

21. Northwest

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13 Key Messages

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

29 Introduction

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

34 Snow accumulates in mountains, melting in spring to power both the region’s rivers and
35 economy, creating enough hydropower (40% of national total)¹ to export 2 to 6 million megawatt
36 hours per month.² Snowmelt waters crops in the dry interior, helping the region produce tree fruit
37 (number one in the world) and almost \$17 billion worth of agricultural commodities, including
38 55% of potatoes, 15% of wheat, and 11% of milk production.³

1 Seasonal water patterns shape the life cycles of the region’s flora and fauna, including iconic
2 salmon and steelhead, and forested ecosystems, which cover 47% of the landscape (Smith et al.
3 2009). Along more than 4,400 miles of coastline, regional economic centers are juxtaposed with
4 diverse habitats and ecosystems that support thousands of species of fish and wildlife, including
5 commercial fish and shellfish resources valued at \$480 million in 2011.⁴

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

12 The Northwest’s economy, infrastructure, natural systems, public health, and vitally important
13 agriculture sector all face important climate change related risks. Those risks – and possible
14 adaptive responses – will vary significantly across the region.⁵ Impacts on infrastructure, natural
15 systems, human health and economic sectors, combined with issues of social and ecological
16 vulnerability, will play out quite differently in largely natural areas, like the Cascade Range or
17 Crater Lake National Park, than in urban areas like Seattle and Portland (Ch 11: Urban),⁶ or
18 among the region’s many Native American tribes like the Umatilla or the Quinault (Ch 12:
19 Indigenous Peoples).⁷ As climatic conditions diverge from those that determined patterns of
20 development and resource use in the 1900s, and as demographic, economic, and technological
21 changes also stress local systems, coping with climate change will benefit from an evolving,
22 iterative risk management approach.⁸

23 **Observed Climate Change**

24 Temperatures increased across the region from 1895 to 2011, with a regionally averaged
25 warming of about 1.3°F.⁹ While precipitation has generally increased, trends are small as
26 compared to natural variability. Both increasing and decreasing trends are observed among
27 various locations, seasons, and time periods of analysis (Ch 2: Our Changing Climate, Figure
28 2.12). Studies of observed changes in extreme precipitation use different time periods and
29 definitions of “extreme,” but none find statistically significant changes in the Northwest.¹⁰ These
30 and other climate trends include contributions from both human influences (chiefly heat-trapping
31 gas emissions) and natural climate variability, and consequently are not projected to be uniform
32 or smooth across the country or over time (Ch. 2: Our Changing Climate, Key Message 3). They
33 are also consistent with expected changes due to human activities (Ch. 2: Our Changing Climate,
34 Key Message 1).

35 **Projected Climate Change**

36 An increase in average annual temperature of 3.3°F to 9.7°F is projected by 2070 to 2099
37 (compared to the period 1970 to 1999), depending largely on total global emissions of heat-
38 trapping gases. The increases are projected to be largest in summer. This chapter examines a
39 range of scenarios, including ones where emissions increase and then decline, leading to lower
40 (B1 and RCP4.5) and medium (A1B) total emissions, and scenarios where emissions continue to
41 rise with higher totals (A2, A1FI, RCP8.5 scenarios). Change in annual average precipitation in
42 the Northwest, is projected to be within a range of an 11% decrease to a 12% increase for 2030

1 to 2059 and a 10% decrease to an 18% increase for 2070 to 2099¹¹ for the B1, A1B (an
2 emissions scenario that assumes eventual reductions from current trends), and A2 scenarios (Ch.
3 2: Our Changing Climate). For every season, some models project decreases and some project
4 increases (Ch. 2: Our Changing Climate; Key Message 5),^{9,11} yet one aspect of seasonal changes
5 in precipitation is largely consistent across climate models: for scenarios of continued growth in
6 global heat-trapping gas emissions, summer precipitation is projected to decrease by as much as
7 30% by the end of the century (Ch. 2: Our Changing Climate).^{9,11} Northwest summers are
8 already dry and although a 10% reduction (the average projected change for summer) is a small
9 amount of precipitation, unusually dry summers have many noticeable consequences, including
10 low streamflow west of the Cascades¹² and greater extent of wildfires throughout the region.¹³
11 Note that while projected temperature increases are large relative to natural variability, the
12 relatively small projected changes in precipitation are likely to be masked by natural variability
13 for much of the century.¹⁴

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

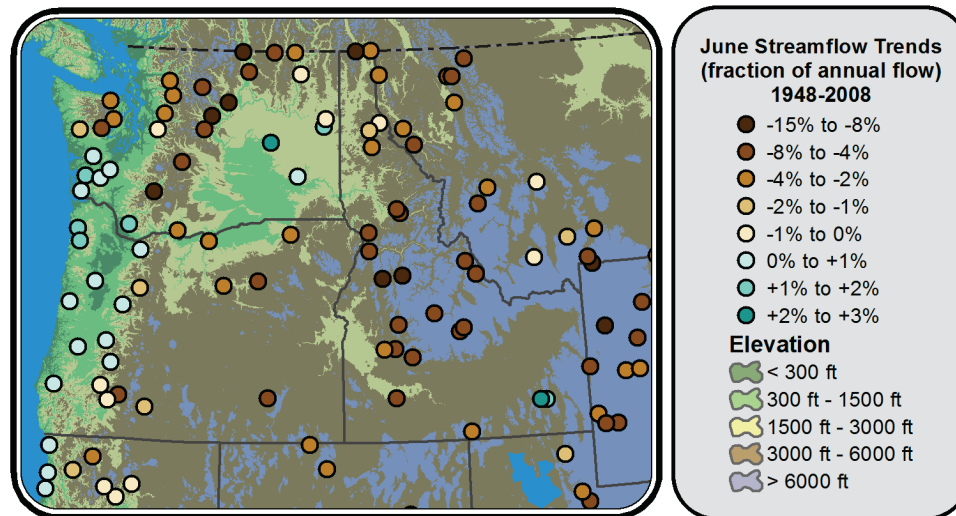
18 *Water-related Challenges*

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

22 **Description of observed and projected changes**

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

Observed Shifts in Streamflow Timing



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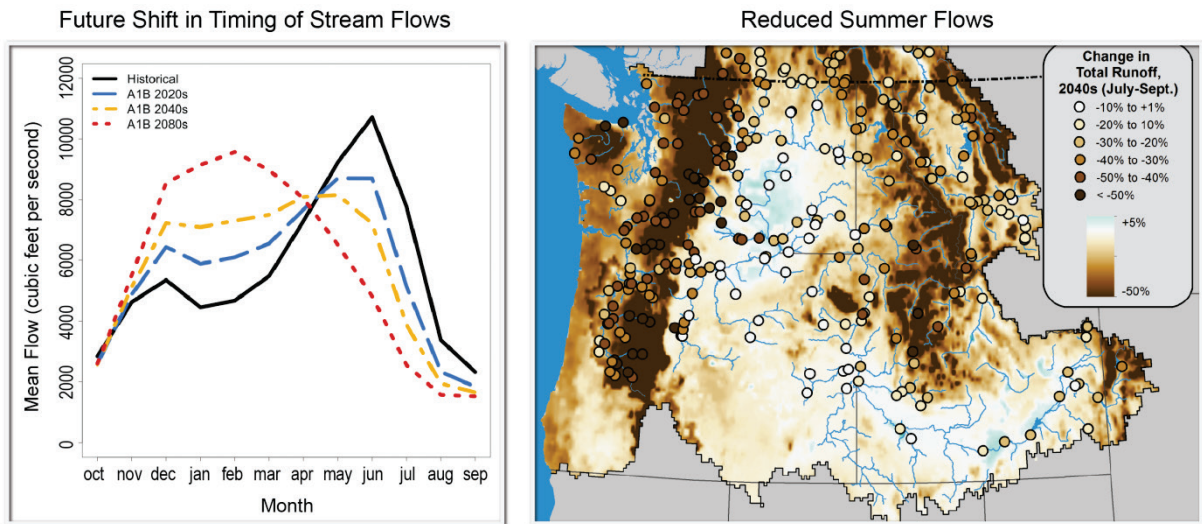
2 **Figure 21.1:** Observed Shifts in Streamflow Timing

3 **Caption:** Reduced June flows in many Northwest snow-fed rivers is a signature of
 4 warming in basins that have a significant snowmelt contribution. The fraction of annual
 5 flow occurring in June increased slightly in rain-dominated coastal basins and decreased
 6 in mixed rain-snow basins and snowmelt dominated basins over the period 1948 to
 7 2008.²⁰ The high flow period is in June for most Northwest river basins; decreases in
 8 summer flows can make it more difficult to meet a variety of competing human and
 9 natural demands for water. (Figure source: adapted from Fritze et al. 2011²⁰).

10 Hydrologic response to climate change will depend upon the dominant form of precipitation in a
 11 particular watershed, as well as other local characteristics including elevation, aspect, geology,
 12 vegetation, and changing land use.²¹ The largest responses are expected to occur in basins with
 13 significant snow accumulation, where warming increases winter flows and advances the timing
 14 of spring melt.^{17,22} By 2050, snowmelt is projected to shift three to four weeks earlier than the
 15 20th century average and summer flows are projected to be substantially lower even for an
 16 emissions scenario that assumes substantial emissions reductions (B1).²³ In some North Cascade
 17 rivers, a significant fraction (10% to 30%) of late summer flow originates as glacier melt;²⁴ the
 18 consequences of eventual glacial disappearance are not well quantified. Basins with a significant
 19 groundwater component may be less responsive to climate change than indicated here.²⁵

20 Changes in river-related flood risk depends on many factors, but warming is projected to
 21 increase flood risk the most in mixed basins (those with both winter rainfall and late spring
 22 snowmelt-related runoff peaks) and remain largely unchanged in snow-dominant basins.²⁶
 23 Regional climate models project increases of 0% to 20% in extreme daily precipitation,
 24 depending on location and definition of “extreme” (for example, annual wettest day). Averaged

1 over the region, the number of days with more than one inch of precipitation is projected to
 2 increase 13% in 2041 to 2070 compared with 1971 to 2000 under a scenario that assumes a
 3 continuation of current rising emissions trends (A2),⁹ though these projections are not consistent
 4 across models.²⁷ This increase in heavy downpours could increase flood risk in mixed rain-snow
 5 and rain-dominant basins, and could also increase stormwater management challenges in urban
 6 areas.



7
 8 **Figure 21.2 (left):** Future Shift in Timing of Stream Flows

9 **Figure 21.2 (right):** Reduced Summer Flows

10 **Caption:** (Left) Projected increased winter flows and decreased summer flows in many
 11 Northwest rivers will cause widespread impacts. Mixed rain-snow watersheds, such as
 12 the Yakima River basin, an important agricultural area in eastern Washington, will see
 13 increased winter flows, earlier spring peak flows, and decreased summer flows in a
 14 warming climate. Changes in average monthly streamflow by the 2020s, 2040s, and
 15 2080s (as compared to the period 1916 to 2006) indicate that the Yakima River basin
 16 could change from a snow-dominant to a rain-dominant basin by the 2080s under the
 17 A1B emissions scenario (with eventual reductions from current rising emissions trends).
 18 (Figure source: adapted from Elsner et al. 2010).²³

19 (Right) Natural surface water availability during the already dry late summer period is
 20 projected to decrease across most of the Northwest. The map shows projected changes in
 21 local runoff (shading) and streamflow (colored circles) for the 2040s (compared to the
 22 period 1915 to 2006) under the same scenario as the left figure (A1B).²⁸ Streamflow
 23 reductions such as these would stress freshwater fish species (for instance, endangered
 24 salmon and bull trout) and necessitate increasing trade-offs among conflicting uses of
 25 summer water. Watersheds with significant groundwater contributions to summer
 26 streamflow may be less responsive to climate change than indicated here.²⁵

1 Consequences and likelihoods of changes

2 Reservoir systems have multiple objectives, including irrigation, municipal and industrial use,
3 hydropower production, flood control, and preservation of habitat for aquatic species. Modeling
4 studies indicate, with near 100% likelihood and for all emissions scenarios, that reductions in
5 summer flow will occur by 2050 in basins with significant snowmelt (for example,²³). These
6 reduced flows will require more trade-offs among objectives of the whole system of reservoirs,²⁹
7 especially with the added challenges of summer increases in electric power demand for cooling³⁰
8 and additional water consumption by crops and forests.^{9,31} For example, reductions in
9 hydropower production of as much as 20% by the 2080s could be required to preserve in-stream
10 flow targets for fish in the Columbia River basin.³² Springtime irrigation diversions increased
11 between 1970 and 2007 in the Snake River basin, as earlier snowmelt led to reduced spring soil
12 moisture.³³ In the absence of human adaptation, annual hydropower production is much more
13 likely to decrease than to increase in the Columbia River basin; economic impacts of hydropower
14 changes could be hundreds of millions of dollars per year.³⁴

15 Region-wide summer temperature increases, and in certain basins, increased river flooding and
16 winter flows and decreased summer flows, will threaten many freshwater species, particularly
17 salmon, steelhead, and trout.²⁶ Rising temperatures will increase disease and/or mortality in
18 several iconic salmon species, especially for spring/summer Chinook and sockeye in the interior
19 Columbia and Snake River basins.³⁵ Some Northwest streams²⁹ and lakes have already warmed
20 over the past three decades, contributing to changes such as earlier Columbia River sockeye
21 salmon migration³⁶ and earlier blooms of algae in Lake Washington.³⁷ Relative to the rest of the
22 United States, Northwest streams dominated by snowmelt runoff appear to be less sensitive, in
23 the short term, to warming due to the temperature buffering provided by snowmelt and
24 groundwater contributions to those streams.³⁸ However, as snowpack declines, the future
25 sensitivity to warming is likely to increase in these areas.³⁹ By the 2080s, suitable habitat for the
26 four trout species of the interior western U.S. is projected to decline 47% on average, compared
27 to the period 1978-1997.⁴⁰ As species respond to climate change in diverse ways, there is a
28 potential for ecological mismatches to occur – such as in the timing of the emergence of
29 predators and their prey.³⁷

30 Adaptive capacity and implications for vulnerability

31 The ability to adapt to climate changes is strengthened by extensive water resources
32 infrastructure, diversity of institutional arrangements,⁴¹ and management agencies that are
33 responsive to scientific input. However, over-allocation of existing water supply, conflicting
34 objectives, limited management flexibility caused by rigid water allocation and operating rules,
35 and other institutional barriers to changing operations continue to limit progress towards
36 adaptation in many parts of the Columbia River basin.^{42,43} Vulnerability to projected changes in
37 snowmelt timing is probably highest in basins with the largest hydrologic response to warming
38 and lowest management flexibility – that is, fully allocated, mid-elevation, temperature-sensitive,
39 mixed rain-snow watersheds with existing conflicts among users of summer water. Regional
40 power planners have expressed concerns over the existing hydroelectric system's potential
41 inability to provide adequate summer electricity given the combination of climate change,
42 demand growth, and operating constraints.¹ Vulnerability is probably lowest where hydrologic
43 change is likely to be smallest (in rain-dominant basins), and where institutional arrangements

1 are simple, and current natural and human demands rarely exceed current water
2 availability.^{42,44,45}

3 The adaptive capacity of freshwater ecosystems also varies and, in managed basins, will depend
4 on the degree to which the need to maintain streamflows and water quality for fish and wildlife is
5 balanced with human uses of water resources. In highly managed rivers, release of deeper, colder
6 water from reservoirs could offer one of the few direct strategies to lower water temperatures
7 downstream.⁴⁶ Actions to improve stream habitat, including planting trees for shade, are being
8 tested. Some species may be able to change behavior or take advantage of cold-water refuges.⁴⁷

9 ***Coastal Vulnerabilities***

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

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

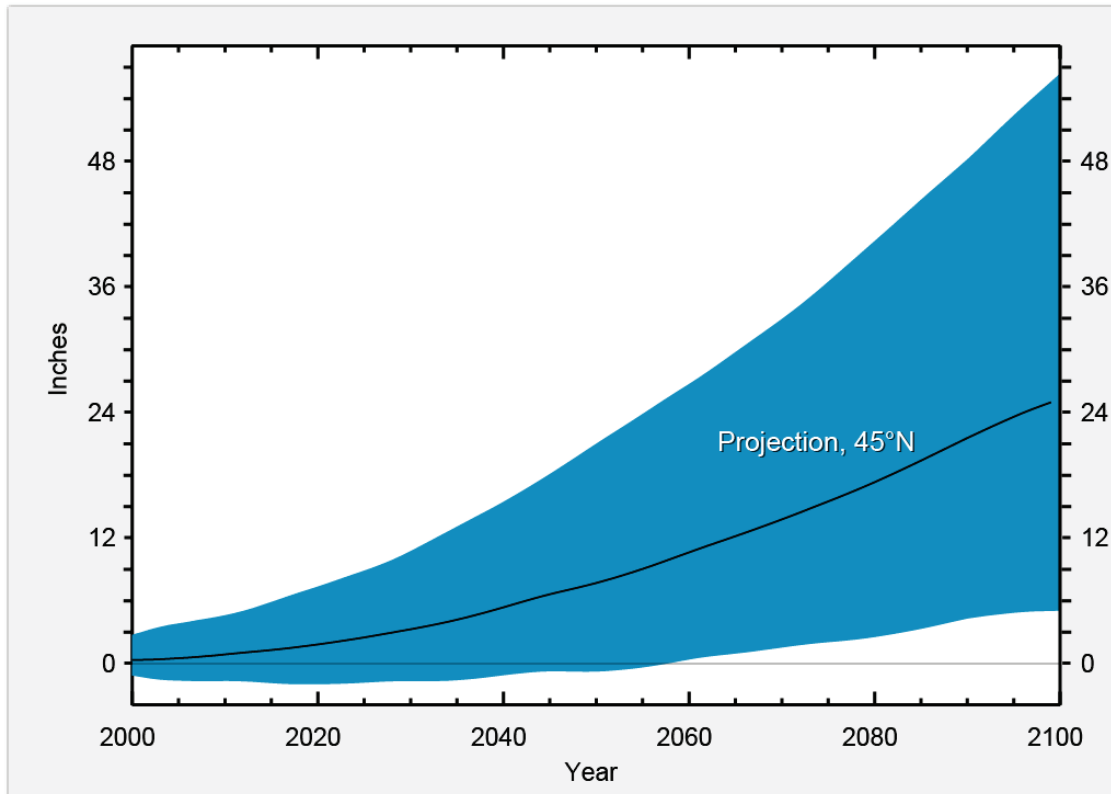
16 **Description of observed and projected changes**

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

23 Much of the Northwest coastline is rising due to a geophysical force known as “tectonic uplift,”
24 which raises the land surface. Because of this, apparent sea level rise is less than the currently
25 observed global average. However, a major earthquake along the Cascadia subduction zone,
26 expected within the next few hundred years, would immediately reverse centuries of uplift and,
27 based on historical evidence, increase relative sea level 40 inches or more.^{48,49} On the other hand,
28 some Puget Sound locations are currently experiencing subsidence (where land is sinking or
29 settling) and could see the reverse effect, witnessing immediate uplift during a major earthquake
30 and lowered relative sea levels.^{50,51}

31 Taking into account many of these factors and considering a wider range of emissions scenarios
32 than are used in this assessment (Appendix 5: Scenarios and Models), a recent evaluation
33 calculated projected sea level rise and ranges for the years 2030, 2050, and 2100 (relative to
34 2000) based on latitude for Washington, Oregon, and California (see Figure 21.3).⁴⁹ In addition
35 to long-term climate-driven changes in sea level projected for the Northwest, shorter-term El
36 Niño conditions can increase regional sea level by about 4 to 12 inches for periods of many
37 months.^{49,52}

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



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2 **Figure 21.3:** Projected Relative Sea Level Rise for the Latitude of Newport, OR

3 **Caption:** Projected relative sea level rise for the latitude of Newport, OR (relative to the
 4 year 2000) is based⁴⁹ on a broader suite of emissions scenarios (ranging from B1 to
 5 A1FI) and a more detailed and regionally-focused calculation than those generally used
 6 in this assessment (See Ch. 2: Our Changing Climate). The blue area shows the range of
 7 relative sea level rise, and the black line shows the projection, which incorporates global
 8 and regional effects of warming oceans, melting land ice, and vertical land movements.⁴⁹
 9 Given the difficulty of assigning likelihood to any one possible trajectory of sea level rise
 10 at this time, a reasonable risk assessment would consider multiple scenarios within the
 11 full range of possible outcomes shown, in conjunction with long- and short-term
 12 compounding effects, such as El Niño-related variability and storm surge. (Data from
 13 NRC 2012⁴⁹).

14 Northwest coastal waters, some of the most productive on the West Coast,⁵³ have highly variable
 15 physical and ecological conditions as a result of seasonal and year-to-year changes in upwelling
 16 of deeper marine water that make longer-term changes difficult to detect. Coastal sea surface
 17 temperatures have increased,⁵⁴ and summertime fog has declined between 1900 and early 2000s,
 18 both of which could be consequences of weaker upwelling winds.⁵⁵ Projected changes include

1 increasing but highly variable acidity,^{56,57,58} increasing surface water temperature (2.2°F from the
2 period 1970 to 1999 to the period 2030 to 2059),⁵⁹ and possibly changing storminess.⁶⁰ Climate
3 models show inconsistent projections for the future of Northwest coastal upwelling.^{11,61}

4 **Consequences and likelihoods of changes**

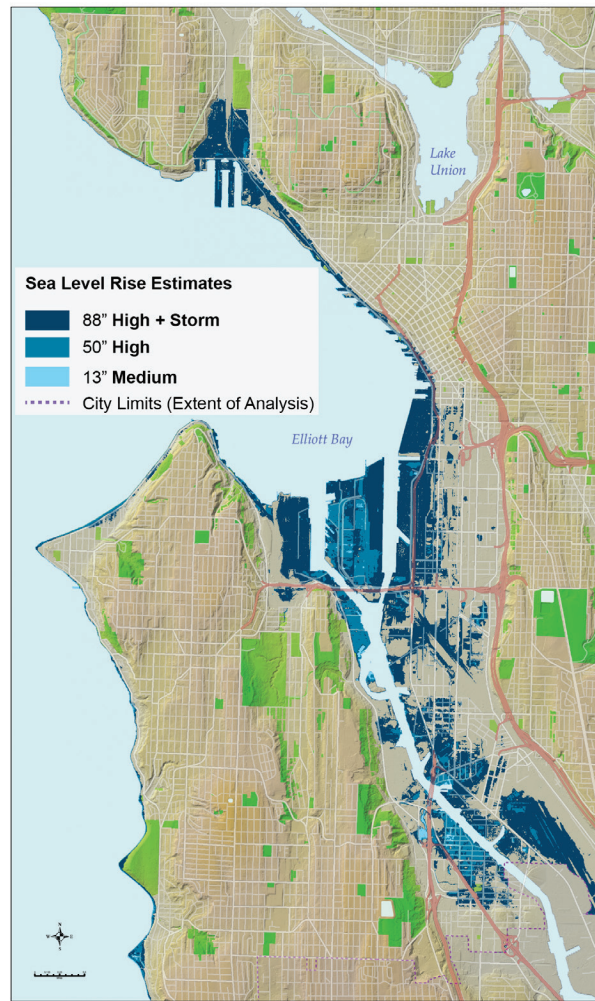
5 In Washington and Oregon, more than 140,000 acres of coastal lands lie within 3.3 feet in
6 elevation of high tide.⁶² As sea levels continue to rise, these areas will be inundated more
7 frequently. Many coastal wetlands, tidal flats, and beaches will probably decline in quality and
8 extent as a result of sea level rise, particularly where habitats cannot shift inland because of
9 topographical limitations or physical barriers resulting from human development. Species such
10 as shorebirds and forage fish (small fish eaten by larger fish, birds, or mammals) would be
11 harmed, and coastal infrastructure and communities would be at greater risk from coastal
12 storms.⁶³

13 Ocean acidification threatens culturally and commercially significant marine species directly
14 affected by changes in ocean chemistry (such as oysters) and those affected by changes in the
15 marine food web (such as Pacific salmon⁶⁴). Northwest coastal waters are among the most
16 acidified worldwide, especially in spring and summer with coastal upwelling^{57,58,65} combined
17 with local factors in estuaries.^{56,57}

18 Increasing coastal water temperatures and changing ecological conditions may alter the ranges,
19 types, and abundances of marine species.^{66,67} Recent warm periods in the coastal ocean, for
20 example, saw the arrival of subtropical and offshore marine species from zooplankton to top
21 predators such as striped marlin, tuna, and yellowtail more common to the Baja area.⁶⁸ Warmer
22 water in regional estuaries (such as Puget Sound) may contribute to a higher incidence of
23 harmful blooms of algae linked to paralytic shellfish poisoning,⁶⁹ and result in adverse economic
24 impacts from beach closures affecting recreational shellfish harvesting, such as razor clams.⁷⁰
25 Toxicity of some harmful algae appears to be increased by acidification.⁷¹

26 Many human uses of the coast – for living, working, and recreating – will also be negatively
27 affected by the physical and ecological consequences of climate change. Erosion, inundation,
28 and flooding will threaten: public and private property along the coast; infrastructure, including
29 wastewater treatment plants;^{6,72} stormwater outfalls;^{73,74} ferry terminals;⁷⁵ and coastal road and
30 rail transportation, especially in Puget Sound.⁷⁶ Municipalities from Seattle⁷³ and Olympia,⁷⁴
31 Washington, to Neskowin, Oregon, have mapped risks from the combined effects of sea level
32 rise and other factors.

Rising Sea Levels and Changing Flood Risks in Seattle



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Figure 21.4: Rising Sea Levels and Changing Flood Risks in Seattle

Caption: 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,⁷⁷ 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 Seattle⁷⁸). 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 sea water. (Figure source: Seattle Public Utilities⁷⁹).

1 **Adaptive capacity and implications for vulnerability**

2 Human activities have increased the vulnerability of many coastal ecosystems, by degrading and
 3 eliminating habitat⁸⁰ and by building structures that, along with natural bluffs, thwart inland
 4 movement of many remaining habitats. In Puget Sound, for example, seawalls, bulkheads, and
 5 other structures have modified an estimated one-third of the shoreline,⁸¹ though some restoration
 6 has occurred. Human responses to erosion and sea level rise, especially shoreline armoring, will
 7 largely determine the viability of many shallow-water and estuarine ecosystems.^{67,81,82} In
 8 communities with few alternatives to existing coastal transportation networks, such as on parts of
 9 Highway 101 in Oregon, sea level rise and storm surges will pose an increasing threat to local
 10 commerce and livelihoods. Finally, there are few proven options for ameliorating projected
 11 ocean acidification.⁸³

Adapting the Nisqually River Delta to Sea Level Rise



12
13 **Figure 21.5:** Adapting the Nisqually River Delta to Sea Level Rise

14 **Caption:** In Washington's Nisqually River Delta, estuary restoration on a large scale to
 15 assist salmon and wildlife recovery provides an example of adaptation to climate change
 16 and sea level rise. After a century of isolation behind dikes (left), much of the Nisqually
 17 National Wildlife Refuge was reconnected with tidal flow in 2009 by removal of a major
 18 dike and restoration of 762 acres (right), with the assistance of Ducks Unlimited and the
 19 Nisqually Indian Tribe. This reconnected more than 21 miles of historical tidal channels
 20 and floodplains with Puget Sound.⁸⁴ A new exterior dike was constructed to protect
 21 freshwater wetland habitat for migratory birds from tidal inundation and future sea level
 22 rise. Combined with expansion of the authorized Refuge boundary, ongoing acquisition
 23 efforts to expand the Refuge will enhance the ability to provide diverse estuary and
 24 freshwater habitats despite rising sea level, increasing river floods, and loss of estuarine
 25 habitat elsewhere in Puget Sound. This project is considered a major step in increasing
 26 estuary habitat and recovering the greater Puget Sound estuary. (Photo credits: (left) Jesse
 27 Barham, U.S. Fish and Wildlife Service; (right) Jean Takekawa, U.S. Fish and Wildlife
 28 Service).

1 *Impacts on Forests*

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

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

11 **Description of observed and projected changes**

12 Climate change will alter Northwest forests by increasing wildfire risk, insect and tree disease
13 outbreaks, and by forcing longer-term shifts in forest types and species (See Ch 7: Forests).
14 Many impacts will be driven by water deficits, which increase tree stress and mortality, tree
15 vulnerability to insects, and fuel flammability. The cumulative effects of disturbance – and
16 possibly interactions between insects and fires – will cause the greatest changes in Northwest
17 forests.^{85,86} A similar outlook is expected for the Southwest region (See Ch. 20: Southwest, Key
18 Message 3).

19 Although wildfires are a natural part of most Northwest forest ecosystems, warmer and drier
20 conditions have helped increase the number and extent of wildfires in western U.S. forests since
21 the 1970s.^{13,86,87,88} This trend is expected to continue under future climate conditions. By the
22 2080s, the median annual area burned in the Northwest would quadruple relative to the 1916 to
23 2007 period to 2 million acres (range of 0.2 to 9.8 million acres) under the A1B scenario.
24 Averaged over the region, this would increase the probability that 2.2 million acres would burn
25 in a year from 5 percent to nearly 50 percent.¹³ Within the region, this probability will vary
26 substantially with sensitivity of fuels to climatic conditions and local variability in fuel type and
27 amount, which are in turn a product of forest type, effectiveness of fire suppression, and land
28 use. For example, in the Western Cascades, the year-to-year variability in area burned is difficult
29 to attribute to climate conditions, while fire in the eastern Cascades and other specific vegetation
30 zones is responsive to climate.¹³ How individual fires behave in the future and what impacts they
31 have will depend on factors we cannot yet project, such as extreme daily weather and forest fuel
32 conditions.

Forest Mortality



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2 **Figure 21.6:** Forest mortality

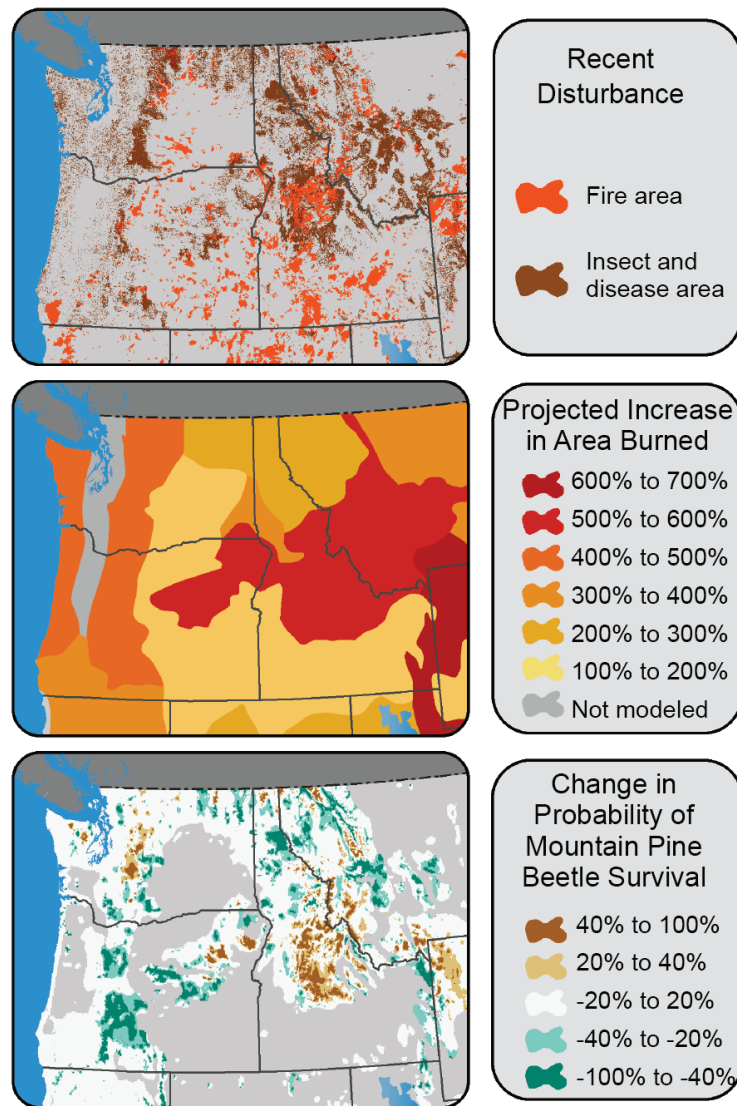
3 **Caption:** Forest mortality due to fire and insect activity is already evident in the
 4 Northwest. Continued changes in climate in coming decades are expected to increase
 5 these effects. Trees killed by a fire (left side of watershed) and trees killed by mountain
 6 pine beetle and spruce beetle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

10 Higher temperatures and drought stress are contributing to outbreaks of mountain pine beetles
 11 that are increasing pine mortality in drier Northwest forests.^{89,90} This trend is projected to
 12 continue with ongoing warming.^{13,91,92,93} Between now and the end of this century, the elevation
 13 of suitable beetle habitat is projected to increase as temperature increases, exposing higher
 14 elevation forests to the pine beetle, but ultimately limiting available area as temperatures exceed
 15 the beetles' optimal temperatures.^{13,91,92} As a result, the proportion of Northwest pine forests
 16 where mountain pine beetles are most likely to survive is projected to first increase (27% higher
 17 in 2001 to 2030 compared to 1971 to 2000) and then decrease (about 49% to 58% lower by 2071
 18 to 2100).⁹¹ For many tree species, the most climatically suited areas will shift from their current
 19 locations, increasing vulnerability to insects, disease, and fire in areas that become unsuitable.
 20 Eighty-five percent of the current range of three species that are host to pine beetles is projected

1 to be climatically unsuitable for one or more of those species by the 2060s,^{13,94} while 21 to 38
 2 currently existing plant species may no longer find climatically appropriate habitat in the
 3 Northwest by late this century.⁹⁵

4

Insects and Fire in Northwest Forests



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6 **Figure 21.7:** Insects and Fire in Northwest Forests

7 **Caption:** (Top) Insects and fire have cumulatively affected large areas of the Northwest
 8 and are projected to be the dominant drivers of forest change in the near future. Map
 9 shows areas recently burned (1984 to 2008)^{96,97} or affected by insects or disease (1997 to
 10 2008).⁹⁸ (Middle) Map indicates the increases in area burned that would result from the
 11 regional temperature and precipitation changes associated with a 2.2°F global warming⁹⁹

1 across areas that share broad climatic and vegetation characteristics.¹⁰⁰ Local impacts will
2 vary greatly within these broad areas with sensitivity of fuels to climate.¹³ (Bottom)
3 Projected changes in the probability of climatic suitability for mountain pine beetles for
4 the period 2001 to 2030 (relative to 1971 to 2000), where brown indicate areas where
5 pine beetles are projected to increase in the future and green indicates areas where pine
6 beetles are expected to decrease in the future. Changes in probability of survival are
7 based on climate-dependent factors important in beetle population success, including cold
8 tolerance,¹⁰¹ spring precipitation,¹⁰² and seasonal heat accumulation.^{90,91}

9 **Consequences and likelihoods of changes**

10 The likelihood of increased disturbance (fire, insects, diseases and other sources of mortality)
11 and altered forest distribution are very high in areas dominated by natural vegetation, and the
12 resultant changes in habitat would affect native species and ecosystems. Subalpine forests and
13 alpine ecosystems are especially at risk and may undergo almost complete conversion to other
14 vegetation types by the 2080s (A2 and B1, Lenihan et al. 2008;¹⁰³ A2, Rogers et al. 2011;¹⁰⁴
15 Ensemble A2, B1, B2 Rehfeldt et al. 2012¹⁰⁵). While increased area burned can be statistically
16 estimated from climate projections, changes in the risk of very large, high-intensity, stand-
17 replacing fires cannot yet be predicted, but such events could have enormous impacts for forest-
18 dependent species.⁸⁷ Increased wildfire could exacerbate respiratory and cardiovascular illnesses
19 in nearby populations due to smoke and particulate pollution (Baron et al. 2008; Ch. 9: Human
20 Health).^{106,107}

21 These projected forest changes will have moderate economic impacts for the region as a whole,
22 but could significantly affect local timber revenues and bioenergy markets.¹⁰⁸

23 **Adaptive capacity and implications for vulnerability**

24 Ability to prepare for these changes varies with land ownership and management priorities.
25 Adaptation actions that decrease forest vulnerability exist, but none is appropriate across all of
26 the Northwest's diverse climate threats, land-use histories, and management objectives.^{85,109}
27 Surface and canopy thinning can reduce the occurrence and effects of high severity fire in
28 currently low severity fire systems, like drier eastern Cascades forests,¹¹⁰ but may be ineffective
29 in historically high severity fire forests, like the western Cascades, Olympics, and some
30 subalpine forests. It is possible to use thinning to reduce tree mortality from insect
31 outbreaks,^{85,111} but not on the scale of the current outbreaks in much of the West.

32

1 *Adapting Agriculture*

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

6 Agriculture provides the economic and cultural foundation for Northwest rural populations and
7 contributes substantively to the overall economy. Agricultural commodities and food production
8 systems contributed 3% and 11% of the region’s gross domestic product, respectively in 2009.¹¹²
9 Although the overall consequences of climate change will probably be lower in the Northwest
10 than in certain other regions, sustainability of some Northwest agricultural sectors is threatened
11 by soil erosion¹¹³ and water supply uncertainty, both of which could be exacerbated by climate
12 change.

13 **Description of observed and projected changes**

14 Northwest agriculture’s sensitivity to climate change stems from its dependence on irrigation
15 water, a specific range of temperatures, precipitation, and growing seasons, and the sensitivity of
16 crops to temperature extremes. Projected warming will reduce the availability of irrigation water
17 in snowmelt-fed basins and increase the probability of heat stress to field crops and tree fruit.
18 Some crops will benefit from a longer growing season¹¹⁴ and/or higher atmospheric carbon
19 dioxide, at least for a few decades.^{114,115} Longer-term consequences are less certain. Changes in
20 plant diseases, pests, and weeds present additional potential risks. Higher average temperatures
21 generally can exacerbate pest pressure through expanded geographic ranges, earlier emergence
22 or arrival, and increased numbers of pest generations (for example, Ch. 6: Agriculture¹¹⁶).
23 Specifics differ among pathogen and pest species and depend upon multiple interactions (Ch. 6:
24 Agriculture)¹¹⁷ preventing region-wide generalizations. Research is needed to project changes in
25 vulnerabilities to pest, disease, and weed complexes for specific cropping systems in the
26 Northwest.

27 **Consequences of changes**

28 Because much of the Northwest has low annual precipitation, many crops require irrigation.
29 Reduction in summer flows in snow-fed rivers (see “Reduced Summer Flows” figure), coupled
30 with warming that could increase agricultural and other demands, potentially produces irrigation
31 water shortages.¹⁰⁷ The risk of a water-short year – when Yakima basin junior water rights
32 holders are allowed only 75% of their water right amount – is projected to increase from 14% in
33 the late 20th century to 32% by 2020 and 77% by 2080, assuming no adaptation and under the
34 A1B scenario.⁴⁵

35 Assuming adequate nutrition and excluding effects of pests, weeds, and diseases, projected
36 increases in average temperature and hot weather episodes and decreases in summer soil
37 moisture would reduce yields of spring and winter wheat in rain-fed production zones of
38 Washington State by the end of this century by as much as 25% relative to 1975 to 2005.
39 However, carbon dioxide fertilization should offset these effects, producing net yield increases as
40 great as 33% by 2080.¹¹⁴ Similarly, for irrigated potatoes in Washington State, carbon dioxide
41 fertilization is projected to mostly offset direct climate change related yield losses, although

1 yields are still projected to decline by 2% to 3% under the A1B emissions scenario.¹¹⁴ Higher
2 temperatures could also reduce potato tuber quality.¹¹⁸

3 Irrigated apple production is projected to increase in Washington State by 6% in the 2020s, 9%
4 in the 2040s, and 16% in the 2080s (relative to 1975 to 2005) when offsetting effects of carbon
5 dioxide fertilization are included.¹¹⁴ However, because tree fruit requires chilling to ensure
6 uniform flowering and fruit set, and wine grape varieties have specific chilling requirements for
7 maturation,¹¹⁹ warming could adversely affect currently grown varieties of these commodities.
8 Most published projections of climate change impacts on Northwest agriculture are limited to
9 Washington State and have focused on major commodities, although more than 300 crops are
10 grown in the region. More studies are needed to identify the implications of climate change for
11 additional cropping systems and locations within the region. The economic consequences for
12 Northwest agriculture will be influenced by input and output prices driven by global economic
13 conditions as well as by regional and local changes in productivity.

14 **Adaptive capacity and implications for vulnerability**

15 Of the four areas of concern discussed here, agriculture is perhaps best positioned to adapt to
16 climate trends without explicit planning and policy, because it already responds to annual climate
17 variations and exploits a wide range of existing climates across the landscape.¹²⁰ Some projected
18 changes in climate, including warmer winters, longer annual frost-free periods, and relatively
19 unchanged or increased winter precipitation, could be beneficial to some agriculture systems.
20 Nonetheless, rapid climate change could present difficulties. Adaptation could occur slowly if
21 substantial investments or significant changes in farm operations and equipment are required.
22 Shifts to new varieties of wine grapes and tree fruit, if indicated, and even if ultimately more
23 profitable, are necessarily slow and expensive. Breeding for drought- and heat-resistance
24 requires long-term effort. Irrigation water shortages that necessitate shifts away from more
25 profitable commodities could exact economic penalties.¹⁰⁷ Risk aversion among farmers,
26 although prudent under typical circumstances, could hamper responsiveness to climatic changes.

27

1 Traceable Accounts

3 Chapter 21: Northwest

5 **Key Message Process:** The authors and several dozen collaborators undertook a risk evaluation
6 of the impacts of climate change in the Northwest that informed the development of the four key
7 messages in this chapter (See also Ch. 26: Decision Support). This process considered the
8 combination of impact likelihood and the consequences for the region’s economy, infrastructure,
9 natural systems, human health, and the economically-important and climate sensitive regional
10 agriculture sector (see Dalton et al. 2013⁵ for details). The qualitative comparative risk
11 assessment underlying the key messages in the Northwest Chapter was informed by the
12 Northwest Regional Climate Risk Framing workshop (December 2, 2011 in Portland, OR). The
13 workshop brought together stakeholders and scientists from a cross-section of sectors and
14 jurisdictions within the region to discuss and rank the likelihood and consequences for key
15 climate risks facing the Northwest region and previously identified in the Oregon Climate
16 Change Adaptation Framework.¹²¹ The approach consisted of an initial qualitative likelihood
17 assessment based on expert judgment and consequence ratings based on the conclusions of a
18 group of experts and assessed for four categories: human health, economy, infrastructure, and
19 natural systems.¹²²

20 This initial risk exercise was continued by the lead author team of the Northwest chapter,
21 resulting in several white papers that were 1) condensed and synthesized into the Northwest
22 chapter and 2) expanded into a book-length report on Northwest impacts.⁵ The NCA Northwest
23 chapter author team engaged in multiple technical discussions via regular teleconferences and
24 two all-day meetings. These included careful review of the foundational technical input report¹²²
25 of approximately 80 additional technical inputs provided to the NCA by the public, as well
26 additional published literature. They also drew heavily from two state climate assessment
27 reports.¹²³

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

42 Each author produced a white paper synthesizing the findings in his/her sectoral area, and a
43 number of key messages pertaining to climate impacts in that area. These syntheses were

1 followed by expert deliberation of draft key messages by the authors wherein each key message
 2 was defended before the entire author team before this key message was selected for inclusion in
 3 the Report. These discussions were supported by targeted consultation with additional experts by
 4 the lead author of each message, and they were based on criteria that help define “key
 5 vulnerabilities”, including likelihood of climate change and relative magnitude of its
 6 consequences for the region as a whole, including consequences for the region’s economy,
 7 human health, ecosystems, and infrastructure.¹²²

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

15

Key message #1/4	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	<p>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; 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), these impacts and any societal adjustments to them will have far-reaching ecological and socioeconomic consequences.</p> <p>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.</p> <p>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.</p> <p>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:</p> <ul style="list-style-type: none"> (1) 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; (2) documented competition among existing water uses (irrigation, power, municipal, in stream flows) and inability for all water systems to meet all summer water needs all of the time, especially during drier years;

	<p>(3) empirical and theoretical studies that indicate increased water demand for many uses under climate change;</p> <p>(4) 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.</p> <p>Evidence for far-reaching ecological and socioeconomic consequences of the above is based on:</p> <p>(1) 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);</p> <p>(2) model simulations of future agricultural water allocation in the Yakima⁴⁵ and the Snake River Basin,³¹ showing increased likelihood of water curtailments for junior water rights holders;</p> <p>(3) 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;</p> <p>(4) regional and extra-regional dependence on Northwest-produced hydropower;</p> <p>(5) legal requirements to manage water resources for threatened & endangered fish as well as for human uses.</p> <p>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:</p> <p>(1) observed, theoretical, and simulated sensitivity of watershed hydrologic response to warming by basin type</p> <p>(2) historical observations and modeled simulations of trade-offs required among water management objectives under specific climatic conditions</p> <p>(3) analyses from water management agencies of potential system impacts and adaptive responses to projected future climate</p> <p>(4) institutional and policy analyses documenting sources and types of management rigidity (for example, difficulty adjusting management practices to account for changing conditions)</p>
<p>New information and remaining uncertainties</p>	<p>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.</p> <p>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.</p> <p>Uncertainty in how much increasing temperatures will affect crop evapotranspiration affects future estimates of irrigation demand.</p> <p>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.</p> <p>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.</p> <p>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-</p>

	affected economic variables (prices of inputs, 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 is very high based on strong strength of evidence and high level of agreement among experts. See specifics under “description of evidence” above.

1

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

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- 1 **Chapter 21: Northwest**
- 2 **Key Message Process:** See Key Message #1

Key message #2/4	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	<p>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.</p> <p>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 report⁴⁹ that includes a detailed discussion of the U.S. west coast, and Parris et al. 2012.¹²⁴</p> <p>Evidence of erosion associated with coastal storms is based on observations of storm damage in some areas of the Northwest.</p> <p>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.</p> <p>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.</p> <p>Evidence for impacts of climate change on coastal habitat is based on:</p> <p>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 WA & OR.</p> <p>Observations of extent and location of coastal armoring and other structures that would potentially impede inland movement of coastal wetlands.</p> <p>Observed changes in coastal ocean conditions (upwelling, nutrients, sea surface temperatures); biogeographical, physiological and paleoecological studies indicating a historical decline in coastal upwelling; global climate model projections of future increases in sea surface temperatures (SST).</p> <p>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).</p> <p>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 (ENSO) and inter-decadal Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO).</p> <p>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</p>

	<p>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.</p> <p>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.</p> <p>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.</p>
<p>New information and remaining uncertainties</p>	<p>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 2012⁴⁹) 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 also in 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 NW 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 2009⁵⁰].</p> <p>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.</p> <p>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.</p> <p>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).</p> <p>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.</p> <p>Projections of future coastal ocean conditions (for example, temperature, nutrients, pH, 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</p>

	<p>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.</p> <p>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.</p>
<p>Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence</p>	<p>There is very high confidence in the global upward trend of sea level rise and ocean acidification. There is high confidence that sea level rise (SLR) over the next century will remain under an upper bound of approximately 2 meters. Projections for SLR and ocean acidification (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.</p> <p>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.</p> <p>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.</p> <p>There is high confidence in the projections of increased erosion and inundation.</p> <p>There is very high confidence that ocean acidity will continue to increase.</p>

1

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

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1 **Chapter 21: Northwest**

2 **Key Message Process:** See Key Message #1

<p>Key message #3/4</p>	<p>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.</p>
<p>Description of evidence base</p>	<p>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.^{97,125}</p> <p>Evidence that the interannual variation in area burned is 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 of the area and number of fires in the Pacific Northwest. Future 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 changes for Pacific Northwest forests, though the degree of increase depends on the climate change scenario and modeling approach.</p> <p>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.</p> <p>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 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.</p> <p>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.</p> <p>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.</p>

<p>New information and remaining uncertainties</p>	<p>The key uncertainties are primarily the timing and magnitude of future projected changes in forests, rather than the direction (sign) of changes.</p> <p>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 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 A2.</p> <p>Statistical fire models do not include changes in vegetation that occur in the 21st century due to disturbance (such as fire, insects, 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, 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.</p> <p>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 future areas of forest mortality due to insects.</p> <p>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.</p> <p>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 forest, but disagree about what will replace it. 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 scenario. Because these statistical models do not simulate 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.</p>
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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-21 st 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.
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CONFIDENCE LEVEL			
Very High	High	Medium	Low
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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- 1 **Chapter 21: Northwest**
- 2 **Key Message Process:** See Key Message #1

<p>Key message #4/4</p>	<p>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.</p>
<p>Description of evidence base</p>	<p>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.</p> <p>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 CO₂. 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 CO₂ fertilization.</p> <p>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.</p> <p>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.</p> <p>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.</p> <p>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 the hydrology section of the Northwest region 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.</p> <p>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 the Hydrology report for the Northwest chapter of this report.</p> <p>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.</p>

<p>New information and remaining uncertainties</p>	<p>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 may be adversely affected by warming directly or through enhancement of their natural enemy base, while others become more serious.</p> <p>Uncertainty exists in models in how increasing temperatures will impact crop evapotranspiration, which affects future estimates of irrigation demand (from hydrology section of the Northwest Regional chapter)</p> <p>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.</p> <p>Estimates of changes in crop yields as a result of changing climate and CO₂ are based on very few model simulations, so the uncertainty has not been well quantified.</p>
<p>Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence</p>	<p>Confidence is very high based on strong strength of evidence and high level of agreement among experts.</p> <p>See specifics under “description of evidence” above.</p>

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

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1 **References**

- 2 1. NWPCC, cited 2012: A guide to major hydropower dams of the Columbia River Basin. Northwest Power and
3 Conservation Council
- 4 2. EIA, 2011: A Quarter of California's Energy Comes From Outside the State. Department of Energy, Energy
5 Information Administration. [Available online at <http://www.eia.gov/todayinenergy/detail.cfm?id=4370>]
- 6 3. USDA, 2012: Crop Production 2012 Summary, 96 pp., U.S. Department of Agriculture, National Agricultural
7 Statistics Service, Washington, D.C. [Available online at
8 <http://usda01.library.cornell.edu/usda/current/CropProdSu/CropProdSu-01-11-2013.pdf>];
9 —, 2012: Milk Production, Disposition, and Income, 2011 Summary, 15 pp., U.S. Department of Agriculture,
10 National Agricultural Statistics Service. [Available online at
11 <http://usda01.library.cornell.edu/usda/current/MilkProdDi/MilkProdDi-04-25-2012.pdf>]
- 12 4. NOAA, cited 2012: Annual Commercial Landing Statistics. [Available online at
13 http://www.st.nmfs.noaa.gov/st1/commercial/landings/annual_landings.html]
- 14 5. Dalton, M. M., P. Mote, and A. K. Snover, Eds., 2013: *Climate Change in the Northwest: Implications for Our*
15 *Landscapes, Waters, And Communities*. Island Press, 224 pp
- 16 6. Solecki, W., and C. Rosenzweig, 2012: U.S. Cities and Climate Change: Urban, Infrastructure, and Vulnerability
17 Issues, Technical Input Report Series, U.S. National Climate Assessment. S. W., and C. Rosenzweig, Eds., U.S.
18 Global Change Research Program, Washington, D.C.
- 19 7. Lynn, K., O. Grah, P. Hardison, J. Hoffman, E. Knight, A. Rogerson, P. Tillmann, C. Viles, and P. Williams, 2013:
20 Tribal Communities. *Climate Change in the Northwest: Implications for Our Landscapes, Waters, And*
21 *Communities*, P. Mote, M. M. Dalton, and A. K. Snover, Eds., Island Press, 224;
22 Voggesser, G., K. Lynn, J. Daigle, F. K. Lake, and D. Ranco, 2013: Cultural impacts to tribes from climate change
23 influences on forests. *Climatic Change*, **120**, 615-626, doi:10.1007/s10584-013-0733-4
- 24 8. Brunner, R., and J. Nordgren, 2012: Climate Adaptation as an Evolutionary Process: A White Paper. *Kresge*
25 *Grantees and Practitioners Workshop On Climate Change Adaptation*, Portland, OR, The Kresge Foundation,
26 12 pp. [Available online at <http://kresge.org/library/climate-adaptation-evolutionary-process-white-paper>]
- 27 9. Kunkel, K. E., L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, K. T. Redmond, and J. G. Dobson,
28 2013: Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 6. Climate of the
29 Northwest U.S. NOAA Technical Report NESDIS 142-6, 83 pp, National Oceanic and Atmospheric
30 Administration, National Environmental Satellite, Data, and Information Service, Washington, D.C. [Available
31 online at [http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-6-](http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-6-Climate_of_the_Northwest_U.S.pdf)
32 [Climate_of_the_Northwest_U.S.pdf](http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-6-Climate_of_the_Northwest_U.S.pdf)]
- 33 10. Groisman, P. Y., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore, 2004: Contemporary
34 changes of the hydrological cycle over the contiguous United States: trends derived from in situ observations.
35 *Journal of Hydrometeorology*, **5**, 64-85, doi:10.1175/1525-7541(2004)005<0064:CCOTHC>2.0.CO;2 [Available
36 online at [http://journals.ametsoc.org/doi/abs/10.1175/1525-7541\(2004\)005%3C0064:CCOTHC%3E2.0.CO;2](http://journals.ametsoc.org/doi/abs/10.1175/1525-7541(2004)005%3C0064:CCOTHC%3E2.0.CO;2)];
37 Madsen, T., and E. Figdor, 2007: *When It Rains, It Pours: Global Warming and the Rising Frequency of Extreme*
38 *Precipitation in the United States*. Environment America Research & Policy Center, 48 pp;
- 39 Rosenberg, E. A., P. W. Keys, D. B. Booth, D. Hartley, J. Burkey, A. C. Steinemann, and D. P. Lettenmaier, 2010:
40 Precipitation extremes and the impacts of climate change on stormwater infrastructure in Washington State.
41 *Climatic Change*, **102**, 319-349, doi:10.1007/s10584-010-9847-0. [Available online at
42 http://www.stillwatersci.com/resources/2010stormwater_infrastructure_climate_change.pdf]

- 1 11. Mote, P. W., and E. P. Salathé, 2010: Future climate in the Pacific Northwest. *Climatic Change*, **102**, 29-50,
2 doi:10.1007/s10584-010-9848-z. [Available online at
3 http://www.atmos.washington.edu/~salathe/papers/published/Mote_Salathe_2010.pdf]
- 4 12. Bumbaco, K., and P. W. Mote, 2010: Three recent flavors of drought in the Pacific Northwest. *Journal of*
5 *Applied Meteorology and Climatology*, **1244**, 2058-2068, doi:10.1175/2010JAMC 2423.1. [Available online at
6 <http://journals.ametsoc.org/doi/pdf/10.1175/2010JAMC2423.1>]
- 7 13. Littell, J. S., E. E. Oneil, D. McKenzie, J. A. Hicke, J. A. Lutz, R. A. Norheim, and M. M. Elsner, 2010: Forest
8 ecosystems, disturbance, and climatic change in Washington State, USA. *Climatic Change*, **102**, 129-158,
9 doi:10.1007/s10584-010-9858-x
- 10 14. Deser, C., A. Phillips, V. Bourdette, and H. Teng, 2012: Uncertainty in climate change projections: The role of
11 internal variability. *Climate Dynamics*, **38**, 527-546, doi:10.1007/s00382-010-0977-x
- 12 15. Mote, P. W., 2006: Climate-Driven Variability and Trends in Mountain Snowpack in Western North America*.
13 *Journal of Climate*, **19**, 6209-6220;
- 14 Pierce, D. W., T. P. Barnett, H. G. Hidalgo, T. Das, C. Bonfils, B. D. Santer, G. Bala, M. D. Dettinger, D. R. Cayan,
15 A. Mirin, A. W. Wood, and T. Nozawa, 2008: Attribution of declining western US snowpack to human effects.
16 *Journal of Climate*, **21**, 6425-6444, doi:10.1175/2008JCLI2405.1 [Available online at
17 <http://journals.ametsoc.org/doi/abs/10.1175/2008JCLI2405.1>]
- 18 16. Stewart, I. T., D. R. Cayan, and M. D. Dettinger, 2005: Changes Toward Earlier Streamflow Timing across
19 Western North America. *Journal of Climate*, **18**, 1136-1155, doi:10.1175/JCLI3321.1
- 20 17. Hidalgo, H. G., T. Das, M. D. Dettinger, D. R. Cayan, D. W. Pierce, T. P. Barnett, G. Bala, A. Mirin, A. W. Wood,
21 C. Bonfils, B. D. Santer, and T. Nozawa, 2009: Detection and attribution of streamflow timing changes to
22 climate change in the western United States. *Journal of Climate*, **22**, 3838-3855, doi:10.1175/2009jcli2470.1.
23 [Available online at <http://journals.ametsoc.org/doi/abs/10.1175/2009JCLI2470.1>]
- 24 18. USBR, 2011: Reclamation Managing Water in the West: Climate and Hydrology Datasets for Use in the River
25 Management Joint Operating Committee (RMJOC) Agencies' Longer Term Planning Studies: Part II Reservoir
26 Operations Assessment for Reclamation Tributary Basins, 201 pp., U.S. Department of the Interior, U.S.
27 Bureau of Reclamation Pacific Northwest Region, Boise, ID. [Available online at
28 <http://www.usbr.gov/pn/programs/climatechange/reports/part2.pdf>]
- 29 19. Mote, P. W., A. Hamlet, and E. Salathé, 2008: Has spring snowpack declined in the Washington Cascades?
30 *Hydrology and Earth System Sciences Discussions*, **12**, 193-206. [Available online at [http://hal.archives-](http://hal.archives-ouvertes.fr/docs/00/30/51/28/PDF/hess-12-193-2008.pdf)
31 [ouvertes.fr/docs/00/30/51/28/PDF/hess-12-193-2008.pdf](http://hal.archives-ouvertes.fr/docs/00/30/51/28/PDF/hess-12-193-2008.pdf)]
- 32 20. Fritze, H., I. T. Stewart, and E. J. Pebesma, 2011: Shifts in Western North American snowmelt runoff regimes
33 for the recent warm decades. *Journal of Hydrometeorology*, **12**, 989-1006, doi:10.1175/2011JHM1360.1.
34 [Available online at <http://journals.ametsoc.org/doi/pdf/10.1175/2011JHM1360.1>]
- 35 21. Mote, P. W., 2003: Trends in temperature and precipitation in the Pacific Northwest during the twentieth
36 century. *Northwest Science*, **77**, 271-282. [Available online at
37 [http://research.wsulibs.wsu.edu/xmlui/bitstream/handle/2376/1032/v77%20p271%20Mote.PDF?sequence=](http://research.wsulibs.wsu.edu/xmlui/bitstream/handle/2376/1032/v77%20p271%20Mote.PDF?sequence=1)
38 [1](http://research.wsulibs.wsu.edu/xmlui/bitstream/handle/2376/1032/v77%20p271%20Mote.PDF?sequence=1)];
- 39 Safeeq, M., G. E. Grant, S. L. Lewis, and C. L. Tague, 2013: Coupling snowpack and groundwater dynamics to
40 interpret historical streamflow trends in the western United States. *Hydrological processes*, **27**, 655-668,
41 doi:10.1002/hyp.9628. [Available online at <http://onlinelibrary.wiley.com/doi/10.1002/hyp.9628/pdf>]
- 42 22. Hamlet, A. F., and D. P. Lettenmaier, 2005: Production of temporally consistent gridded precipitation and
43 temperature fields for the continental United States. *Journal of Hydrometeorology*, **6**, 330-336,
44 doi:10.1175/JHM420.1. [Available online at <http://journals.ametsoc.org/doi/full/10.1175/JHM420.1>]

- 1 23. Elsner, M. M., L. Cuo, N. Voisin, J. S. Deems, A. F. Hamlet, J. A. Vano, K. E. B. Mickelson, S. Y. Lee, and D. P.
2 Lettenmaier, 2010: Implications of 21st century climate change for the hydrology of Washington State.
3 *Climatic Change*, **102**, 225-260, doi:10.1007/s10584-010-9855-0
- 4 24. Riedel, J., and M. A. Larrabee., 2011: North Cascades National Park Complex Glacier Mass Balance Monitoring
5 Annual Report, Water Year 2009. North Coast and Cascades Network. Natural Resource Technical Report
6 NPS/NCCN/NRTR—2011/483., 38 pp., National Park Service, U.S. Department of the Interior, Fort Collins, CO.
7 [Available online at
8 http://www.nps.gov/noca/naturescience/upload/134_NCCN_NOCA_GlacierAnnualReport2009_20110825.pdf
9 f]
- 10 25. Tague, C. L., J. S. Choate, and G. Grant, 2013: Parameterizing sub-surface drainage with geology to improve
11 modeling streamflow responses to climate in data limited environments. *Hydrology and Earth System*
12 *Sciences*, **17**, 341-354, doi:10.5194/hess-17-341-2013. [Available online at [http://www.hydrol-earth-syst-](http://www.hydrol-earth-syst-sci.net/17/341/2013/)
13 [sci.net/17/341/2013/](http://www.hydrol-earth-syst-sci.net/17/341/2013/)]
- 14 26. Mantua, N., I. Tohver, and A. Hamlet, 2010: Climate change impacts on streamflow extremes and
15 summertime stream temperature and their possible consequences for freshwater salmon habitat in
16 Washington State. *Climatic Change*, **102**, 187-223, doi:10.1007/s10584-010-9845-2
- 17 27. Wehner, M. F., 2013: Very extreme seasonal precipitation in the NARCCAP ensemble: Model performance
18 and projections. *Climate Dynamics*, **40**, 59-80, doi:10.1007/s00382-012-1393-1
- 19 28. Hamlet, A. F., M. M. Elsner, G. S. Mauger, S.-Y. Lee, I. Tohver, and R. A. Norheim, 2013: An overview of the
20 Columbia Basin Climate Change Scenarios Project: approach, methods, and summary of key results.
21 *Atmosphere-Ocean*, **in press**, doi:10.1080/07055900.2013.819555. [Available online at
22 <http://www.tandfonline.com/doi/pdf/10.1080/07055900.2013.819555>]
- 23 29. Isaak, D. J., S. Wollrab, D. Horan, and G. Chandler, 2011: Climate change effects on stream and river
24 temperatures across the northwest US from 1980–2009 and implications for salmonid fishes. *Climatic*
25 *Change*, **113**, 499-524, doi:10.1007/s10584-011-0326-z. [Available online at
26 <http://link.springer.com/content/pdf/10.1007%2Fs10584-011-0326-z>]
- 27 30. Hamlet, A. F., S. Y. Lee, K. E. B. Mickelson, and M. M. Elsner, 2010: Effects of projected climate change on
28 energy supply and demand in the Pacific Northwest and Washington State. *Climatic Change*, **102**, 103-128,
29 doi:10.1007/s10584-010-9857-y
- 30 31. USBR, 2011: Reclamation Managing Water in the West. SECURE Water Act Section 9503(c) - Reclamation
31 Climate Change and Water 2011. P. Alexander, L. Brekke, G. Davis, S. Gangopadhyay, K. Grantz, C. Hennig, C.
32 Jerla, D. Llewellyn, P. Miller, T. Pruitt, D. Raff, T. Scott, M. Tansey, and T. Turner, Eds., 226 pp., U.S.
33 Department of the Interior, Policy and Administration, U.S. Bureau of Reclamation, Denver, CO. [Available
34 online at <http://www.usbr.gov/climate/SECURE/docs/SECUREWaterReport.pdf>]
- 35 32. Payne, J. T., A. W. Wood, A. F. Hamlet, R. N. Palmer, and D. P. Lettenmaier, 2004: Mitigating the Effects of
36 Climate Change on the Water Resources of the Columbia River Basin. *Climatic Change*, **62**, 233-256,
37 doi:10.1023/B:CLIM.0000013694.18154.d6. [Available online at
38 <http://link.springer.com/content/pdf/10.1023%2FB%3ACLIM.0000013694.18154.d6>]
- 39 33. Hoekema, D. J., and V. Sridhar, 2011: Relating climatic attributes and water resources allocation: a study
40 using surface water supply and soil moisture indices in the Snake River Basin, Idaho. *Water Resources*
41 *Research*, **47**, W07536, doi:10.1029/2010WR009697. [Available online at
42 <http://onlinelibrary.wiley.com/doi/10.1029/2010WR009697/pdf>]
- 43 34. Markoff, M. S., and A. C. Cullen, 2008: Impact of climate change on Pacific Northwest hydropower. *Climatic*
44 *Change*, **87**, 451-469, doi:10.1007/s10584-007-9306-8

- 1 35. Crozier, L. G., A. P. Hendry, P. W. Lawson, T. P. Quinn, N. J. Mantua, J. Battin, R. G. Shaw, and R. B. Huey,
2 2008: Potential responses to climate change in organisms with complex life histories: evolution and plasticity
3 in Pacific salmon. *Evolutionary Applications*, **1**, 252-270, doi:10.1111/j.1752-4571.2008.00033.x. [Available
4 online at <http://onlinelibrary.wiley.com/doi/10.1111/j.1752-4571.2008.00033.x/pdf>]
- 5 36. Crozier, L. G., M. D. Scheuerell, and R. W. Zabel, 2011: Using time series analysis to characterize evolutionary
6 and plastic responses to environmental change: a case study of a shift toward earlier migration date in
7 sockeye salmon. *The American Naturalist*, **178**, 755-773, doi:10.1086/662669
- 8 37. Winder, M., and D. E. Schindler, 2004: Climate change uncouples trophic interactions in an aquatic
9 ecosystem. *Ecology*, **85**, 2100-2106, doi:10.1890/04-0151
- 10 38. Mohseni, O., T. R. Erickson, and H. G. Stefan, 1999: Sensitivity of stream temperatures in the United States to
11 air temperatures projected under a global warming scenario. *Water Resources Research*, **35**, 3723-3733,
12 doi:10.1029/1999WR900193. [Available online at
13 <http://onlinelibrary.wiley.com/doi/10.1029/1999WR900193/pdf>]
- 14 39. Rieman, B. E., and D. J. Isaak, 2010: Climate change, aquatic ecosystems, and fishes in the Rocky Mountain
15 West: implications and alternatives for management. Gen. Tech. Rep. RMRS-GTR-250, 46 pp., U.S.
16 Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. [Available
17 online at [http://www.regions.noaa.gov/western/wp-](http://www.regions.noaa.gov/western/wp-content/uploads/2011/08/2010_USFW_Climate_Change_Aquatic_Ecosystems_and_Fishes.pdf)
18 [content/uploads/2011/08/2010_USFW_Climate_Change_Aquatic_Ecosystems_and_Fishes.pdf](http://www.regions.noaa.gov/western/wp-content/uploads/2011/08/2010_USFW_Climate_Change_Aquatic_Ecosystems_and_Fishes.pdf)]
- 19 40. Wenger, S. J., D. J. Isaak, C. H. Luce, H. M. Neville, K. D. Fausch, J. B. Dunham, D. C. Dauwalter, M. K. Young,
20 M. M. Elsner, B. E. Rieman, A. F. Hamlet, and J. E. Williams, 2011: Flow regime, temperature, and biotic
21 interactions drive differential declines of trout species under climate change. *Proceedings of the National*
22 *Academy of Science of the United States of America*, **108**, 14175–14180, doi:10.1073/pnas.1103097108.
23 [Available online at <http://www.pnas.org/content/108/34/14175.full.pdf+html>]
- 24 41. Slaughter, R. A., A. F. Hamlet, D. Huppert, J. Hamilton, and P. W. Mote, 2010: Mandates vs markets:
25 addressing over-allocation of Pacific Northwest River Basins. *Water Policy*, **12**, 305-317,
26 doi:10.2166/wp.2009.152
- 27 42. Hamlet, A. F., 2011: Assessing water resources adaptive capacity to climate change impacts in the Pacific
28 Northwest region of North America. *Hydrology and Earth System Sciences*, **15**, 1427-1443, doi:10.5194/hess-
29 15-1427-2011. [Available online at [http://www.hydrol-earth-syst-sci.net/15/1427/2011/hess-15-1427-](http://www.hydrol-earth-syst-sci.net/15/1427/2011/hess-15-1427-2011.html)
30 [2011.html](http://www.hydrol-earth-syst-sci.net/15/1427/2011/hess-15-1427-2011.html)]
- 31 43. Miles, E. L., A. K. Snover, A. F. Hamlet, B. Callahan, and D. Fluharty, 2000: Pacific Northwest Regional
32 Assessment: the Impacts of Climate Variability and Climate Change on the Water Resources of the Columbia
33 River Basin. *JAWRA Journal of the American Water Resources Association*, **36**, 399-420. [Available online at
34 <http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2000.tb04277.x/pdf>]
- 35 44. EPA, 2010: Climate Change Vulnerability Assessments: A Review of Water Utility Practices. EPA 800-R-10-001,
36 32 pp., U.S. Environmental Protection Agency, Washington, D.C. [Available online at
37 [http://water.epa.gov/scitech/climatechange/upload/Climate-Change-Vulnerability-Assessments-Sept-](http://water.epa.gov/scitech/climatechange/upload/Climate-Change-Vulnerability-Assessments-Sept-2010.pdf)
38 [2010.pdf](http://water.epa.gov/scitech/climatechange/upload/Climate-Change-Vulnerability-Assessments-Sept-2010.pdf)];
- 39 King County Department of Natural Resources and Parks, 2009: Synthesis of the Regional Water Supply
40 Planning Process. Final Report, 115 pp, Seattle, WA. [Available online at [http://www.govlink.org/regional-](http://www.govlink.org/regional-water-planning/docs/process-synthesis-report/main-report.pdf)
41 [water-planning/docs/process-synthesis-report/main-report.pdf](http://www.govlink.org/regional-water-planning/docs/process-synthesis-report/main-report.pdf)];
- 42 Palmer, R. N., and M. Hahn, 2002: The impacts of climate change on Portland's water supply: an investigation
43 of potential hydrologic and management impacts on the Bull Run system. Report prepared for the Portland
44 Water Bureau, 139 pp., University of Washington, Seattle, WA. [Available online at
45 <http://www.cses.washington.edu/db/pdf/palmerhahnportland111.pdf>]

- 1 45. Vano, J. A., N. Voisin, L. Cuo, A. F. Hamlet, M. M. G. Elsner, R. N. Palmer, A. Polebitski, and D. P. Lettenmaier,
2 2010: Climate change impacts on water management in the Puget Sound region, Washington State, USA.
3 *Climatic Change*, **102**, 261-286, doi:10.1007/s10584-010-9846-1
- 4 46. Yates, D., H. Galbraith, D. Purkey, A. Huber-Lee, J. Sieber, J. West, S. Herrod-Julius, and B. Joyce, 2008: Climate
5 warming, water storage, and Chinook salmon in California's Sacramento Valley. *Climatic Change*, **91**, 335-350,
6 doi:10.1007/s10584-008-9427-8
- 7 47. Goniea, T. M., M. L. Keefer, T. C. Bjornn, C. A. Peery, D. H. Bennett, and L. C. Stuehrenberg, 2006: Behavioral
8 thermoregulation and slowed migration by adult fall Chinook salmon in response to high Columbia River
9 water temperatures. *Transactions of the American Fisheries Society*, **135**, 408-419, doi:10.1577/T04-113.1;
10 High, B., C. A. Peery, and D. H. Bennett, 2006: Temporary staging of Columbia River summer steelhead in
11 coolwater areas and its effect on migration rates. *Transactions of the American Fisheries Society*, **135**, 519-
12 528, doi:10.1577/T04-224.1
- 13 48. Atwater, B. F., M.-R. Satoko, S. Kenji, T. Yoshinobu, U. Kazue, and D. K. Yamaguchi, 2005: *The Orphan Tsunami*
14 *of 1700—Japanese Clues to a Parent Earthquake in North America*. U.S. Geological Survey Professional Paper
15 1707. United States Geological Survey and the University of Washington Press, 144 pp;
16 Atwater, B. F., and D. K. Yamaguchi, 1991: Sudden, probably coseismic submergence of Holocene trees and
17 grass in coastal Washington State. *Geology*, **19**, 706-709, doi:10.1130/0091-
18 7613(1991)019<0706:SPCSOH>2.3.CO;2. [Available online at
19 <http://geology.geoscienceworld.org/content/19/7/706.full.pdf+html>]
- 20 49. NRC, 2012: *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*.
21 National Research Council, Committee on Sea Level Rise in California, Oregon, Washington, Board on Earth
22 Sciences Resources, Ocean Studies Board, Division on Earth Life Studies The National Academies Press, 201
23 pp. [Available online at http://www.nap.edu/openbook.php?record_id=13389]
- 24 50. Chapman, J. S., and T. I. Melbourne, 2009: Future Cascadia megathrust rupture delineated by episodic tremor
25 and slip. *Geophysical Research Letters*, **36**, L22301, doi:10.1029/2009gl040465. [Available online at
26 <http://onlinelibrary.wiley.com/doi/10.1029/2009GL040465/pdf>]
- 27 51. UNAVCO: Plate Boundary Observatory (PBO) GPS Data Products. [Available online at
28 <http://pbo.unavco.org/data/gps>]
- 29 52. Zervas, C., 2001: Sea Level Variations of the United States 1854–1999, NOAA Technical Report NOS CO-OPS
30 36, 80 pp., National Oceanic and Atmospheric Administration, Silver Spring, Maryland. [Available online at
31 <http://tidesandcurrents.noaa.gov/publications/techrpt36doc.pdf>]
- 32 53. Hickey, B. M., and N. S. Banas, 2008: Why is the northern end of the California current system so productive.
33 *Oceanography*, **21**, 90-107, doi:10.5670/oceanog.2008.07#sthash.38aTxCuz.dpuf
- 34 54. Deser, C., A. S. Phillips, and M. A. Alexander, 2010: Twentieth century tropical sea surface temperature trends
35 revisited. *Geophysical Research Letters*, **37**, L10701, doi:10.1029/2010GL043321;
- 36 Field, D., D. Cayan, and F. Chavez, 2006: Secular warming in the California current and North Pacific. *California*
37 *cooperative oceanic fisheries investigations report*, **47**, 92-108. [Available online at
38 http://www.calcofi.org/publications/calcofireports/v47/Vol_47_Field_Warming_In_The_Ca_Current.pdf]
- 39 55. Johnstone, J. A., and T. E. Dawson, 2010: Climatic context and ecological implications of summer fog decline
40 in the coast redwood region. *Proceedings of the National Academy of Sciences*, **107**, 4533-4538,
41 doi:10.1073/pnas.0915062107. [Available online at
42 <http://www.pnas.org/content/107/10/4533.full.pdf+html>]

- 1 56. Feely, R. A., S. R. Alin, J. Newton, C. L. Sabine, M. Warner, A. Devol, C. Krembs, and C. Maloy, 2010: The
2 combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an
3 urbanized estuary. *Estuarine, Coastal and Shelf Science*, **88**, 442-449, doi:10.1016/j.ecss.2010.05.004,
- 4 57. Feely, R. A., T. Klinger, J. A. Newton, and M. Chadsey, Eds., 2012: *Scientific Summary of Ocean Acidification in*
5 *Washington State Marine Waters. NOAA OAR Special Report #12-01-016*. National oceanic and Atmospheric
6 Administration, Office of Oceanic and Atmospheric Research, 176 pp. [Available online at
7 <https://fortress.wa.gov/ecy/publications/SummaryPages/1201016.html>]
- 8 58. Feely, R. A., C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales, 2008: Evidence for upwelling of
9 corrosive "acidified" water onto the continental shelf. *Science*, **320**, 1490-1492, doi:10.1126/science.1155676.
10 [Available online at <http://www.sciencemag.org/content/320/5882/1490.short>]
- 11 59. Mote, P. W., D. Gavin, and A. Huyer, 2010: Climate change in Oregon's land and marine environments.
12 Oregon Climate Assessment Report, 46 pp, Corvallis, OR. [Available online at [http://occri.net/wp-](http://occri.net/wp-content/uploads/2011/04/chapter1ocar.pdf)
13 [content/uploads/2011/04/chapter1ocar.pdf](http://occri.net/wp-content/uploads/2011/04/chapter1ocar.pdf)]
- 14 60. Gemmrich, J., B. Thomas, and R. Bouchard, 2011: Observational changes and trends in northeast Pacific wave
15 records. *Geophysical Research Letters*, **38**, L22601, doi:10.1029/2011GL049518. [Available online at
16 <http://onlinelibrary.wiley.com/doi/10.1029/2011GL049518/pdf>];
17 Ruggiero, P., P. D. Komar, and J. C. Allan, 2010: Increasing wave heights and extreme value projections: The
18 wave climate of the US Pacific Northwest. *Coastal Engineering*, **57**, 539-552,
19 doi:10.1016/j.coastaleng.2009.12.005. [Available online at
20 http://www.noaaideacenter.org/slr/docs/Ruggiero_etal_CENG_2010_published.pdf]
- 21 61. Wang, M., J. E. Overland, and N. A. Bond, 2010: Climate projections for selected large marine ecosystems.
22 *Journal of Marine Systems*, **79**, 258-266, doi:10.1016/j.jmarsys.2008.11.028
- 23 62. Strauss, B. H., R. Ziemlinski, J. L. Weiss, and J. T. Overpeck, 2012: Tidally adjusted estimates of topographic
24 vulnerability to sea level rise and flooding for the contiguous United States. *Environmental Research Letters*,
25 **7**, 014033, doi:10.1088/1748-9326/7/1/014033
- 26 63. Drut, M., and J. B. Buchanan, 2000: U.S. National Shorebird Management Plan: Northern Pacific Coast
27 Working Group Regional Management Plan U.S. Fish and Wildlife Service, Portland, OR;
- 28 Krueger, K. L., K. B. Pierce, Jr., T. Quinn, and D. E. Penttila, 2010: Anticipated Effects of Sea Level Rise in Puget
29 Sound on Two Beach-Spawning Fishes. *Puget Sound Shorelines and the Impacts of Armoring—Proceedings of*
30 *a State of the Science Workshop, May 2009: U.S. Geological Survey Scientific Investigations Report 2010-5254*,
31 H. Shipman, M. N. Dethier, G. Gelfenbaum, K. L. Fresh, and R. S. Dinicola, Eds., U.S. Geological Survey, 171-
32 178. [Available online at <http://pubs.usgs.gov/sir/2010/5254/pdf/sir20105254.pdf>]
- 33 64. Ries, J. B., A. L. Cohen, and D. C. McCorkle, 2009: Marine calcifiers exhibit mixed responses to CO₂-induced
34 ocean acidification. *Geology*, **37**, 1131-1134, doi:10.1130/G30210A.1. [Available online at
35 <http://geology.gsapubs.org/content/37/12/1131.full.pdf+html>]
- 36 65. Hickey, B. M., and N. S. Banas, 2003: Oceanography of the US Pacific Northwest coastal ocean and estuaries
37 with application to coastal ecology. *Estuaries and Coasts*, **26**, 1010-1031, doi:10.1007/BF02803360;
- 38 NOAA, cited 2012: Coastal Upwelling. NOAA's Northwest Fisheries Science Center. [Available online at
39 <http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/db-coastal-upwelling-index.cfm>]
- 40 66. Hollowed, A. B., S. R. Hare, and W. S. Wooster, 2001: Pacific Basin climate variability and patterns of
41 Northeast Pacific marine fish production. *Progress in Oceanography*, **49**, 257-282, doi:10.1016/S0079-
42 6611(01)00026-X

- 1 67. Tillmann, P., and D. Siemann, 2011: Climate Change Effects and Adaptation Approaches in Marine and Coastal
2 Ecosystems of the North Pacific Landscape Conservation Cooperative Region. Phase 1 Draft Final Report. , 257
3 pp., National Wildlife Federation-Pacific Region, U.S. Fish and Wildlife Service Region 1 Science Applications
4 Program, Seattle, WA. [Available online at [http://www.nwf.org/~media/PDFs/Global-
5 Warming/Reports/NPLCC%20Reports/NPLCC_Marine_Climate-Effects_Draft-
6 Final_FullReport.pdf?dmc=1&ts=20130418T1109311898](http://www.nwf.org/~media/PDFs/Global-Warming/Reports/NPLCC%20Reports/NPLCC_Marine_Climate-Effects_Draft-Final_FullReport.pdf?dmc=1&ts=20130418T1109311898)]
- 7 68. Percy, W. G., 2002: Marine nekton off Oregon and the 1997-98 El Niño. *Progress in Oceanography*, **54**, 399-
8 403, doi:10.1016/S0079-6611(02)00060-5;
- 9 Peterson, W. T., and F. B. Schwing, 2003: A new climate regime in northeast Pacific ecosystems. *Geophysical
10 Research Letters*, **30**, 1896, doi:10.1029/2003GL017528. [Available online at
11 <http://onlinelibrary.wiley.com/doi/10.1029/2003GL017528/pdf>]
- 12 69. Moore, S. K., N. J. Mantua, B. M. Hickey, and V. L. Trainer, 2009: Recent trends in paralytic shellfish toxins in
13 Puget Sound, relationships to climate, and capacity for prediction of toxic events. *Harmful Algae*, **8**, 463-477,
14 doi:10.1016/j.hal.2008.10.003;
- 15 —, 2010: The relative influences of El Niño-Southern Oscillation and Pacific Decadal Oscillation on paralytic
16 shellfish toxin accumulation in Pacific northwest shellfish. *Limnology and Oceanography*, **55**, 2262-2274,
17 doi:10.4319/lo.2010.55.6.2262;
- 18 Moore, S. K., N. J. Mantua, and E. P. Salathé, Jr. , 2011: Past trends and future scenarios for environmental
19 conditions favoring the accumulation of paralytic shellfish toxins in Puget Sound shellfish. *Harmful Algae*, **10**,
20 521-529, doi:10.1016/j.hal.2011.04.004
- 21 70. Dyson, K., and D. D. Huppert, 2010: Regional economic impacts of razor clam beach closures due to harmful
22 algal blooms (HABs) on the Pacific coast of Washington. *Harmful Algae*, **9**, 264-271,
23 doi:10.1016/j.hal.2009.11.003. [Available online at
24 <http://www.sciencedirect.com/science/article/pii/S1568988309001279>]
- 25 71. Sun, J., D. A. Hutchins, Y. Feng, E. L. Seubert, D. A. Caron, and F.-X. Fua, 2011: Effects of changing pCO₂ and
26 phosphate availability on domoic acid production and physiology of the marine harmful bloom diatom
27 *Pseudo-nitzschia multiseries*. *Limnology and Oceanography*, **56**, 12, doi:10.4319/lo.2011.56.3.0829;
- 28 Tatters, A. O., F.-X. Fu, and D. A. Hutchins, 2012: High CO₂ and silicate limitation synergistically increase the
29 toxicity of *Pseudo-nitzschia fraudulenta*. *PLoS ONE*, **7**, e32116. [Available online at
30 [http://www.plosone.org/article/abstract?uri=info%3Adoi%2F10.1371%2Fjournal.pone.0032116&
31 epresentation=PDF](http://www.plosone.org/article/abstract?uri=info%3Adoi%2F10.1371%2Fjournal.pone.0032116&representation=PDF)]
- 32 72. King County Department of Natural Resources and Parks, 2008: Vulnerability of Major Wastewater Facilities
33 to Flooding from Sea-Level Rise, 13 pp., King County (WA) Department of Natural Resources and Parks,
34 Wastewater Treatment Division, Seattle, Washington
- 35 73. Fleming, P., and J. Rufo-Hill, 2012: Seattle Public Utilities and Sea Level Rise, Summary Document
- 36 74. Simpson, D. P., 2011: City of Olympia: Engineered Response to Sea Level Rise. Technical Report prepared for
37 the City of Olympia Public Works Department, Planning & Engineering, 112 pp., Coast & Harbor Engineering,
38 Edmonds, WA. [Available online at
39 [http://olympiawa.gov/community/sustainability/~media/Files/PublicWorks/Sustainability/Sea%20Level%20
40 Rise%20Response%20Technical%20Report.ashx](http://olympiawa.gov/community/sustainability/~media/Files/PublicWorks/Sustainability/Sea%20Level%20Rise%20Response%20Technical%20Report.ashx)]
- 41 75. WSDOT, 2011: Climate Impacts Vulnerability Assessment, 70 pp., Washington State Department of
42 Transportation. [Available online at [http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-
43 EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf](http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf)]
- 44 76. MacArthur, J., P. Mote, J. Ideker, M. Figliozzi, and M. Lee, 2012: Climate Change Impact Assessment for
45 Surface Transportation in the Pacific Northwest and Alaska. WA-RD 772.1. OTREC-RR-12-01, 272 pp.,

- 1 Washington State Department of Transportation, Oregon Transportation Research and Education Consortium,
2 Olympia, WA
- 3 77. Mote, P. W., A. Petersen, S. Reeder, H. Shipman, and L. C. Whitley-Binder, 2008: Sea Level Rise in the Coastal
4 Waters of Washington State. Report prepared by the Climate Impacts Group, Center for Science in the Earth
5 System Joint Institute for the Study of the Atmosphere and Oceans, 11 pp., Center for Science in the Earth
6 System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle,
7 Washington; Lacey, Washington. [Available online at
8 <http://www.cses.washington.edu/db/pdf/moteetalslr579.pdf>]
- 9 78. Zervas, C. E., 2005: Response of extreme storm tide levels to long-term sea level change. *OCEANS, 2005.*
10 *Proceedings of MTS/IEEE*, Washington, D.C., 2501-2506 pp. [Available online at
11 <http://tidesandcurrents.noaa.gov/est/050415-53.pdf>]
- 12 79. Seattle Public Utilities, 2010: Sea level rise, Year 2100 (map). Scale not given. City of Seattle, Seattle, WA
- 13 80. Good, J. W., 2000: Ch. 33: Summary and current status of Oregon's estuarine ecosystems. *State of the*
14 *Environment Report 2000*, Oregon Progress Board, 33-44. [Available online at
15 http://www.dfw.state.or.us/conservationstrategy/docs/climate_change/ClimateChangeEstuaries_Fact_Sheet
16 [.pdf](http://www.dfw.state.or.us/conservationstrategy/docs/climate_change/ClimateChangeEstuaries_Fact_Sheet.pdf)];
- 17 WDNR, 1998: *Our changing nature: natural resource trends in Washington State*. Washington Department of
18 Natural Resources, 75 pp
- 19 81. Fresh, K., M. Dethier, C. Simenstad, M. Logsdon, H. Shipman, C. Tanner, T. Leschine, T. Mumford, G.
20 Gelfenbaum, R. Shuman, and J. Newton, 2011: Implications of Observed Anthropogenic Changes to the
21 Nearshore Ecosystems in Puget Sound. Technical Report 2011-03, 34 pp., Puget Sound Nearshore Ecosystem
22 Restoration Project. [Available online at
23 http://www.pugetsoundnearshore.org/technical_papers/implications_of_observed_ns_change.pdf]
- 24 82. Huppert, D. D., A. Moore, and K. Dyson, 2009: Coasts: Impacts of Climate Change on the Coasts of
25 Washington State. *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a*
26 *Changing Climate*, Climate Impacts Group, University of Washington, 285-309
- 27 83. Washington State Blue Ribbon Panel on Ocean Acidification: *Ocean Acidification: From Knowledge to Action.*
28 *Washington State's Strategic Response*. Publication no. 12-01-015. State of Washington, Department of
29 Ecology. [Available online at <https://fortress.wa.gov/ecy/publications/publications/1201015.pdf>]
- 30 84. USFWS, 2010: Rising to the Urgent Challenge: Strategic Plan for Responding to Accelerating Climate Change,
31 32 pp., U.S. Fish and Wildlife Service, U.S. Department of the Interior, Washington, D.C. [Available online at
32 <http://www.fws.gov/home/climatechange/pdf/CCStrategicPlan.pdf>]
- 33 85. Littell, J. S., D. L. Peterson, C. I. Millar, and K. A. O'Halloran, 2012: US National Forests adapt to climate change
34 through Science-Management partnerships. *Climatic Change*, **110**, 269-296, doi:10.1007/s10584-011-0066-0
- 35 86. McKenzie, D., D. L. Peterson, and J. J. Littell, 2008: Global warming and stress complexes in forests of western
36 North America. *Developments in Environmental Sciences*, **8**, 319-337, doi:10.1016/S1474-8177(08)00015-6.
37 [Available online at http://www.fs.fed.us/psw/publications/4451/psw_2009_4451-001_319-338.pdf]
- 38 87. McKenzie, D., Z. Gedalof, D. L. Peterson, and P. Mote, 2004: Climatic change, wildfire, and conservation.
39 *Conservation Biology*, **18**, 890-902, doi:10.1111/j.1523-1739.2004.00492.x. [Available online at
40 <http://onlinelibrary.wiley.com/doi/10.1111/j.1523-1739.2004.00492.x/pdf>]
- 41 88. Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam, 2006: Warming and earlier spring increase
42 western U.S. forest wildfire activity. *Science*, **313**, 940-943, doi:DOI 10.1126/science.1128834

- 1 89. Carroll, A. L., S. W. Taylor, J. Régnière, and L. Safranyik, 2003: Effect of climate change on range expansion by
2 the mountain pine beetle in British Columbia. Natural Resources Canada, Information Report BC-X-399.
3 *Mountain Pine Beetle Symposium: Challenges and Solutions*, Kelowna, Victoria, BC, Utah State University,
4 223-232 pp;
- 5 Oneil, E. E., 2006: Developing stand density thresholds to address mountain pine beetle susceptibility in
6 eastern Washington forests, College of Forest Resources, University of Wisconsin, 99 pp. [Available online at
7 http://www.ruraltech.org/pubs/theses/oneil/phd/oneil_dissertation.pdf]
- 8 90. Logan, J. A., and J. A. Powell, 2001: Ghost forests, global warming, and the mountain pine beetle (Coleoptera:
9 Scolytidae). *American Entomologist*, **47**, 160-173. [Available online at
10 <http://digitalcommons.usu.edu/barkbeetles/187/>]
- 11 91. Bentz, B. J., J. Régnière, C. J. Fettig, E. M. Hansen, J. L. Hayes, J. A. Hicke, R. G. Kelsey, J. F. Negrón, and S. J.
12 Seybold, 2010: Climate change and bark beetles of the Western United States and Canada: direct and indirect
13 effects. *BioScience*, **60**, 602-613, doi:Doi 10.1525/Bio.2010.60.8.6. [Available online at
14 <http://www.bioone.org/doi/pdf/10.1525/bio.2010.60.8.6>]
- 15 92. Hicke, J. A., J. A. Logan, J. Powell, and D. S. Ojima, 2006: Changing temperatures influence suitability for
16 modeled mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the western United States. *Journal*
17 *of Geophysical Research*, **111**, G02019, doi:10.1029/2005JG000101
- 18 93. Mitchell, R. G., and P. Buffam, 2001: Patterns of long-term balsam woolly adelgid infestations and effects in
19 Oregon and Washington. *Western Journal of Applied Forestry*, **16**, 121-126
- 20 94. Rehfeldt, G. E., 2006: A Spline Model of Climate for the Western United States. General Technical Report
21 RMRS-GTR-165, 21 pp., US Department of Agriculture, Forest Service U.S. Department of Agriculture, Forest
22 Service, Rocky Mountain Research Station Ft. Collins, Colorado, USA. [Available online at
23 http://www.fs.fed.us/rm/pubs/rmrs_gtr165.pdf]
- 24 95. McKenney, D. W., J. H. Pedlar, R. B. Rood, and D. Price, 2011: Revisiting projected shifts in the climate
25 envelopes of North American trees using updated general circulation models. *Global Change Biology*, **17**,
26 2720-2730, doi:10.1111/j.1365-2486.2011.02413.x. [Available online at
27 <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2011.02413.x/pdf>]
- 28 96. Eidenshink, J., B. Schwind, K. Brewer, Z. Zhu, B. Quayle, and S. Howard, 2007: A project for monitoring trends
29 in burn severity. *Fire Ecology*, **3**, 3-21. [Available online at
30 <http://fireecology.org/docs/Journal/pdf/Volume03/Issue01/003.pdf>]
- 31 97. USGS, cited 2012: National Monitoring Trends in Burn Severity (MTBS) Burned Area Boundaries Dataset. U.S.
32 Geological Survey. [Available online at [http://www.mtbs.gov/compositfire/mosaic/bin-](http://www.mtbs.gov/compositfire/mosaic/bin-release/burnedarea.html)
33 [release/burnedarea.html](http://www.mtbs.gov/compositfire/mosaic/bin-release/burnedarea.html)]
- 34 98. USFS, cited 2012: Forest Service, Insect & Disease Detection Survey Data Explorer. U.S. Department of
35 Agriculture, U.S. Forest Service. [Available online at <http://foresthealth.fs.usda.gov/portal>]
- 36 99. NRC, 2011: Ch. 5: Impacts in the next few decades and coming centuries. *Climate Stabilization Targets:*
37 *Emissions, Concentrations, and Impacts over Decades to Millennia*, Committee on Stabilization Targets for
38 Atmospheric Greenhouse Gas Concentration, The National Academies Press, 298
- 39 100. Bailey, R. G., 1995: Description of the ecoregions of the United States (2nd ed.). 1995. Misc. Pub. No. 1391.
40 U.S. Department of Agriculture, Forest Service
- 41 101. Régnière, J., and B. Bentz, 2007: Modeling cold tolerance in the mountain pine beetle, *Dendroctonus*
42 *ponderosae*. *Journal of Insect Physiology*, **53**, 559-572, doi:10.1016/j.jinsphys.2007.02.007
- 43 102. Safranyik, L., D. M. Shrimpton, and H. S. Whitney, 1975: An interpretation of the interaction between
44 *lodgepole pine*, the mountain pine beetle and its associated blue stain fungi in western Canada. *Management*

- 1 of Lodgepole Pine Ecosystems Symposium Proceedings, Pullman, Washington, Washington State University
2 Cooperative Extension Service 406-428 pp
- 3 103. Lenihan, J. M., D. Bachelet, R. P. Neilson, and R. Drapek, 2008: Simulated response of conterminous United
4 States ecosystems to climate change at different levels of fire suppression, CO₂ emission rate, and growth
5 response to CO₂. *Global and Planetary Change*, **64**, 16-25, doi:10.1016/j.gloplacha.2008.01.006
- 6 104. Rogers, B. M., R. P. Neilson, R. Drapek, J. M. Lenihan, J. R. Wells, D. Bachelet, and B. E. Law, 2011: Impacts of
7 climate change on fire regimes and carbon stocks of the US Pacific Northwest. *Journal of Geophysical*
8 *Research*, **116**, G03037, doi:10.1029/2011JG001695. [Available online at
9 http://terraweb.forestry.oregonstate.edu/pubs/Rogers_2011.pdf]
- 10 105. Rehfeldt, G. E., N. L. Crookston, C. Sáenz-Romero, and E. M. Campbell, 2012: North American vegetation
11 model for land-use planning in a changing climate: a solution to large classification problems. *Ecological*
12 *Applications*, **22**, 119-141, doi:10.1890/11-0495.1
- 13 106. Karl, T. R., J. T. Melillo, and T. C. Peterson, Eds., 2009: *Global Climate Change Impacts in the United States*.
14 Cambridge University Press, 189 pp. [Available online at
15 <http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts>]
- 16 107. Washington State Department of Ecology, 2011: Columbia River Basin 2011 Long Term Water Supply and
17 Demand Forecast. Publication No. 11-12-011, 54 pp., Washington State Department of Ecology, Washington
18 State University, Washington Department of Fish and Wildlife, Olympia, WA. [Available online at
19 <https://fortress.wa.gov/ecy/publications/summarypages/1112011.html>]
- 20 108. Capalbo, S., J. Julian, T. Maness, and E. Kelly, 2010: Ch. 8: Toward assessing the economic impacts of climate
21 change on Oregon. *The Oregon Climate Assessment Report*, K. D. Dello, and P. W. Mote, Eds., Oregon Climate
22 Change Research Institute, College of Oceanic and Atmospheric Sciences, Oregon State University, 363-396
- 23 109. Millar, C. I., N. L. tephenson, and S. L. Stephens, 2007: Climate change and forests of the future: managing in
24 the face of uncertainty. *Ecological Applications*, **17**, 2145-2151, doi:10.1890/06-1715.1. [Available online at
25 <http://www.jstor.org/stable/pdfplus/40061917.pdf>];
- 26 Peterson, D. L., C. I. Millar, L. A. Joyce, M. J. Furniss, J. E. Halofsky, R. P. Neilson, and T. L. Morelli, 2011:
27 Responding to climate change on national forests: a guidebook for developing adaptation options. General
28 Technical Report PNW-GTR-855, 118 pp., U.S. Department of Agriculture, U.S Forest Service, Pacific
29 Northwest Research Station
- 30 110. Peterson, D. L., and M. C. Johnson, 2007: Science-based strategic planning for hazardous fuel treatment. *Fire*
31 *Management Today*, **67**, 13-18;
- 32 Prichard, S. J., D. L. Peterson, and K. Jacobson, 2010: Fuel treatments reduce the severity of wildfire effects in
33 dry mixed conifer forest, Washington, USA. *Canadian Journal of Forest Research*, **40**, 1615-1626
- 34 111. Chmura, D. J., P. D. Anderson, G. T. Howe, C. A. Harrington, J. E. Halofsky, D. L. Peterson, D. C. Shaw, and J. B.
35 St Clair, 2011: Forest responses to climate change in the northwestern United States: Ecophysiological
36 foundations for adaptive management. *Forest Ecology and Management*, **261**, 1121-1142,
37 doi:10.1016/j.foreco.2010.12.040
- 38 112. Brady, M., and J. Taylor, 2011: Agriculture's Contribution to Washington's Economy, IMPACT Center Fact
39 Sheet, 2 pp., Washington State University, Pullman, WA;
- 40 ISDA, 2012: Idaho Agriculture Facts 2011. Idaho State Department of Agriculture. [Available online at
41 <http://www.agri.idaho.gov/Categories/Marketing/Documents/English%20Final%202011%20-%20for%20emailing.pdf>];
42

- 1 ODA, 2009: Oregon Agriculture, Oregon Agripedia, 252 pp., Oregon Agriculture, Oregon Agripedia. [Available
2 online at <http://www.oregon.gov/ODA/docs/pdf/pubs/2009agripedia.pdf>.];
- 3 U.S. Government Revenue, cited 2012: Comparison of State and Local Government Revenue and Debt in the
4 United States Fiscal Year 2010 Christopher Chantrill. [Available online at
5 http://www.usgovernmentrevenue.com/state_rev_summary.php?chart=Z0&year=2010&units=d&rank=a]
- 6 113. Kok, H., R. I. Papendick, and K. E. Saxton, 2009: STEEP: Impact of long-term conservation farming research
7 and education in Pacific Northwest wheatlands. *Journal of Soil and Water Conservation*, **64**, 253-264,
8 doi:10.2489/jswc.64.4.253. [Available online at <http://www.jswconline.org/content/64/4/253.full.pdf+html>];
- 9 Mulla, D. J., 1986: Distribution of slope steepness in the Palouse region of Washington. *Soil Science Society of
10 America Journal*, **50**, 1401-1406, doi:10.2136/sssaj1986.03615995005000060006x
- 11 114. Stöckle, C. O., R. L. Nelson, S. Higgins, J. Brunner, G. Grove, R. Boydston, M. Whiting, and C. Kruger, 2010:
12 Assessment of climate change impact on Eastern Washington agriculture. *Climatic Change*, **102**, 77-102,
13 doi:10.1007/s10584-010-9851-4
- 14 115. Hatfield, J. L., K. J. Boote, B. A. Kimball, L. H. Ziska, R. C. Izaurralde, D. Ort, A. M. Thomson, and D. Wolfe, 2011:
15 Climate impacts on agriculture: Implications for crop production. *Agronomy Journal*, **103**, 351-370, doi:DOI
16 10.2134/agronj2010.0303
- 17 116. Parmesan, C., 2006: Ecological and evolutionary responses to recent climate change. *Annual review of
18 ecology, Evolution, and Systematics*, **37**, 637-669. [Available online at
19 <http://www.jstor.org/stable/pdfplus/30033846.pdf>];
- 20 Trumble, J., and C. Butler, 2009: Climate change will exacerbate California's insect pest problems. *California
21 Agriculture*, **63**, 73-78, doi:10.3733/ca.v063n02p73
- 22 117. Juroszek, P., and A. Von Tiedemann, 2013: Plant pathogens, insect pests and weeds in a changing global
23 climate: a review of approaches, challenges, research gaps, key studies and concepts. *The Journal of
24 Agricultural Science*, **151**, 163-188, doi:10.1017/S0021859612000500. [Available online at
25 http://journals.cambridge.org/download.php?file=%2FAGS%2FAGS151_02%2FS0021859612000500a.pdf&code=e45daa08fa3264c4a8274c4fdfabca59]
- 26
- 27 118. Alva, A. K., T. Hodges, R. A. Boydston, and H. P. Collins, 2002: Effects of irrigation and tillage practices on yield
28 of potato under high production conditions in the Pacific Northwest. *Communications in Soil Science and
29 Plant Analysis*, **33**, 1451-1460, doi:10.1081/CSS-120004293
- 30 119. Jones, G. V., 2005: Climate Change in the Western United States Growing Regions. *Acta Hort. (ISHS). VII
31 International Symposium on Grapevine Physiology and Biotechnology*, L. E. Williams, Ed., International Society
32 for Horticultural Science, 41-60. [Available online at http://www.actahort.org/books/689/689_2.htm]
- 33 120. Reilly, J. M., and D. Schimmelpfennig, 1999: Agricultural impact assessment, vulnerability, and the scope for
34 adaptation. *Climatic Change*, **43**, 745-788, doi:10.1023/A:1005553518621. [Available online at
35 <http://link.springer.com/content/pdf/10.1023%2FA%3A1005553518621>]
- 36 121. Oregon Department of Land Conservation and Development, 2010: The Oregon Climate Change Adaptation
37 Framework, Salem, OR. [Available online at
38 http://www.oregon.gov/ENERGY/GBLWRM/docs/Framework_Final_DLCD.pdf]
- 39 122. Dalton, M., P. Mote, J. A. Hicke, D. Lettenmaier, J. Littell, J. Newton, P. Ruggiero, and S. Shafer, 2012: A
40 workshop in risk-based framing of climate impacts in the Northwest: implementing the National Climate
41 Assessment risk-based approach (*unpublished*), 77. [Available online at
42 <http://downloads.usgcrp.gov/NCA/Activities/northwestncariskframingworkshop.pdf>]
- 43 123. CIG, 2009: The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a
44 Changing Climate. M. M. Elsner, J. Littell, and L. W. Binder, Eds., 414 pp., Climate Impacts Group, Center for

- 1 Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of
2 Washington, Seattle, Washington;
- 3 Oregon Climate Change Research Institute, 2010: Oregon Climate Assessment Report. K. D. Dello, and P. W.
4 Mote, Eds., College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR. [Available
5 online at http://occri.net/wp-content/uploads/2011/01/OCAR2010_v1.2.pdf]
- 6 124. Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A.
7 Sallenger, and J. Weiss, 2012: Global Sea Level Rise Scenarios for the United States National Climate
8 Assessment. NOAA Tech Memo OAR CPO-1, 37 pp., National Oceanic and Atmospheric Administration, Silver
9 Spring, MD. [Available online at http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf]
- 10 125. NIFC, 2012: Wildland Fire Summary and Statistics Annual Report 2011 59 pp., National Interagency Fire
11 Center, Boise, ID. [Available online at
12 http://www.predictiveservices.nifc.gov/intelligence/2011_statssumm/charts_tables.pdf]
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