th century observations of climate and streamflow and is also based on hydrologic model simulation of streamflow responses to climate variability and change. There is good agreement on the sign of trends (many studies), though the magnitude of current and near-term future trends is less certain because of climate variability.

Evidence that declining snowpack and changes in the timing of snowmelt-driven streamflow will reduce water supply for many competing and time-sensitive demands is based on:

- hydrologic simulations, driven by future climate projections, that consistently show reductions in spring and summer flows in mixed rain-snow and some snow-dominant watersheds;
- documented competition among existing water uses (irrigation, power, municipal, and in-stream flows) and inability for all water systems to meet all summer water needs all of the time, especially during drier years;
- empirical and theoretical studies that indicate increased water demand for many uses under climate change; and
- policy and institutional analyses of the complex legal and institutional arrangements governing Northwest water management and the challenges associated with adjusting water management in response to changing conditions.

Evidence for far-reaching ecological and socioeconomic consequences of the above is based on:

- model simulations showing negative impacts of projected climate and altered streamflow on many water resource uses at scales ranging from individual basins (for example, Skagit, Yakima) to the region (for example, Columbia River basin);
- model simulations of future agricultural water allocation in the Yakima[46] and the Snake River Basin,[32] showing increased likelihood of water curtailments for junior water rights holders;
- model and empirical studies documenting sensitivity of coldwater fish to water temperatures, sensitivity of water temperature to air temperature, and projected warming of summer stream temperatures;
- regional and extra-regional dependence on Northwest-produced hydropower; and
- legal requirements to manage water resources for threatened & endangered fish as well as for human uses.

Evidence that water users in managed mixed rain-snow basins are likely to be the most vulnerable to climate change and less vulnerable in rain-dominated basins is based on:

- observed, theoretical, and simulated sensitivity of watershed hydrologic response to warming by basin type;
- historical observations and modeled simulations of tradeoffs required among water management objectives under specific climatic conditions;
- analyses from water management agencies of potential system impacts and adaptive responses to projected future climate; and
- institutional and policy analyses documenting sources and types of management rigidity (for example, difficulty adjusting management practices to account for changing conditions).

New information and remaining uncertainties

A key uncertainty is the degree to which current and future interannual and interdecadal variations in climate will enhance or obscure long-term anthropogenic climate trends.

Uncertainty over local groundwater or glacial inputs and other local effects may cause overestimates of increased stream temperature based solely on air temperature. However, including projected decreases in summer streamflow would increase estimates of summer stream temperature increases above those based solely on air temperature.

Uncertainty in how much increasing temperatures will affect crop evapotranspiration affects future estimates of irrigation demand.

Uncertainty in future population growth and changing per capita water use affects estimates of future municipal demand and therefore assessments of future reliability of water resource systems.

A major uncertainty is the degree to which water resources management operations of regulated systems can be adjusted to account for climate-driven changes in the amount and timing of streamflow, and how competing resource objectives will be accommodated or prioritized. Based on current institutional inertia, significant changes are unlikely to occur for several decades.

There is uncertainty in economic assessment of the impacts of hydrologic changes on the Northwest because much of the needed modeling and analysis is incomplete. Economic impacts assessment would require quantifying both potential behavioral responses to future climate-affected economic variables (prices of inputs and products) and to climate change itself. Some studies have sidestepped the issue of behavioral response to these and projected economic impacts based on future scenarios that do not consider adaptation, which lead to high estimates of "costs" or impacts.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Confidence is **very high** based on strong strength of evidence and **high** level of agreement among experts.

See specifics under "description of evidence" above.

Key message #2 Traceable Account

In the coastal zone, the effects of sea level rise, erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.

Description of evidence base

Given the extent of the coastline, the importance of coastal systems to the region's ecology, economy, and identity, and the difficulty of adapting in response, the consequences of sea level rise, ocean acidification, and other climate driven changes in ocean conditions and coastal weather are expected to be significant and largely negative, which is why this message was included.

Evidence for observed global (eustatic) sea level rise and regional sea level change derives from satellite altimetry and coastal tide gauges. Evidence for projected global sea level rise is described in Ch. 2: Our Changing Climate, in the recent NRC report[50] that includes a detailed discussion of the U.S. West Coast, and Parris et al. 2012.[125]

Evidence of erosion associated with coastal storms is based on observations of storm damage in some areas of the Northwest.

Evidence for erosion and inundation associated with projected sea level rise is based on observations and mapping of coastal elevations and geospatial analyses of the extent and location of inundation associated with various sea level rise and storm surge scenarios.

Evidence for climate change impacts on coastal infrastructure derives from geospatial analyses (mapping infrastructure locations likely to be affected by various sea level rise scenarios, storm surge scenarios and/or river flooding scenario), such as those undertaken by various local governments to assess local risks of flooding for the downtown area (Olympia), of sea level rise and storm surge for marine shoreline inundation and risk to public utility infrastructure (Seattle – highest observed tide from NOAA tide gauge added to projected sea levels), and of sea level rise for wastewater treatment plants and associated infrastructure (King County). Vulnerability of coastal transportation infrastructure to climate change has been assessed by combining geospatial risk analyses with expert judgment of asset sensitivity to climate risk and criticality to the transportation system in Washington State and by assessing transportation infrastructure exposure to climate risks associated with sea level rise and river flooding in the region as a whole.

Evidence for impacts of climate change on coastal habitat is based on:

- model-based studies of projected impacts of sea level rise on tidal habitat showing significant changes in the composition and extent of coastal wetland habitats in Washington and Oregon;
- observations of extent and location of coastal armoring and other structures that would potentially impede inland movement of coastal wetlands;
- observed changes in coastal ocean conditions (upwelling, nutrients, and sea surface temperatures); biogeographical, physiological, and paleoecological studies indicating a historical decline in coastal upwelling; and global climate model projections of future increases in sea surface temperatures;
- modeled projections for increased risk of harmful algal blooms (HABs) in Puget Sound associated with higher air and water temperatures, reduced streamflow, low winds, and small tidal variability (i.e., these conditions offer a favorable window of opportunity for HABs); and
- observed changes in the geographic ranges, migration timing, and productivity of marine species due to changes in sea surface temperatures associated with cyclical events, such as the interannual El Niño Southern Oscillation and the inter-decadal Pacific Decadal Oscillation and North Pacific Gyre Oscillation.

Evidence for historical increases in ocean acidification is from observations of changes in coastal ocean conditions, which also indicate high spatial and temporal variability. Evidence for acidification's effects on various species and the broader marine food web is still emerging but is based on observed changes in abundance, size, and mortality of marine calcifying organisms and laboratory based and in situ acidification experiments.

Evidence for marine species responses to climate change derives from observations of shifts in marine plankton, fish, and seabird species associated with historical changes in ocean conditions, including temperature and availability of preferred foods.

Evidence for low adaptive capacity is from observations of extent of degraded or fragmented coastal habitat, existence of few options for mitigating changes in marine chemical properties, observed extent of barriers to inland habitat migration, narrow coastal transportation corridors, and limited transportation alternatives for rural coastal towns. Evidence for low adaptive capacity is also based on the current limitations (both legal and political) of local and state governments to restrict and/or influence shoreline modifications on private lands.

New information and remaining uncertainties

There is significant but well-characterized uncertainty about the rate and extent of future sea level rise at both the global and regional/sub-regional scales. However, there is virtually no uncertainty in the direction (sign) of global sea level rise. There is also a solid understanding of the primary contributing factors and mechanisms causing sea level rise. Other details concerning uncertainty in global sea level rise are treated elsewhere (for example, NRC 2012[50]) and in Ch. 2: Our Changing Climate). Regional uncertainty in projected Northwest sea level rise results primarily from global factors such as ice sheet mass balance and local vertical land movement (affecting relative sea level rise). An accurate determination of vertical land deformation requires a sufficient density of monitoring sites (for example, NOAA tide gauges and permanent GPS sites that monitor deformation) to capture variations in land deformation over short spatial scales, and in many Northwest coastal locations such dense networks do not exist. There is a general trend, however, of observed uplift along the northwestern portion of the Olympic Peninsula and of subsidence within the Puget Sound region (GPS data gathered from PBO data sets -- http://pbo.unavco.org/data/gps; see also Chapman and Melbourne 2009[51]).

There is also considerable uncertainty about potential impacts of climate change on processes that influence storminess and affect coastal erosion in the Northwest. These uncertainties relate to system complexity and the limited number of studies and lack of consensus on future atmospheric and oceanic conditions that will drive changes in regional wind fields. Continued collection and assessment of meteorological data at ocean buoy locations and via remote sensing should improve our understanding of these processes.

Uncertainty in future patterns of sediment delivery to the coastal system limit projections of future inundation, erosion, and changes in tidal marsh. For example, substantial increases in riverine sediment delivery, due to climate-related changes in the amount and timing of streamflow, could offset erosion and/or inundation projected from changes in sea level alone. However, there are areas in the Northwest where it is clear that man-made structures have interrupted sediment supply and there is little uncertainty that shallow water habitat will be lost.

Although relatively well-bounded, uncertainty over the rate of projected relative sea level rise limits our ability to assess whether any particular coastal habitat will be able to keep pace with future changes through adaptation (for example, through accretion).

The specific implications of the combined factors of sea level rise, coastal climate change, and ocean acidification for coastal ecosystems and specific individual species remain uncertain due to the complexity of ecosystem response. However, there is general agreement throughout the peer-reviewed literature that negative impacts for a number of marine calcifying organisms are projected, particularly during juvenile life stages.

Projections of future coastal ocean conditions (for example, temperature, nutrients, pH, and productivity) are limited, in part, by uncertainty over future changes in upwelling – climate model scenarios show inconsistent projections for likely future upwelling conditions. Considerable uncertainty also remains in whether, and how, higher average ocean temperatures will influence geographical ranges, abundances, and diversity of marine species, although evidence of changes in pelagic fish species ranges and in production associated with Pacific Ocean temperature variability during cyclical events have been important indicators for potential species responses to climate change in the future. Consequences from ocean acidification for commercial fisheries and marine food web dynamics are potentially very high – while the trend of increasing acidification is very likely, the rate of change and spatial variability within coastal waters are largely unknown and are the subject of ongoing and numerous nascent research efforts.

Additional uncertainty surrounds non-climate contributors to coastal ocean chemistry (for example, riverine inputs, anthropogenic carbon, and nitrogen point and non-point source inputs) and society's ability to mitigate these inputs.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

There is **very high** confidence in the global upward trend of sea level rise (SLR) and ocean acidification (OA). There is **high** confidence that SLR over the next century will remain under an upper bound of approximately 2 meters. Projections for SLR and OA at specific locations are much less certain (**medium to low**) because of the high spatial variability and multiple factors influencing both phenomena at regional and sub-regional scales.

There is **medium** confidence in the projections of species response to sea level rise and increased temperatures, but **low** confidence in species response to ocean acidification. Uncertainty in upwelling changes result in **low** confidence for projections of future change that depend on specific coastal ocean temperatures, nutrient contents, dissolved oxygen content, stratification, and other factors.

There is **high** confidence that significant changes in the type and distribution of coastal marsh habitat are likely, but **low** confidence in our current ability to project the specific location and timing of changes.

There is **high** confidence in the projections of increased erosion and inundation.

There is **very high** confidence that ocean acidity will continue to increase.

Key message #3 Traceable Account

The combined impact of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Under higher emissions scenarios, extensive conversion of subalpine forests to other forest types is projected by the 2080s.

Description of evidence base

Evidence that the area burned by fire has been high, relative to earlier in the century, since at least the 1980s is strong. Peer-reviewed papers based on federal fire databases (for example, National Interagency Fire Management Integrated Database [NIFMID], 1970/1980-2011) and independent satellite data (Monitoring Trends in Burn Severity [MTBS], 1984-2011) indicate increases in area burned.[98,126]

Evidence that the interannual variation in area burned was at least partially controlled by climate during the period 1980-2010 is also strong. Statistical analysis has shown that increased temperature (related to increased potential evapotranspiration, relative humidity, and longer fire seasons) and decreased precipitation (related to decreased actual evapotranspiration, decreased spring snowpack, and longer fire seasons) are moderate to strong (depending on forest type) correlates to the area and number of fires in the Pacific Northwest. Projections of area burned with climate change are documented in peer-reviewed literature, and different approaches (statistical modeling and dynamic global vegetation modeling) agree on the order of magnitude of those changes for Pacific Northwest forests, though the degree of increase depends on the climate change scenario and modeling approach.

Evidence from aerial disease and detection surveys jointly coordinated by the U.S. Forest Service and state level governments supports the statement that the area of forest mortality caused by insect outbreaks (including the mountain pine beetle) and by tree diseases is increasing.

Evidence that mountain pine beetle and spruce bark beetle outbreaks are climatically controlled is from a combination of laboratory experiments and mathematical modeling reported in peer-reviewed literature. Peer-reviewed future projections of climate have been used to develop projections of mountain pine beetle and spruce beetle habitat suitability based on these models, and show increases in the area of climatically suitable habitat (particularly at mid- to high elevations) by the mid-21st century, but subsequent (late 21st century) declines in suitable habitat, particularly at low- to mid-elevation. There is considerable spatial variability in the patterns of climatically suitable habitat.

Evidence for long-term changes in the distribution of vegetation types and tree species comes from statistical species models, dynamic vegetation models, and other approaches and uses the correlation between observed climate and observed vegetation distributions to model future climatic suitability. These models agree broadly in their conclusions that future climates will be unsuitable for historically present species over significant areas of their ranges and that broader vegetation types will likely change, but the details depend greatly on climate change scenario, location within the region, and forest type.

Evidence that subalpine forests are likely to undergo almost complete conversion to other vegetation types is moderately strong (relatively few studies, but good agreement) and comes from dynamic global vegetation models that include climate, statistical models that relate climate and biome distribution, and individual statistical species distribution models based on climatic variables. The fact that these three different approaches generally agree about the large decrease in area of subalpine forests despite different assumptions, degrees of "mechanistic" simulation, and levels of ecological hierarchy justifies the key message.

New information and remaining uncertainties

The key uncertainties are primarily the timing and magnitude of future projected changes in forests, rather than the direction (sign) of changes.

The rate of expected change is affected by the rate of climate change – higher emissions scenarios have higher impacts earlier in studies that consider multiple scenarios. Most impacts analyses reported in the literature and synthesized here use emissions scenario A1B or A2. Projections of changes in the proportion of Northwest pine forests where mountain pine beetles are likeliest to survive and of potential conversion of subalpine forests used scenario A2.

Statistical fire models do not include changes in vegetation that occur in the 21st century due to disturbance (such as fire, insects, and tree diseases) and other factors such as land-use change and fire suppression changes. As conditions depart from the period used for model training, projections of future fire become more uncertain, and by the latter 21st century (beyond about the 2060s to 2080s), statistical models may over-predict area burned. Despite this uncertainty, the projections from statistical models are broadly similar to those from dynamic global vegetation models (DGVMs), which explicitly simulate changes in future vegetation. A key difference is for forest ecosystems where fire has been rare since the mid 20th century, such as the Olympic Mountains and Oregon coast range, and statistical models are comparatively weak. In these systems, statistical fire models likely underestimate the future area burned, whereas DGVMs may capably simulate future events that are outside the range of the statistical model's capability. In any case, an increase in forest area burned is nearly ubiquitous in these studies regardless of method, but the amount of increase and the degree to which it varies with forest type is less certain. However, fire risk in any particular location or at any particular time is beyond the capability of current model projections. In addition, the statistical model approaches to future fire cannot address fundamental changes in fire behavior due to novel extreme weather patterns, so conclusions about changes in fire severity are not necessarily warranted.

Only a few insects have had sufficient study to understand their climatic linkages, and future insect outbreak damage from other insects, currently unstudied, could increase the estimate of future areas of forest mortality due to insects.

Fire-insect interactions and diseases are poorly studied – the actual effects on future landscapes could be greater if diseases and interactions were considered more explicitly.

For subalpine forests, what those forests become instead of subalpine forests is highly uncertain – different climate models used to drive the same dynamic global vegetation model agree about loss of subalpine forests, but disagree about what will replace them. In addition, statistical approaches that consider biome level and species level responses without the ecological process detail of DGVMs show similar losses, but do not agree on responses, which depend on climate scenarios. Because these statistical models simulate neither the regeneration of seedlings nor the role of disturbances, the future state of the system is merely correlative and based on the statistical relationship between climate and historical forest distribution.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

The observed effects of climate on fires and insects combined with the agreement of future projections across modeling efforts warrants **very high** confidence that increased disturbance will increase forest mortality due to area burned by fire, and increases in insect outbreaks also have **very high** confidence until at least the 2040s in the Northwest. The timing and nature of the rates and the sources of mortality may change, but current estimates may be conservative for insect outbreaks due to the unstudied impacts of other insects. But in any case, the rate of projected forest disturbance suggests that changes will be driven by disturbance more than by gradual changes in forest cover or species composition. After mid-21st century, uncertainty about the interactions between disturbances and landscape response limits confidence to **high** because total area disturbed could begin to decline as most of the landscape becomes outside the range of historical conditions. The fact that different modeling approaches using a wide variety of climate scenarios indicate similar losses of subalpine forests justifies **high** confidence; however, comparatively little research that simulates ecological processes of both disturbance and regeneration as a function of climate, so there is **low** confidence on what will replace them.

Key message #4 Traceable Account

While agriculture's technical ability to adapt to changing conditions can offset some of the adverse impacts of a changing climate, there remain critical concerns for agriculture with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.

Description of evidence base

Northwest agriculture's sensitivity to climate change stems from its dependence on irrigation water, adequate temperatures, precipitation and growing seasons, and the sensitivity of crops to temperature extremes. Projected warming trends based on global climate models and emissions scenarios potentially increase temperature-related stress on annual and perennial crops in the summer months.

Evidence for projected impacts of warming on crop yields consists primarily of published studies using crop models indicating increasing vulnerability with projected warming over 1975-2005 baselines. These models also project that thermal-stress-related losses in agricultural productivity will be offset or overcompensated by fertilization from accompanying increases in atmospheric CO_2. These models have been developed for key commodities including wheat, apples, and potatoes. Longer term, to end of century, models project crop losses from temperature stress to exceed the benefits of CO_2 fertilization.

Evidence for the effects of warming on suitability of parts of the region for specific wine grape and tree fruit varieties are based on well-established and published climatic requirements for these varieties.

Evidence for negative impacts of increased variability of precipitation on livestock productivity due to stress on range and pasture consists of a few economic studies in states near the region; relevance to Northwest needs to be established.

Evidence for negative impacts of warming on dairy production in the region is based on a published study examining projected summer heat-stress on milk production.

Evidence for reduction in available irrigation water is based on peer-reviewed publications and state and federal agency reports utilizing hydrological models and precipitation and snowpack projections. These are outlined in more detail in the traceable account for Key Message 1 of this chapter. Increased demands for irrigation water with warming are based on cropping systems models and projected increases in acres cultivated. These projections, coupled with those for water supply, indicate that some areas will experience increased water shortages. Water rights records allow predictions of the users most vulnerable to the effects of these shortages.

Projections for surface water flows include decreases in summer flow related to changes in snowpack dynamics and reductions in summer precipitation. Although these precipitation projections are less certain than those concerning temperatures, they indicate that water shortages for irrigation will be more frequent in some parts of the region, based especially on a Washington State Department of Ecology-sponsored report that considered the Columbia basin. Other evidence for these projected changes in water is itemized in Key Message 1 of this chapter.

Evidence that agriculture has a high potential for autonomous adaptation to climate change, assuming adequate water availability, is inferred primarily from the wide range of production practices currently being used across the varied climates of the region.

New information and remaining uncertainties

Although increasing temperatures can affect the distribution of certain pest, weed, and pathogen species, existing models are limited. Without more comprehensive studies, it is not possible to project changes in overall pressure from these organisms, so overall effects remain uncertain. Some species may be adversely affected by warming directly or through enhancement of their natural enemy base, while others become more serious threats.

Uncertainty exists in models in how increasing temperatures will impact crop evapotranspiration, which affects future estimates of irrigation demand (Key Message 1 of this chapter).

Shifting international market forces including commodity prices and input costs, adoption of new crops, which may have different heat tolerance or water requirements, and technological advances are difficult or impossible to project, but may have substantial effects on agriculture's capacity to adapt to climate change.

Estimates of changes in crop yields as a result of changing climate and CO_2 are based on very few model simulations, so the uncertainty has not been well quantified.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

Confidence is **very high** based on strong strength of evidence and high level of agreement among experts.

See specifics under "description of evidence" above.