Climate Change Effects and Adaptation Approaches for Ecosystems, Habitats, and Species

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A Compilation of the Scientific Literature for the North Pacific Landscape Conservation Cooperative Region

Executive Summaries for Marine & Coastal, Freshwater, and Terrestrial Systems

National Wildlife Federation

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Introduction

These executive summaries synthesize what is known – and not known – about climate change effects on marine and coastal, freshwater, and terrestrial ecosystems in the geographic extent of the North Pacific Landscape Conservation Cooperative (NPLCC). These summaries, and the reports of which they are a part, were funded by the U.S. Fish and Wildlife Service (FWS) Region 1 Science Applications Program (R1 SAP) and the NPLCC to help inform members of the NPLCC as they assess priorities and continue operations. Specifically, the marine & coastal and freshwater reports were funded by the U.S. FWS R1 SAP, and the terrestrial report was funded by the NPLCC.

Approach

The executive summaries synthesize the information contained in their respective reports on climate change effects, implications for ecosystems, habitats and species, and adaptation approaches for marine & coastal, freshwater, and terrestrial systems. To produce the reports, we drew from peer-reviewed studies, government reports, and publications from non-governmental organizations to summarize climate change and ecological literature on historical baselines, observed trends, future projections, policy and management options, and knowledge gaps. We reviewed major synthesis documents and seminal papers relevant to these topics in the marine & coastal, freshwater, and terrestrial environments in the NPLCC region, as well as resources providing information on broader regional and global trends and projections. Reference lists from these sources provided a starting point for acquiring additional depth and nuance on climate change impacts to the NPLCC's ecosystems, habitats, and species, and adaptation approaches. For topics lacking information in synthesis documents, seminal papers, and their reference lists, we searched scientific literature databases to find additional resources. Each report, including its executive summary, was reviewed by climate change scientists and subject-matter experts in the NPLCC region.

Because the reports strive to reflect the state of knowledge as represented in the literature, in most cases language is drawn directly from cited sources. By compiling and presenting verbatim material from relevant studies rather than paraphrasing or interpreting information from these sources, we sought to reduce inaccuracies and possible mis-characterizations by presenting data and findings in their original form. The content herein does not, therefore, necessarily reflect the views of National Wildlife Federation or the sponsors of this report. In general, verbatim and near verbatim materials are found in the main chapters of the report, while these executive summaries reflect our synthesis of multiple sources.

The executive summary for marine and coastal ecosystems is provided on p. 2-16, for freshwater ecosystems on p. 17-31, and for terrestrial ecosystems on p. 32-61. The full reports are available for download at http://www.northpacificlcc.org/Projects.

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Climate Change Effects & Adaptation Approaches in Marine & Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region: Executive Summary.

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This report provides a first-ever compilation of what is known—and not known—about climate change effects on marine and coastal ecosystems in the geographic extent of the North Pacific Landscape Conservation Cooperative (NPLCC). The U.S. Fish & Wildlife Service funded this report to help inform members of the newly established NPLCC as they assess priorities and begin operations. Production of this report was guided by University of Washington's Climate Impacts Group and information was drawn from more than 250 documents and more than 100 interviews.

Information in this report focuses on the NPLCC region, which extends from Kenai Peninsula in southcentral Alaska to Bodega Bay in northern California west of the Cascade Mountain Range and Coast Mountains. The region contains approximately 38,200 miles (~ 61,500 km)[1] of coastline and is home to iconic salmon and orca, a thriving fish and shellfish industry, and a wide range of habitats essential for the survival of fish, wildlife, birds, and other organisms. Many of these species, habitats, and ecosystems are already experiencing the effects of a changing climate.

Carbon dioxide, temperature, and precipitation

The atmospheric concentration of carbon dioxide (CO_2) is increasing in the earth's atmosphere, leading to increases in temperature, altered precipitation patterns, and consequent effects for biophysical processes, ecosystems, and species.

- **Atmospheric CO_2 concentrations have increased** to ~392 parts per million (ppm)[2] from the pre-industrial value of 278 ppm,[3] higher than any level in the past 650,000 years.[4] By 2100, CO_2 concentrations are projected to exceed ~600 ppm and may exceed 1000 ppm.[5] As CO_2 levels increase, a concomitant decline in ocean pH is projected for the NPLCC region,[6] hampering calcification processes for many calcifying organisms such as pteropods,[7] corals, and mollusks.[8]
- **Annual average temperatures increased** ~1-2°F (~0.6-1°C) from coastal British Columbia to northwestern California over the 20th century[9] and 3.4°F (~1.9°C) in Alaska from 1949 to 2009.[10] By 2100, the range of projected increases in the NPLCC region varies from 2.7 to 13°F (1.5-7.2°C), with the largest increases projected in Alaska.[11] These temperature increases will drive a rise in sea surface temperature and contribute to declining oxygen solubility in seawater,[12] species range shifts,[13] and potential uncoupling of phenological interdependencies among species.[14]
- **Seasonal precipitation varies but is generally wetter in winter.** Cool season precipitation (Oct-March) increased 2.17 inches (5.51 cm) in Alaska from the 1971-2000 to 1981-2010 period.[15] In Washington and Oregon winter precipitation (Jan-March) increased 2.47 inches (6.27 cm) from 1920 to 2000.[16] In California, winter precipitation increased between 1925 and 2008,[17] while in

British Columbia, both increases and decreases in winter precipitation were observed, depending on the time period studied.[18] Over the 21st Century, winter and fall precipitation are projected to increase 6-11% in BC and 8% in Washington and Oregon, while summer precipitation is projected to decrease (-8 to -13% in BC and -14% in WA and OR).[19] In southeast Alaska, however, warm season precipitation is projected to increase 5.7%.[20] Projected increases in winter rainfall, declining snow accumulation[21] and glacial extent,[22] and decreased summer precipitation (where occurring) will shift the frequency, volume,[23] and timing[24] of freshwater inflow to marine systems. Coastal areas with enhanced riverine input such as the Columbia River estuary will see greater stratification associated with increases in precipitation,[25] a condition that exacerbates low-oxygen conditions associated with harmful algal blooms and hypoxic waters.[26]

Impacts of climate change on marine and coastal systems

Increases in CO_2 and air temperature, combined with changing precipitation patterns, are already altering conditions and processes in marine and coastal ecosystems. These trends are projected to continue.

- **The oceans are increasing in acidity.** Increasing atmospheric CO_2 concentrations have caused global ocean pH to decline from 8.2 to 8.1 since pre-industrial times, increasing the ocean's acidity by approximately 26%.[27] pH declines in the NPLCC region are generally consistent with those observed globally, although some coastal areas such as Hood Canal (WA) report significantly lower pH (less than 7.6 in 2008).[28] By the end of this century, global surface water pH is projected to drop to approximately 7.8, increasing the ocean's acidity by about 150% relative to the beginning of the industrial era.[29] If atmospheric CO_2 levels reach 550 ppm, pH in the NPLCC region is projected to decline approximately 0.14 units[30] and the saturation state of aragonite will approach the critical threshold for undersaturation ($\Omega < 1$), below which the shells of some marine organisms may begin to dissolve or have difficulty forming.[31] Ocean water detrimental to shell-making has already been observed in shallow waters from Queen Charlotte Sound (BC) south to Baja California.[32] Aragonite-shelled pteropods, which are prey for salmon[33] and other fish,[34] appear particularly vulnerable to continued ocean acidification.[35]

- **Sea surface temperatures are rising.** Global mean sea surface temperature (SST) increased approximately 1.1°F (0.6°C) since 1950.[36] By 2050, an increase in winter SST of 1.8 to 2.9°F (1.0-1.6°C) is projected for most of the northern Pacific Ocean (compared to 1980-1999).[37] Warmer SST contributes to sea level rise, increased storm intensity, and greater stratification of the water column.[38] Increased SST is also associated with species range shifts,[39] altered nutrient availability and primary production,[40] and changes in algal, plankton and fish abundance in high-latitude oceans.[41]

- **Storm intensity and extreme wave heights are projected to increase.** Off the Oregon and Washington coasts, the heights of extreme storm waves increased as much as eight feet since the mid-1980s and deliver 65% more force when they come ashore.[42] During the 21st century, extra-tropical storms are likely to become more intense in the NPLCC region.[43] This will combine with higher sea levels to increase storm surges, the height of extreme waves[44] and the frequency of extreme events. [45] Increased extreme wave heights and more intense storms are projected to increase beach and bluff erosion[46] and lead to shoreline retreat,[47] loss of coastal habitat,[48] and damage to coastal infrastructure.[49]

- **Sea levels are rising, but the relative effect varies by location.** Since the end of the 19th century global sea levels have risen approximately 6.7 inches (17 cm).[50] In the NPLCC region, however, relative sea level change from 1898 to 2007 ranges from -0.67 to +0.23 inches/yr (-1.7 to 0.575 mm/yr).[51] Relative sea level rise in the NPLCC region is less than the global average at most monitoring stations because of localized increases in land elevation as a result of glacier recession, plate tectonics, and/or sediment accretion.[52] By the end of the 21st century, global sea level is projected to increase 5.1 to 70.0 inches (13-179 cm) compared to the end of the 20th century.[53] In the NPLCC region by 2100, relative change in sea levels are projected to range from -25.2 inches (-64 cm) to +55 inches (+139.7 cm).[54] Sea level is projected to rise in British Columbia and parts of Washington, Oregon, and California,[55] while sea level is projected to decline or remain relatively stable in southcentral and southeast Alaska and the northwest Olympic Peninsula (WA).[56] Rising sea level often results in loss of nearshore or coastal habitat[57] and harm to dependent species.[58]
- **Recent anomalous hypoxic events in the California Current Ecosystem may be characteristic of future change.** Severe hypoxia, corresponding to dissolved oxygen (DO) levels ranging from 0.21 to 1.57 mL/L, was observed off the central Oregon coast in 2002.[59] Dungeness crab surveys showed mortality rates of up to 75% in some regions during this period.[60] In 2006 off the Washington coast, the lowest DO concentrations to-date (<0.5 mL/L) were recorded at the inner shelf.[61] During an anoxic event in 2006 off the Oregon coast, surveys revealed the complete absence of all fish from rocky reefs[62] and near-complete mortality of macroscopic benthic invertebrates.[63] While anomalous events such as these are consistent with potential climate-induced changes in coastal systems, it has not been shown that climate change is the cause of the anomalies.[64]

Implications of climate change for ecosystems, habitats, and species

Climate change effects, independently or in combination, are fundamentally altering ocean ecosystems.[65] Effects on habitats (habitat loss and transition) and species (invasive species interactions, range shifts and phenological decoupling) are highlighted here.

Coastal Erosion and Habitat Loss

Rising sea-level and increases in storms and erosion are projected to result in significant habitat impacts. In Alaska, low-lying habitats critical to the productivity and welfare of coastal dependent species could be lost or degraded,[66] including staging areas that support millions of shorebirds, geese, and ducks.[67] As sea level rises along Puget Sound’s armored beach shorelines, most surf smelt spawning habitat is likely to be lost by 2100.[68] In Skagit Delta marshes (WA), the rearing capacity for threatened juvenile Chinook salmon is projected to decline by 211,000 fish with 18 inches (45 cm) of sea level rise.[69]

Habitat loss due to sea level rise is likely to vary substantially depending on geomorphology and other factors. In Washington and Oregon, analysis of coastal habitats under 27.3 inches (0.69 m) of sea level rise projects loss of two-thirds of low tidal areas in Willapa Bay and Grays Harbor and a loss of 11 to 56% of freshwater tidal marsh in Grays Harbor, Puget Sound, and Willapa Bay.[70] Much of these habitats are replaced by transitional marsh.[71] However, the Lower Columbia River may be fairly resilient to sea level rise because losses to low tidal, saltmarsh, and freshwater tidal habitats are minimized (-2%, -19%,

-11%, respectively), while gains in transitional areas are substantial (+160%).[72]

Invasive Species, Range Shifts, and Altered Phenology

Climate change will affect species in varying ways. Ocean acidification significantly and negatively impacts survival, calcification, growth and reproduction in many marine organisms, but thus far, has no significant effect on photosynthesis.[73] Among calcifying organisms, corals, calcifying algae, coccolithophores, and mollusks are negatively affected, while crustaceans and echinoderms are positively affected.[74] Warmer waters are likely to promote increased populations of Pacific salmon in Alaska while promoting decreased populations elsewhere in the NPLCC region.[75] If oxygen levels decline[76] and coastal upwelling strengthens as some studies project,[77] oxygenated habitat will be lost.[78] A few species, such as sablefish and some rock fishes, tolerate low-oxygen conditions and may expand their territory.[79] However, most species will be forced to find shallower habitat or perish.[80] Overall, smaller specimens seem to be the winners under low-oxygen conditions, as they outcompete larger organisms due to their advantageous body-mass to oxygen-consumption ratio.[81]

Many sea and shorebirds have medium or high vulnerability to climate change.[82] These include the Aleutian Tern, Kittlitz's Murrelet,[83] beach-nesting black oystercatchers,[84] and the Cassin's auklet.[85] For coastal birds, loss of habitat and food sources are the largest climate change-related concerns.[86] Reproductive failure among seabirds has been documented as a result of changes in marine productivity, often observed during El Niño years when sea surface temperatures are warmer than average.[87] Population recovery is less likely if climate change results in catastrophic events that are more frequent, more intense, or of longer duration.[88]

Climate change may enhance environmental conditions such that some species are able to survive in new locations, known invasive species expand into new territories, and species that currently are not considered invasive could become invasive, causing significant impacts.[89] Invasive and non-native species that appear to benefit from climate change include Spartina, Japanese eelgrass, and New Zealand mud snail.[90]

In response to warming temperatures and changing currents, many marine species are expanding their ranges toward the poles.[91] The abundance and distribution of jumbo squid in the NPLCC region increased between 2002 and 2006, with sightings as far north as southeast Alaska.[92] Loggerhead turtle, brown pelican, and sunfish are reported recent arrivals to the northern Washington coast.[93]

Climate change may also lead to significant phenological decoupling, such as occurred in the Pacific Northwest in 2005 when the upwelling season occurred three months later than usual, resulting in a lack of significant plankton production until August (rather than the usual April-May time period).[94] The delay was accompanied by recruitment failure among plankton-reliant rockfish species, low survival of coho and Chinook salmon, complete nesting failure by Cassin's Auklet, and widespread deaths of other seabirds (common murres, sooty shearwaters).[95] Similar mismatches also occurred in 2006 and 2007 when upwelling began early but was interrupted at a critical time (May-June).[96]

As a result of these effects, novel assemblages of organisms will inevitably develop in the near future due to differing tolerances for changes in environmental conditions.[97] These novel communities will have no past or present counterparts and are likely to present serious challenges to marine resource managers.[98]

Adaptation to climate change for marine and coastal systems

Given that CO_2 concentrations will continue to increase and exacerbate climate change effects for the foreseeable future,[99] adaptation is emerging as an appropriate response to the unavoidable impacts of climate change.[100] Adaptive actions reduce a system's vulnerability,[101] increase its capacity to withstand or be resilient to change,[102] and/or transform systems to a new state compatible with likely future conditions.[103] Adaptation actions typically reflect three commonly cited tenets: (1) remove other threats and reduce non-climate stressors that exacerbate climate change effects;[104] (2) establish, increase, or adjust protected areas, habitat buffers, and corridors;[105] and, (3) increase monitoring and facilitate management under uncertainty, including scenario-based planning and adaptive management.[106]

Adaptation actions may occur in legal, regulatory, or decision-making processes, as well as in on-the-ground conservation activities.[107] For example, to counteract loss of coastal habitat due to erosion and sea level rise, options include removing shoreline hardening structures,[108] enhancing sediment transport,[109] establishing ecological buffer zones,[110] and acquiring rolling easements.[111] To manage invasive species, whose spread is exacerbated by increased sea surface temperatures and other climate-related effects, options include restoring native species, physically removing invasive species, and strengthening regulatory protections against invasive species introduction.[112] Decision-makers may also create or modify laws, regulations, and policies governing coastal management to promote living shorelines that protect coastal property and habitat,[113] incorporate climate projections into land use planning to safeguard coastal habitats,[114] and implement coastal development setbacks to address rising sea levels and increased storm intensity, maintain natural shore dynamics, and minimize damage from erosion.[115]

Although uncertainty and gaps in knowledge exist, sufficient scientific information is available to plan for and address climate change impacts now.[116] Implementing strategic adaptation actions early may reduce severe impacts and prevent the need for more costly actions in the future.[117] To identify and implement adaptation actions, practitioners highlight four broad steps:

1. Assess current and future climate change effects and conduct a vulnerability assessment.[118]
2. Select conservation targets and a course of action that reduce the vulnerabilities and/or climate change effects identified in Step 1.[119]
3. Measure, evaluate, and communicate progress through the design and implementation of monitoring programs.[120]
4. Create an iterative process to reevaluate and revise the plan, policy, or program, including assumptions. [121]

Adaptive approaches to addressing climate change impacts will vary by sector and management goal, across space and time, and by the goals and preferences of those engaged in the process.[122] In all cases, adaptation is not a one-time activity, but is instead a continuous process, constantly evolving as new information is acquired and interim goals are achieved or reassessed.[123] Ultimately, successful climate change adaptation supports a system's capacity to maintain its past or current state in light of climate impacts or transform to a new state amenable to likely future conditions.[124]

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[1] USFWS. (2010)
[2] NOAA. (2011c)
[3] Forster et al. (2007, p. 141)
[4] CIG. (2008).
[5] Meehl et al. (2007, p. 803)
[6] Feely et al. (2009, Table 2, p. 46). By 2100, the projected declines are associated with a doubling (~550 ppm) or tripling (~830 ppm) of atmospheric CO_2 compared to ~1750: -0.14 to -0.15 or -0.30 to -0.31, respectively.
[7] Hauri et al. (2009, p. 67-68)
[8] Kroeker et al. (2010, p. 1424, 1427)
[9] Mote (2003, p. 276); Butz and Safford (Butz and Safford 2010, 1)
[10] U.S. Global Change Research Program (2009, p. 139)
[11] For AK, Karl, Melillo and Peterson. (2009, p. 139). For WA and OR, CIG. (2008, Table 3) and Mote et al. (2010, p. 21). For CA, California Natural Resources Agency. (2009, p. 16-17) and PRBO. (2011, p. 8).
[12] California Natural Resources Agency (2009, p. 66); Levin et al. (2009, p. 3568); Najjar et al. (2000, p. 226)
[13] Cheung et al. (2010, p. 31); IPCC. (2007e, p. 8); Karl, Melillo, and Peterson. (2009, p. 144)
[14] NABCI. (2010, p. 7)
[15] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011. Data for 1971-2000 are official data from the National Climatic Data Center (NCDC). Data for 1981-2010 are preliminary, unofficial data acquired from Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on May 12, 2011. The NCDC defines a climate normal, in the strictest sense, as the 30-year average of a particular variable (e.g., temperature).
[16] Mote (2003, p. 279)
[17] Killam et al. (2010, p. 4)
[18] Pike et al. (2010, Table 19.1, p. 701)
[19] For BC, BC Ministry of Environment. (2006, Table 10, p. 113); For OR and WA, Mote and Salathé, Jr. (2010, p. 42-44); Seasonal precipitation projections for California were not available.
[20] Alaska Center for Climate Assessment and Policy. (2009, p. 31).
[21] Elsner et al. (2010, Table 5, p. 244); Pike et al. (2010, p. 715); PRBO. (2011, p. 8)
[22] AK Department of Environmental Conservation (DEC). (2010, p. 2-3); Chang and Jones. (2010, p. 84); Howat et al. (2007, p. 96); Pike et al. (2010, p. 716)
[23] AK DEC. (2010, p. 2-3, 5-2); Chang and Jones. (2010, p. 94); Mantua, Tohver and Hamlet. (2010, p. 204-205); Pike et al. (2010, p. 719); Stewart. (2009, p. 89); Tohver and Hamlet. (2010, p. 8)
[24] Chang and Jones. (2010, p. 192); Pike et al. (2010, p. 719); Stewart. (2009, p. 89)
[25] Peterson, W. & Schwing, F. (2008, p. 56)
[26] Levin et al. (2009, p. 3567)
[27] Orr et al. (2005); Feely, Doney and Cooley. (2009)
[28] Feely et al. (2010, Table 1, p. 446).
[29] Feely et al. (2009, p. 37)
[30] Feely et al. (2009, Table 2, p. 46). The projected decline is associated with a doubling of atmospheric CO_2 compared to ~1750, to ~550 ppm by 2100. With a tripling of atmospheric CO_2 (~830 ppm by 2100 compared to ~1750), pH is projected to decline -0.30 to -0.31 in North Pacific Ocean waters.
[31] Feely et al. (2009, p. 39); Hauri et al. (2009, p. 67-68)
[32] Feely, Sabine, et al. (2008, p. 1491)
[33] Sigler et al.(2008, p. 7)
[34] Sigler et al.(2008, p. 12)
[35] Hauri et al. (2009, p. 67-68); Sigler et al.(2008, p. 12)
[36] Nicholls et al. (2007, p. 320)
[37] Overland and Wang. (2007, Fig. 2b, p. 7)
[38] Hoegh-Guldberg and Bruno. (2010, p. 1524)
[39] IPCC. (2007e, p. 8)
[40] Hoegh-Guldberg and Bruno. (2010, p. 1524)
[41] IPCC. (2007e, p. 8)
[42] OCMP. (2009, p. 66)
[43] Field et al. (2007, p. 627)

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[44] Field et al. (2007, p. 627)
[45] Hoffman. (2003, p. 135)
[46] Bauman et al. (2006); OCMP. (2009)
[47] OCMP. (2009, p. 17)
[48] AK State Legislature. (2008); Brown and McLachlan. (2002, p. 62); Littell et al. (2009); Nicholls et al. (2007, p. 325-326).
[49] OCMP. (2009)
[50] IPCC. (2007f, p. 7)
[51] NOAA. (2007)
[52] B.C. Ministry of Environment. (2007, p. 26); Bornhold. (2008, p. 6); Mote et al. (2008)
[53] Grinsted, Moore and Jevrejeva. (2009, Table 2, p. 467); IPCC. (2007c, Table 3.1, p. 45); Meehl et al. (2005, p. 1770-1771); Rahmstorf. (2007, p. 369); Vermeer and Rahmstorf. (2009, Table 1, p. 21530-21531).
[54] AK DEC. (2010, p. 2-4); Bornhold (2008, Table 1, p. 8); CA Natural Resources Agency. (2009, p. 18); Mote et al. (2008); Ruggiero et al. (2010, p. 218)
[55] Bornhold (2008, Table 1, p. 8); CA Natural Resources Agency. (2009, p. 18); Mote et al. (2008); Ruggiero et al. (2010, p. 218)
[56] AK DEC. (2010, p. 2-4); Mote et al. (2008)
[57] AK State Legislature. (2008, p. 91); Glick, Clough and Nunley. (2007); Philip Williams and Associates, Ltd. (2009)
[58] AK State Legislature. (2008, p. 91); Krueger et al. (2010, p.176)
[59] Grantham et al. (2004, p. 750)
[60] Grantham et al. (2004, p. 750)
[61] Connolly et al. (2010, p. 1, 8)
[62] Chan et al. (2008, p. 920)
[63] Chan et al. (2008, p. 920)
[64] PISCO. (2009)
[65] Hoegh-Guldberg and Bruno. (2010, p. 1523)
[66] AK State Legislature. (2008, p. 91). Report by the Alaska State Legislature, available online at http://www.housemajority.org/coms/cli/cli_final report_20080301.pdf (last accessed 12.14.2010).
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[71] DU. (2010a); DU. (2010c); DU. (2010d)
[72] DU. (2010b)
[73] Kroeker et al. (2010, p. 1424)
[74] Kroeker et al. (2010, p. 1424)
[75] ISAB. (2007, p. 64)
[76] Whitney, Freeland and Robert. (2007)
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[78] Whitney, Freeland and Robert. (2007, p. 197)
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[81] Ekau et al. (2010, p. 1690)
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[88] NABCI. (2010, p. 6-7)
[89] U.S. EPA. (2008, p. 2-14)
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[92] Field et al. (2007)

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[93] Papiez. (2009, p. 17) (2009)
[94] Peterson, W. & Schwing, F. (2008, p. 45)
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[96] Peterson, W. & Schwing, F. (2008, p. 45)
[97] Hoegh-Guldberg and Bruno. (2010, p. 1526)
[98] Hoegh-Guldberg and Bruno. (2010, p. 1526-1527)
[99] ADB. (2005, p. 7)
[100] Gregg et al. (2011, p. 30)
[101] Gregg et al. (2011, p. 29)
[102] Glick et al. (2009, p. 12)
[103] Glick et al. (2009, p. 13); U.S. Fish and Wildlife Service. (2010, Sec1:16)
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[107] Gregg et al. (2011); Heinz Center. (2008); Littell et al. (2009)
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[109] NOAA. (2010, p. 83)
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[111] Kling and Sanchirico. (2009, p. 46)
[112] Kling and Sanchirico. (2009, p. 41); U.S. EPA. (2009, p. 16)
[113] NOAA. (2010, p. 80)
[114] U.S. EPA. (2009, p. 17)
[115] U.S. AID. (2009, p. 98)
[116] Littell et al. (2009)
[117] Binder. (2010, p. 355)
[118] Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010a); U.S. AID. (2009); CIG (2007); ADB (2005); Pew Center (2009)
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[120] Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010a); U.S. AID. (2009); CIG (2007); ADB (2005)
[121] Gregg et al. (2011); Glick et al. (2009); NOAA (2010a); U.S. AID. (2009); CIG (2007); ADB (2005)
[122] Gregg et al. (2011); Littell et al. (2009)
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Climate Change Effects & Adaptation Approaches in Freshwater Aquatic & Riparian Ecosystems of the North Pacific Landscape Conservation Cooperative Region: Executive Summary.

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This report provides a first-ever compilation of what is known—and not known—about climate change effects on freshwater aquatic and riparian ecosystems in the geographic extent of the North Pacific Landscape Conservation Cooperative (NPLCC). The U.S. Fish and Wildlife Service funded this report to help inform members of the newly established NPLCC as they assess priorities and begin operations. Production of this report was guided by University of Washington's Climate Impacts Group and information was drawn from more than 250 documents and more than 100 interviews.

Information in this report focuses on the NPLCC region, which extends from Kenai Peninsula in southcentral Alaska to Bodega Bay in northwestern California, west of the Cascade Mountain Range and Coast Mountains. The extent of the NPLCC reaches inland up to 150 miles (~240 km) and thus only includes the lower extent of most large watersheds. This area is home to iconic salmon, productive river, lake, and wetland systems, and a wide variety of fish, wildlife, amphibians, and other organisms. Many of these species, habitats, and ecosystems are already experiencing the effects of a changing climate.

Carbon Dioxide Concentrations, Temperature, and Precipitation

Increased atmospheric carbon dioxide (CO_2) contributes to the earth's greenhouse effect, leading to increased air temperature, altered precipitation patterns, and consequent effects for biophysical processes, ecosystems, and species.

- **Atmospheric CO_2 concentrations have increased** to ~392 parts per million (ppm)[125] from the pre-industrial value of 278 ppm,[126] higher than any level in the past 650,000 years.[127] By 2100, CO_2 concentrations are projected to exceed ~600 ppm and may exceed 1000 ppm.[128]
- **Annual average temperatures have increased** ~1-2°F (~0.56-1.1°C) from coastal British Columbia to northwestern California over the 20th century[129] and 3.4°F (~1.9°C) in Alaska from 1949 to 2009.[130] Winter temperatures increased most: 6.2°F (3.4°C) in Alaska[131] and ranging from 1.8 to 3.3°F (1.0-1.83°C) in the remainder of the region.[132] By 2100, the range of projected annual increases varies from 2.7 to 13°F (1.5-7.2°C), with the largest increases projected in Alaska.[133] Seasonally, winter temperatures will continue to warm most in Alaska,[134] while summers are projected to warm most in the remainder of the region (2.7-9.0°F, 1.5-5.0°C).[135] These changes are projected to reduce snowpack[136] and summer streamflow,[137] increase water temperature,[138] and will likely lead to increasing physiological stress on temperature-sensitive species,[139] drying of alpine ponds and wetlands, and reduced habitat quality for dependent reptiles and amphibians.[140]

- **Seasonal precipitation varies but is generally wetter in winter.** Cool season precipitation (Oct-March) increased 2.17 inches (5.51 cm) in Alaska from the periods 1971-2000 to 1981-2010.[141] In Washington and Oregon, winter precipitation (Jan-March) increased 2.47 inches (6.27 cm) from 1920 to 2000.[142] In California, winter precipitation increased between 1925 and 2008,[143] while in British Columbia, both increases and decreases in winter precipitation were observed, depending on the time period studied.[144] Increased cool season precipitation raised winter flood risk in much of the Puget Sound basin and coastal areas of Washington, Oregon, and California.[145] Over the 21st Century, winter and fall precipitation is projected to increase 6 to 11% in BC and 8% in Washington and Oregon, while summer precipitation is projected to decrease (-8 to -13% in BC and -14% in WA and OR).[146] In southeast Alaska, however, warm season precipitation is projected to increase 5.7%.[147] These changes have implications for future patterns of winter flooding and summer low flows and will affect the water quality and supply that freshwater species rely upon.[148]

Impacts of climate change on freshwater aquatic and riparian systems

Increases in CO_2 and air temperature, combined with changing precipitation patterns, are already altering numerous conditions, processes, and interactions in freshwater aquatic and riparian ecosystems. In most cases, these trends are projected to continue.

- **Reduced snowfall and snowpack, especially at lower and mid elevations:** In Juneau (AK), winter snowfall decreased ~15%, or nearly 1.5 feet (~0.45 m) between 1943 and 2005.[149] In the Cascade Mountains, April 1 snow water equivalent (SWE) has declined 16%[150] to 25%[151] since 1930. And in the lower Klamath Basin (CA), April 1 SWE decreased significantly at most monitoring sites lower than 5,905 feet (1,800 m) but increased slightly at higher elevations.[152] By 2059, April 1 SWE is projected to decline from 28%[153] up to 46%[154] in the NPLCC region. A 73% decline in snow accumulation is projected for California's North Coast under a doubling of atmospheric CO_2 concentrations.[155] For all but the highest elevation basins, loss of winter snowpack is projected to result in reduced summer streamflow, transforming many perennial streams into intermittent streams and reducing available habitat for fish, amphibians, and invertebrates dependent on constant flow and associated wetland conditions.[156]
- **Earlier spring runoff:** In the NPLCC region, the timing of the center of mass of annual streamflow (CT) shifted one to four weeks earlier and snow began to melt approximately 10 to 30 days earlier from 1948 to 2002.[157] From 1995 to 2099, CT is projected to shift 30 to 40 days earlier in Washington, Oregon and Northern California and 10 to 20 days earlier in Alaska and western Canada.[158] Both the spring freshet and spring peak flows are projected to occur earlier for basins currently dominated by glaciers, snow, or a mix of rain and snow.[159] In currently rain-dominant basins, runoff patterns will likely mimic projected precipitation changes.[160] In snowmelt-dominant streams where the seaward migration of Pacific salmon has evolved to match the timing of peak snowmelt flows, reductions in springtime snowmelt may negatively impact the success of smolt migrations.[161]
- **Increased winter streamflow and flooding:** In six glaciated basins in the North Cascades, mean winter streamflow (Nov-March) increased 13.8% from 1963 to 2003.[162] Winter streamflow also increased in non-rain-dominated basins in British Columbia and the Pacific Northwest from 1956

to 2006.[163] In the western U.S. from ~1975 to 2003, flood risk increased in rain-dominant and particularly in warmer mixed rain-snow-dominant basins, and probably remained unchanged in many snowmelt- and cooler mixed-rain-snow-dominant basins in the interior.[164] Under a warmer future climate with increased rainfall and decreased snowfall, winter streamflow and flood risk will increase, particularly for mixed rain-snow basins in the region.[165] At Ross Dam on the Skagit River (WA), the magnitude of 50-year-return flood events is projected to increase 15% by the 2040s (compared to 1916-2006).[166] The egg-to-fry survival rates for pink, chum, sockeye, Chinook, and coho salmon will be negatively impacted as more intense and frequent winter floods wash away the gravel beds salmon use as nesting sites.[167]

- **Decreased summer streamflow:** In the Pacific Northwest, northwestern California, and coastal British Columbia, those watersheds receiving some winter precipitation as snow experienced a decrease in summer streamflow from 3% to more than 40% between 1942 and 2006.[168] By 2100, further declines in the number and magnitude of summer low flow days are projected throughout the region.[169] In Washington's rain- and mixed rain-snow basins, the 7-day low flow magnitude is projected to decline by up to 50% by the 2080s.[170] Projected declines in summer streamflow will reduce the capacity of freshwater to dilute pollutants.[171] Combined with increased summer stream temperature, this will reduce habitat quality and quantity for stream-type Chinook and coho salmon, steelhead, and other freshwater fishes.[172]
- **Reduced glacier size and abundance in most of the region:** Fifty-three glaciers have disappeared in the North Cascades since the 1950s,[173] glaciers in the Oregon Cascades lost 40% to 60% of their area from 1901 to 2001,[174] and the Lemon Glacier near Juneau (AK) retreated more than 2600 feet (792 m) from 1953 to 1998.[175] However, in California, Mt. Shasta's glaciers exhibited terminal advance and little change in ice volume, as increased temperatures were counteracted by increased winter snow accumulation.[176] Limited projections for the 21st century indicate glacial area losses of 30% to 75% in parts of the NPLCC region.[177] The Hotlum glacier on Mt. Shasta is projected to disappear by 2065.[178] Where the contribution of glacial meltwater to streamflow is reduced or eliminated, the frequency and duration of low flow days is projected to increase,[179] raising stream temperature and suspended sediment concentrations and altering water chemistry.[180]
- **Increased water temperature:** Observed increases in lake and river temperatures are generally projected to continue, exceeding the threshold for salmon survival in some areas of the NPLCC region. Annual average water temperature in Lake Washington increased ~1.6°F (0.9°C) from 1964 to 1998.[181] In Johnson Creek (OR) water temperature variability increased over a recent 10-year period, suggesting that stream temperatures frequently exceed the local threshold level of 64.4°F (18°C).[182] In western Washington, simulations of maximum August stream temperatures from 1970 to 1999 showed most stations remained below 68°F (20°C), the upper threshold for salmon survival.[183] However, in the 21st century, a prolonged duration of water temperatures beyond the thermal maximum for salmon is projected for the Fraser River (BC),[184] the Lake Washington/Lake Union ship canal (WA), the Stillaguamish River (WA),[185] and the Tualatin River (OR).[186] In Washington by the 2080s, stream temperatures are projected to increase by 3.6 to 9°F (2-5°C).[187]

- **Changes in water quality:** Documented effects of climate change on water quality were not found, and water quality projections are both limited and widely varying for the NPLCC region. In seasons and areas where increased flows are projected, nutrient contaminants may be diluted (e.g. northwest BC)[188] or alternatively, sediment nutrient loads may be increased (e.g. during winter in the Tualatin Basin, OR).[189] Projected declines in summer flows and water supply may decrease nutrient sediment loads, but projected increases in development or other stressors may counteract the decline.[190] Lakes may experience a longer stratification period in summer[191] which could enhance eutrophication and lead to oxygen depletion in deep zones during summer, eliminating refuges for coldwater-adapted fish species.[192] In coastal areas, saltwater intrusion due to sea level rise was observed in Island County (WA)[193] and is projected to increase in the neighboring Gulf Islands (BC),[194] as well as other areas where coastal water tables are influenced by marine systems.[195]
- **Reduced seasonal ice cover:** The spatial and seasonal extent of ice cover on lakes will be reduced due to climate change.[196] For example, in several British Columbia lakes, the duration of ice cover decreased by up to 48 days over the 1976 to 2005 period.[197] For mid-latitude lakes, each 1.8°F (1°C) increase in mean autumn temperature leads to a 4 to 5 day delay in ice freeze-up, while the same increase in mean spring temperature leads to a 4 to 5 day advance in the onset of ice break-up.[198] Community and invasion processes may be affected as reduced ice cover increases light levels for aquatic plants, reduces the occurrence of low oxygen conditions in winter, and exposes aquatic organisms to longer periods of predation from terrestrial predators.[199] In northern regions where productivity is limited by ice cover and/or temperature, productivity may increase, providing additional food for fish and other species.[200]

Implications for ecosystems, habitats, and species

Climate-induced changes in air temperature, precipitation, and other stressors are already affecting the physical, chemical and biological characteristics of freshwater ecosystems.[201] Many of these trends will be exacerbated in the future. Impacts on habitat (loss and transition) and species (range shifts, invasive species interactions, and phenology) are highlighted here.

Habitat loss and transition

Increasing temperatures and associated hydrologic changes are projected to result in significant habitat impacts. Lake levels and river inputs are likely to decline if increases in evapotranspiration (due to higher temperatures, longer growing seasons, and extended ice-free periods) are not offset by an equal or greater increase in precipitation.[202] However, areas that become wetter could have higher lake levels.[203] Where lake levels are permanently lowered, the productive nearshore zone may be degraded as more shoreline is exposed.[204] Habitat for fish that require wetlands for spawning and nursery habitat would be reduced if lake-fringing wetlands become isolated.[205]

Warmer temperatures, reduced snowpack, and altered runoff timing is projected to cause drying of alpine ponds and other wetland habitats, reducing habitat quality for Cascades frog, northwestern salamander, long-toed salamander, garter snakes, and other dependent species.[206] However, loss of snowpack may allow alpine vegetation establishment, leading to improved habitat conditions for some high elevation wildlife species.[207] In the short term, vegetation establishment will be limited to areas favorable to rapid soil development.[208]

A modeling study suggests two-thirds of Alaska will experience a potential biome shift in climate this century, although the rate of change will vary across the landscape.[209] Much of southeast Alaska may be shifting from the North Pacific Maritime biome (dominated by old-growth forests of Sitka spruce, hemlock, and cedar) to the more southerly Canadian Pacific Maritime biome (dominated by yellow and western red cedar, western and mountain hemlock, amabilis and Douglas-fir, Sitka spruce, and alder).[210]

Range shifts, invasive species, and altered phenology

Climate warming is expected to alter the extent of habitat available for cold-, cool-, and warm-water organisms, resulting in range expansions and contractions.[211] Range-restricted species and habitats, particularly polar and mountaintop species and habitats that require cold thermal regimes,[212] show more severe range contractions than other groups and have been the first groups in which whole species have gone extinct due to recent climate change.[213] Amphibians are among the most affected.[214]

The effects of climate change on aquatic organisms may be particularly pronounced in streams where movements are constrained by thermal or structural barriers.[215] Bull trout distribution is strongly associated with temperature,[216] and in the southern end of their range (WA, OR, northwest CA), this coldwater species is generally found at sites where maximum daily temperatures remain below 60.8°F (16°C).[217] However, summer stream temperatures in many bull trout waters at the southern end of their range are projected to exceed 68°F (20°C) by 2100.[218]

Climate change may enhance environmental conditions such that some species are able to survive in new locations, known invasive species expand into new territories, and species that currently are not considered invasive could become invasive, causing significant impacts.[219] Invasive aquatic species that appear to benefit from climate change include hydrilla, Eurasian watermilfoil, white waterlily,[220] and reed canarygrass.[221] In Washington, Oregon, and Idaho, a habitat suitability model projects 21% of the region could support suitable habitat for the invasive tamarisk by 2099 (a two- to ten-fold increase).[222] Tamarisk currently occupies less than 1% of this area, and the remainder is considered highly vulnerable to invasion.[223]

Numerous ecological studies support a general pattern of species' phenological responses to climate change: on average, leaf unfolding, flowering, insect emergence, and the arrival of migratory birds occur earlier than in the past.[224] A significant mean advancement of spring events by 2.3 days per decade has been observed.[225] Studies of phenology from the NPLCC region have found:

- Lamprey run timing shifted 13 days earlier from 1939 to 2007 as Columbia River discharge decreased and water temperatures increased.[226] Migration occurred earliest in warm, low-discharge years and latest in cold, high flow years.[227]
- Populations of Lake Washington's keystone herbivore, *Daphnia*, show long-term statistically significant declines associated with an increasing temporal mismatch with its food source (the spring diatom bloom).[228] In contrast, although the phytoplankton peak advanced by 21 days, the herbivorous rotifer *Keratella* maintained a corresponding phenological response and experienced no apparent decoupling of the predator-prey relationship.[229]

In the future, populations that are most mistimed are generally expected to decline most in number.[230] For fishes dependent on water temperature for spawning cues, the spawning time may shift earlier if river waters begin to warm sooner in the spring.[231] Changes in plankton populations such as those described for *Daphnia* and *Keratella* in Lake Washington may have severe consequences for resource flow to upper trophic levels.[232]

Adaptation to climate change for freshwater aquatic and riparian systems

Given that CO_2 concentrations will continue to increase and exacerbate climate change effects for the foreseeable future,[233] adaptation is emerging as an appropriate response to the unavoidable impacts of climate change.[234] Adaptive actions reduce a system's vulnerability,[235] increase its capacity to withstand or be resilient to change,[236] and/or transform systems to a new state compatible with likely future conditions.[237] Adaptation actions typically reflect three commonly cited tenets: (1) remove other threats and reduce non-climate stressors that exacerbate climate change effects;[238] (2) establish, increase, or adjust protected areas, habitat buffers, and corridors;[239] and, (3) increase monitoring and facilitate management under uncertainty, including scenario-based planning and adaptive management.[240]

Adaptation actions may occur in legal, regulatory, institutional, or decision-making processes, as well as in on-the-ground conservation activities.[241] For example, actions that maintain or increase instream flow can counteract increased stream temperatures, reductions in snowpack, and changes in runoff regimes such as reduced summer stream flows and altered flow timing.[242] Actions to restore or protect wetlands, floodplains, and riparian areas can help moderate or reduce stream temperatures, alleviate the flooding and scouring effects of extreme rainfall or rapid snowmelt, improve habitat quality, and enable species migrations.[243] Decision-makers may also modify or create laws, regulations, and policies to incorporate climate change impacts into infrastructure planning to protect freshwater ecosystems,[244] promote green infrastructure and low impact development approaches to reduce extreme flows and improve water quality and habitat,[245] and adapt Early Detection and Rapid Response protocols to identify, control, or eradicate new and existing invasive species before they reach severe levels.[246]

Although uncertainty and gaps in knowledge exist, sufficient scientific information is available to plan for and address climate change impacts now.[247] Implementing strategic adaptation actions early may reduce severe impacts and prevent the need for more costly actions in the future.[248] To identify and implement adaptation actions, practitioners highlight four broad steps:

5. Assess current and future climate change effects and conduct a vulnerability assessment.[249]
6. Select conservation targets and a course of action that reduce the vulnerabilities and/or climate change effects identified in Step 1.[250]
7. Measure, evaluate, and communicate progress through the design and implementation of monitoring programs.[251]
8. Create an iterative process to reevaluate and revise the plan, policy, or program, including assumptions. [252]

Adaptive approaches to addressing climate change impacts will vary by sector and management goal, across space and time, and by the goals and preferences of those engaged in the process.[253] In all cases, adaptation is not a one-time activity, but is instead a continuous process, constantly evolving as new information is acquired and interim goals are achieved or reassessed.[254] Ultimately, successful climate change adaptation supports a system's capacity to maintain its past or current state in light of climate impacts or transform to a new state amenable to likely future conditions.[255]

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[125] NOAA. (2011c)
[126] Forster et al. (2007, p. 141)
[127] CIG. (2008)
[128] Meehl et al. (2007, p. 803)
[129] Mote (2003, p. 276); Butz and Safford. (2010, p. 1).
[130] Karl, Melillo and Peterson. (2009, pp. , p. 139)
[131] Alaska Climate Research Center. (2009)
[132] B.C. Ministry of Environment. (2007, Table 1, p. 7-8); Mote (2003, Fig. 6, p. 276)
[133] For AK, Karl, Melillo and Peterson. (2009, p. 139). For WA and OR, CIG. (2008, Table 3). For OR alone, Mote et al. (2010, p. 21). For CA, CA Natural Resources Agency. (2009, p. 16-17) and Port Reyes Bird Observatory (PRBO). (2011, p. 8)
[134] Cayan et al. (2008, Table 1, p. S25); Karl, Melillo and Peterson. (2009); Mote and Salathé, Jr. (2010, Fig. 9, p. 42); PRBO. (2011, p. 8)
[135] B.C. Ministry of Environment. (2006, Table 10, p. 113).
[136] Elsner et al. (2010, Table 5, p. 244); Pike et al. (2010, p. 715); PRBO. (2011, p. 8)
[137] AK Department of Environmental Conservation (DEC). (2010, p. 2-3); Chang and Jones. (2010, p. 94); Mantua, Tohver and Hamlet. (2010, p. 204-205); Pike et al. (2010, p. 719); Stewart. (2009, p. 89)
[138] Mantua et al. (2010)
[139] Mantua et al. (2010)
[140] Halofsky et al. (n.d., p. 143)
[141] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011. The datum for 1971-2000 is an official datum from the National Climatic Data Center (NCDC). The datum for 1981-2010 is a preliminary, unofficial datum acquired from Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on May 12, 2011. The NCDC defines a climate normal, in the strictest sense, as the 30-year average of a particular variable (e.g., temperature).
[142] Mote (2003, p. 279)
[143] Killam et al. (2010, p. 4)
[144] Pike et al. (2010, Table 19.1, p. 701)
[145] Hamlet and Lettenmaier. (2007, p. 15)
[146] For BC, BC Ministry of Environment. (2006, Table 10, p. 113); For OR and WA, Mote and Salathé, Jr. (2010, 42-44); Seasonal precipitation projections for California were not available.
[147] Alaska Center for Climate Assessment and Policy. (2009, p. 31)
[148] Allan, Palmer and Poff. (2005, p. 279); Hamlet and Lettenmaier. (2007, p. 16); Martin and Glick. (2008, p. 14); Pike et al. (2010, p. 731); Poff, Brinson and Day. (2002, p. 15)
[149] Kelly et al. (2007, p. 36)
[150] Stoelinga, Albright and Mass. (2010, p. 2473)
[151] Pelto. (2008, p. 73); Snover et al. (2005, p. 17)
[152] Van Kirk and Naman. (2008, p. 1035)
[153] Pike et al. (2010, p. 715)
[154] Elsner et al. (2010, Table 5, p. 244)
[155] PRBO. (2011, p. 8)
[156] Poff, Brinson and Day. (2002)
[157] Stewart, Cayan and Dettinger. (2005); Snover et al. (2005)
[158] Stewart, Cayan and Dettinger. (2004, p. 225)
[159] Chang and Jones. (2010, p. 192); Pike et al. (2010, p. 719); Stewart. (2009, p. 89).
[160] Pike et al. (2010, p. 719)
[161] Mantua, Tohver and Hamlet. (2010, p. 207)

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[162] Pelto. (2008, pp. , p. 72-74)
[163] Pelto. (2008, Table 5, p. 72); Pike et al. (2010, pp. , p. 706, 717); Stewart (2009, Table V, p. 89)
[164] Hamlet and Lettenmaier. (2007, p. 15-16)
[165] AK DEC. (2010, p. 5-2); Pike et al. (2010, p. 719); Tohver and Hamlet. (2010, p. 8)
[166] Seattle City Light (2010). The authors cite CIG (2010) for this information.
[167] Mantua, Tohver and Hamlet. (2010, p. 207); Martin and Glick. (2008, p. 14).
[168] Chang and Jones. (2010); Pelto. (2008); Pike et al. (2010); Snover et al. (2005); Van Kirk and Naman. (2008)
[169] AK DEC. (2010, p. 2-3); Chang and Jones. (2010, p. 94); Mantua, Tohver and Hamlet. (2010, p. 204-205); Pike et al. (2010, p. 719); Stewart. (2009, p. 89).
[170] Mantua, Tohver and Hamlet. (2010, p. 204-205)
[171] Pike et al. (2010, p. 730); Kundzewicz et al. (2007, p. 188).
[172] Mantua, Tohver and Hamlet. (2010, p. 209-210); Mantua, Tohver and Hamlet. (2010, p. 207);
[173] WA Department of Ecology (ECY). (2007)
[174] Chang & Jones. (2010)
[175] Kelly et al. (2007, p. 33)
[176] Howat et al. (2007, p. 96)
[177] Chang and Jones. (2010, p. 84); Howat et al. (2007, p. 96); Pike et al. (2010, p. 716)
[178] Howat et al. (2007, p. 96)
[179] Pike et al. (2010, p. 719)
[180] Pike et al. (2010, p. 717)
[181] Arhonditsis et al. (2004, p. 262-263)
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Climate Change Effects and Adaptation Approaches for Terrestrial Ecosystems, Habitats, and Species. Executive Summary.

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This report provides a compilation of what is known – and not known – about climate change effects on terrestrial ecosystems in the geographic extent of the North Pacific Landscape Conservation Cooperative (NPLCC). Where a broader regional context is needed, we also present information from surrounding areas. The NPLCC funded this report to help inform members of the NPLCC as they assess priorities and continue operations.

Information in this report was drawn from approximately 250 documents published in October 2013 or earlier. Because the report strives to reflect the state of knowledge as represented in the literature, in most cases the language in Chapters I and III through X is drawn directly from cited sources. By compiling and presenting verbatim or near verbatim material from relevant studies rather than paraphrasing or interpreting information from these sources, we sought to reduce inaccuracies and possible mis-characterizations by presenting data and findings in their original form. The studies presented also vary considerably in methodological assumptions and represent a wide range of observational and modeling approaches. We encourage the reader to refer to the original studies for details on assumptions and methodology. Chapter II provides additional information on the approach we used to produce this report.

The NPLCC region extends from the Kenai Peninsula in southcentral Alaska to Bodega Bay in northwest California, west of the Cascade and Coast Mountain Ranges. Covering 204,000 square miles (530,000 square kilometers) in seven western U.S. states and Canadian provinces, the region is home to some of the most diverse ecosystems in the world,[256,257] a thriving outdoor recreation economy, and a wide variety of mammals, birds, and other organisms. Many of these species, habitats, and ecosystems are already experiencing the effects of a changing climate.

Carbon dioxide, temperature, precipitation, and novel climates

The atmospheric concentration of carbon dioxide (CO_2) and other heat-trapping greenhouse gases is increasing in the earth's atmosphere, leading to increases in temperature, altered precipitation patterns, and consequent effects for biophysical processes, ecosystems, and species.

- **The atmospheric concentration of CO_2 increased** to ~394 parts per million (ppm)[258] in October 2013 from the pre-industrial value of 278 ppm,[259] higher than any level in the past 650,000 years.[260] By 2100, the atmospheric concentration of CO_2 is projected to exceed 400 ppm and may exceed 1000 ppm, depending on future greenhouse gas emissions.[261,262] As the level of CO_2 increases, ecosystem productivity and carbon storage may also increase, particularly in combination with warmer temperatures and sufficient moisture and nutrients.[263,264]

- **Annual average temperatures increased** ~1-2°F (~0.6-1°C) from coastal British Columbia to northwestern California over the 20th century[265,266] and 3.4°F (~1.9°C) in Alaska from 1949 to 2009.[267] By 2100, the range of projected increases in the NPLCC region varies from 2.7 to 13°F (1.5-7.2°C), with the largest increases projected in Alaska.[268,269,270] Average winter and summer temperature also increased throughout the region during the 20th century, with the largest increase recorded near Juneau, Alaska during the winter (+6.2°F, +3.4°C).[271,272,273] By 2100, summer temperatures are projected to increase 2.7°F to 12.0 °F (1.5-6.4 °C), with the smallest increase projected for British Columbia and the largest for northern California.[274,275,276] Notably, winter temperature may increase more than summer temperature along British Columbia's north coast, a trend that is also projected for Alaska (Table 1).[277] These temperature increases will lengthen the growing season and frost-free season,[278,279,280,281,282] increase risk of larger, more frequent or severe fires especially in combination with drier conditions, promote some insect disturbances, and drive mismatches in the timing of prey availability for many birds, mammals, and invertebrates.[283,284,285]
- **Seasonal precipitation varies but is generally wetter in winter.** However in coastal British Columbia, both increases and decreases in winter precipitation were observed during the 20th century, depending on the time period studied.[286] Over the 21st Century, a shift in the seasonality of precipitation is expected in most of the NPLCC region, with increased cool season precipitation and decreased summer precipitation projected (Table 2),[287] and more intense rain possible.[288,289,290,291,292,293] This shift has already been observed in northwest California, where winter and early spring precipitation increased and fall precipitation decreased from 1925 to 2008.[294] Increased water limitation or drought, driven by changes in the amount and timing of precipitation, will constrain the growth and distribution of many tree species, while making some more susceptible to attack from insects and disease.[295,296,297,298,299] More frequent or intense floods may increase landslides and remove soil nutrients from forest ecosystems.[300,301]
- **Novel climates may develop in specific locations in the western U.S.** as annual and seasonal temperature and precipitation evolve into new patterns unique to an area. For example, northwest California's current coastal climates may be replaced by climates currently located to the south or east by 2100.[302,303] By altering the behavior, growth, development, and survival of existing species, novel climates may disrupt existing species relationships and modify current community composition.[304] Novel or no-analog communities, which have not been observed historically or currently, may develop, potentially challenging existing management and conservation practice.[305]

Impacts of climate change on terrestrial systems

Increases in CO_2 and air temperature, combined with changing precipitation patterns, are already altering numerous conditions, processes, and interactions in terrestrial ecosystems. These trends are projected to continue, and new ones will arise.

Reduced snowpack, earlier snowmelt, more intense rain, and increased drought are projected.

The key hydrologic changes for the NPLCC's terrestrial ecosystems are reduced snowpack and earlier snowmelt, more intense rain, increased drought, and in northwest California, changing fog patterns. Observed trends and future projections for changes in snowpack and snowmelt are covered in a companion report.[306] Briefly, increasing winter temperatures are expected to reduce snowpack and snowmelt as more rain than snow falls, particularly at low- to mid-elevations in the southern NPLCC region. These shifts alter forest water cycles and soil regimes, for example by increasing summer drought stress, altering evapotranspiration, increasing nutrient loss during more intense rain and runoff events, altering soil moisture and snow insulation, and altering erosion, landslide, and avalanche patterns.[307,308,309]

Much of the NPLCC region currently experiences little drought,[310] but changes in potential evaporation and increases in drought and drought stress are projected for the 21st century.[311,312,313] In southcentral and southeast Alaska, June water availability is projected to decrease 10% to 75%, with no change projected in a small area of southeast Alaska (June 2090-2099 vs. June 1961-1990).[314] In Washington, average water deficit for lodgepole pine is projected to increase 432% by the 2080s (vs. 1980-1999).[315] By mid-century, negative soil moisture anomalies are projected to increase substantially along the Washington coast and Cascade Mountains, with smaller increases in much of Oregon and Puget Sound and little to no change expected in northwest California (vs. 1951-1980).[316] However, fog patterns may change in northwest California, altering the annual contribution of fog water and risk of water stress in coast redwood ecosystems.[317,318] These systems already depend on fog water input: the western sword fern canopy absorbed approximately 5% of intercepted fog precipitation in midsummer throughout the coast redwood range. At one site in northern California, fog water input comprised 13 to 45% of annual transpiration in coast redwood and approximately 66% of water in understory plants during the summer from 1992 to 1994.[319,320] Drought stress typically increases fire risk and may reduce the ability of trees to repel insect attacks and disease,[321,322,323,324,325] which may promote prairie expansion where they border affected forests.[326] Conversely, trees weakened by insect infestation or disease often are more prone to drought stress.[327]

Growing seasons and frost-free periods are expected to increase.

The length of the growing season increased 12 ± 4 days globally since the 1960s,[328] at least two days per decade in the western United States since 1948,[329] and up to 6.97 days per decade in southcentral and southeast Alaska from 1949 to 1997.[330,331] However in high-elevation areas of the Cascade Mountains, little change in the length of the growing season was observed from 1950 to 1999.[332] The first snow-free week in Alaska occurred three to five days earlier per decade from 1972 to 2000, while the duration of the snow-free period extended three to six days longer per decade.[333] With a 1.8 °F (1.0 °C) increase in temperature, the growing season is projected to extend five to ten days longer in extratropical regions,[334] with increases of 20 to 40 days projected for Alaska by 2100 (vs. 1961-1990), particularly in coastal areas.[335] Winter freeze events (< 14 °F, < -10 °C) are expected to cease at the edges of the Klamath-Siskiyou Mountains and in a growing area of California's north coast by 2070-2099, relative to 1971-2000.[336] Productivity may increase, particularly in northern latitudes at low- and mid-elevation sites, as the growing season lengthens due to warmer temperatures and a longer frost-free season.[337,338] However, moisture and nutrient limitations such as those associated with drier summers may forestall or prevent significant productivity gains.[339] Fewer freeze events and a longer frost-free season may benefit deer and moose by increasing food availability,[340,341] but hamper species dependent on a winter chilling requirement (the amount of time spent in cold temperatures that is necessary to support optimal growth) such as Douglas-fir and western hemlock in the Pacific Northwest (i.e., WA, OR, ID, and southern B.C.).[342]

Fire frequency and severity is increasing, with the exception of many wet, coastal areas.

With the dominance of relatively wet, temperate forests in the NPLCC region, contemporary fire return intervals (both mean and median; the number of years between consecutive fires at a site) are generally at least 100 to 200 years and exceed 1,000 years in especially wet, mild locations.[343,344,345,346,347,348,349,350,351] When fires occur, typically they are severe (severity is the degree to which fire alters a site).[352] The region's prairies, grasslands, oak woodlands, savanna, and northwest California are characterized by more frequent (6-50 years), low to moderate severity fire.[353,354,355] Wildfire frequency in the western U.S. increased nearly four times from 1987 to 2003 (vs. 1970-1986), with 18% of the increase attributed to the southern Cascades, Sierra Nevada, and Coast Ranges of northern California and southern Oregon, 5% of the increase attributed to the Northwest, and less than 1% of the increase attributed to coastal, central, and southern California.[356] The overall increase in fire frequency was concentrated at mid-elevation sites (5512-8497 feet, 1680-2590 meters) and was associated with unusually warm springs, longer summer dry seasons, drier vegetation, longer fire seasons, and to some extent, reduced winter precipitation and earlier spring snowmelt.[357]

While fire is not currently a significant source of disturbance in southcentral and southeast Alaska, projections for warmer and drier conditions suggest increased fire frequency in southeast Alaska.[358,359] In the Pacific Northwest, area burned is projected to increase 78% by 2050, relative to 2000.[360] For the western three-quarters of Washington and Oregon, larger (+76 to +310%) and more severe (+29 to +41%) fires are expected by 2100, relative to 1971-2000.[361] Extreme fire danger is expected to increase zero to twelve days in the southern NPLCC region.[362] In northern California, the probability of large fires (> 500 acres, > 202 ha) is projected to increase 15% to 90% by 2100 (vs. 1961-1990),[363] while area burned is expected to increase more than 100% as fires grow more frequent and intense (i.e., the rate of heat release increases) (2050-2099 vs. 1895-2003).[364,365] However, declines in area burned are projected for some coastal areas,[366] including an 8% decline in overall area burned in the Humboldt Ranger Unit (2 x CO_2 vs. present climate).[367] Given the wetness of British Columbia's coastal climate, fires in that region should continue to be rare.[368] Increased fire frequency and size can alter vegetation composition by selecting for more fire-tolerant species, while especially intense and severe fires alter regenerative processes and increase carbon losses from the ecosystem.[369,370,371,372,373] Trees weakened by fire are also more susceptible to insect attacks.[374]

Spruce bark beetle, Swiss needle cast, and sudden oak death are expected to remain key insect and disease agents of change for trees. Yellow-cedar decline is also expanding in the north and impacts from mountain pine beetle may increase in some locations.

Spruce bark beetle is the dominant disturbance agent in southcentral Alaska.[375] Historically, outbreaks have occurred every 30 to 50 years (mid-1700s to present) and have affected 3.7 million total acres (1.5 million hectares, ha) since 1989.[376,377] If warming trends continue, spruce beetle populations will likely be sufficient to infect and kill trees in southcentral Alaska as soon as they reach susceptible size, may expand to new areas in the southwest Yukon Territory, and will largely maintain current infestation patterns in British Columbia by the 2050s (vs. 1961-1990).[378379] The probability of spruce beetle offspring developing in a single year (as opposed to the typical two years) increases throughout the region by 2100 (vs. 1961-1990).[380] Combined with increased overwintering survival and higher drought stress in trees, this could increase the overall population of spruce bark beetle over time.[381]

Climate change is expected to affect the incidence and severity of the disease Swiss needle cast, which reduces growth and needle retention in Douglas-fir stands in wet, coastal, low-elevation forests in the southern NPLCC region.[382,383] Needle retention was 38% to 65% lower within the coastal epidemic area where symptoms were observed, ranging from 1.5 to 2.6 years instead of the typical four years from 1996 to 2006.[384] In coastal Oregon, Douglas-fir growth declined 31% to 100% from 1984 to 1986 due to a prior decade of warmer winters and milder, wetter summers.[385] This is approximately double the historic average impact of 18% to 50% from 1590 to 2011.[386] From 1996 to 2012, the extent of infected forest increased 296%, from 130,966 acres (53,000 ha) to 518,921 acres (210,000 ha).[387] Swiss needle cast is expected to expand north from the central Oregon coast and inland as milder, wetter conditions become the norm, and to decrease from California to southern Oregon where June-July precipitation may remain below the limiting threshold of 3.94 inches (110 mm).[388] In particular, the number of infected needles is projected to increase, on average, 9.2% for every 1.8 °F (1 °C) increase in winter temperature.[389]

Especially wet springs have been linked to increased incidence of sudden oak death in California and Oregon, a trend that may continue where warmer temperatures and sufficient moisture coincide with pathogen introduction or persistence.[390]

In coastal British Columbia and southeast Alaska, yellow-cedar decline is responsible for approximately 70% mortality across 617,763 acres (250,000 ha) of yellow-cedar stands since 1900.[391,392] This culturally and economically important tree species grows fine, shallow roots in wet soils to take advantage of nutrients in early spring, but a loss of insulating snowpack combined with more frequent winter warming over the 20th century dehardened roots too early, proving lethal to many trees especially at lower elevations.[393,394,395,396] Healthy trees remained nearby in more well-drained soil or upslope in multiple soil types where annual snow accumulation exceeded the necessary threshold of 9.84 inches (250 mm).[397] Despite the slow regeneration of yellow-cedar, the species may migrate northeast as well as persist in its current range where snow and temperature conditions remain suitable.[398] Where conditions prove unsuitable, western redcedar, which appears more resistant to decline, may begin to replace yellow-cedar.[399] Western hemlock, mountain hemlock, and shore pine may enter the assemblage as well.[400]

The most detailed projections suggest the largest areas with increased risk of mountain pine beetle outbreak are outside the NPLCC region.[401,402,403] However, future outbreaks in the region may stress whitebark pine, ponderosa pine, and lodgepole pine as outbreaks shift to high elevations in Oregon and Washington.[404] Yet by 2100, outbreaks are expected to decline throughout most of the NPLCC region due to a temperature-driven mistiming in the emergence of adult beetles or a lack of suitable climate conditions for host tree species.[405] Since the late 1800s, outbreaks and subsequent tree mortality occurred in Vancouver Island, the Georgia Basin, Cascade Mountains, and southern Oregon, affecting 348,400 acres per year (140,992 ha/yr) across Oregon from 2004 to 2008.[406,407,408]

In addition to impacts from these key insect and disease agents, impacts from spruce budworm, Sitka spruce aphid, hemlock dwarf mistletoe, western balsam bark beetle, *Armillaria* root disease, and other agents have also occurred or are expected.[409,410,411] As trees become weakened by infestation and infection, they are less able to resist drought and heat stress, may become more susceptible to fire, other insects, or pathogens,[412] may increase fuel loads,[413,414] and affect ecosystem processes,[415,416] all of which influence the growth, productivity, and composition of terrestrial habitats and species.[417.418] Oak mortality, for example, reduces habitat for some wildlife and increases fuel loads, soil erosion, and potentially, the population of co-occurring species such as California bay laurel and coast redwood.[419,420] Conversely, fire, drought and heat stress can increase a tree's susceptibility to infestation and infection.[421]

The frequency and size of landslides, windstorms, and avalanches varies across the region.

Landslides occur in response to prolonged periods of increased precipitation, which decreases slope stability, and as a result of rain-on-snow events and other factors. Landslide frequency increased 33% on Vancouver Island since mid-century (from 303 to 402 landslides), which is nearly double the most frequent slide rate observed in the Holocene (range: 121-221 landslides).[422] Future landslide patterns are expected to mimic peak flow regimes in rain-dominant and mixed rain-snow watersheds.[423] For example, projections for reduced snow in the Pacific Northwest's currently mixed rain-snow watersheds may reduce landslides, provided overall precipitation remains unchanged.[424]

Warm or rainy weather following heavy snowfall can also cause avalanches. The area scoured by an avalanche supports slide alder and other vegetation communities distinct from the surrounding area. In coastal northwest British Columbia, the avalanche rate may increase due to more intense storms, decline due to enhanced slope stability from lower temperature gradients in snowpack, or follow the snow line upslope, particularly near the current treeline where vegetation encroachment may increase.[425,426]

Damage or destruction of trees due to windstorms, known as windthrow, is projected to mimic current patterns in southeast Alaska.[427] Ranging from 1 to 1,000 acre patches (0.4-404.7 ha; typically less than 50 acres, 20 ha), windthrow is the predominant source of disturbance in southeast Alaska, although fire is projected to play an increasing role over time.[428] On Kuiu Island, windthrow has affected 20% of forests.[429] North-facing slopes, wetland forests, and cedar forests are least prone to windthrow.[430]

Implications for ecosystems, habitats, and species

Climate-induced changes in hydrology, fog and drought regimes, growing season, freeze and thaw patterns, and disturbance regimes are already affecting the physical, chemical, and biological characteristics of terrestrial ecosystems. Many of these trends will be exacerbated in the future, benefitting some systems and hampering others. In addition to the general trends and implications described previously, specific impacts on valued ecosystem services (altered soil regimes and carbon sequestration), habitats (including habitat loss and transition), and species (including changes in phenology, range shifts, and community composition) are highlighted here.

Altered soil attributes and carbon sequestration

Soil water stress is projected to increase in the spring and summer in much of the region, while increasing winter soil temperatures may promote tree growth in northern areas and delay, reduce, or eliminate the cold temperatures some Pacific Northwest conifers need to flourish. Carbon storage is expected to decrease despite the persistence of some large carbon stores. These changes affect plant growth and have important implications for atmospheric carbon levels.

Soils are the foundation of terrestrial ecosystems, storing and processing key nutrients such as carbon, nitrogen and phosphorus, mediating the reception, storage and redistribution of precipitation to plants, groundwater and streamflow, and providing a home for diverse flora and fauna.[431] The possibility of a warmer, drier climate, particularly in summer, may increase soil water stress.[432] On the other hand, increasing winter temperatures may ease frost limitations to plant growth in northern areas, yet delay, reduce or eliminate the cold soils needed to meet the winter chilling requirements of Douglas-fir, western hemlock, and other Pacific Northwest conifers.[433] In Alaska and British Columbia, reductions in spring soil moisture and increasing soil water deficits were observed in response to increasing spring temperatures and radiation, and resulting increases in evapotranspiration.[434] Soil water stress is projected to increase in May and June in most of British Columbia and to disappear as soils are recharged in winter (2070-2099 vs. 1961-1990).[435] In the Pacific Northwest, mid-21st century soil conditions may mimic those of approximately 6,000 years ago, when fires were more frequent.[436]

Current and potential carbon (C) storage in the NPLCC region's forests is among the highest in the world.[437] Storage capacities range from 997.9 megagrams of carbon (Mg C) per hectare in British Columbia's temperate old-growth rainforests, 544 to 1179 Mg C per hectare in individual forests of the Pacific Maritime and Montane Cordillera Ecozones and 318 Mg C per hectare on average,[438] and 312 to 430 Mg C per hectare in the soils of Oregon's Cascade and Coast Ranges.[439]

Due to the combined influences of fire, insect infestations, and other disturbances,[440] western forests in Oregon and Washington are projected to lose 1.2 billion megagrams of carbon (Mg C; -23.9%) under a hot-dry scenario, but see small increases under hot-wet (+1.7%) and cool-wet (+2.5%) scenarios (2070-2099 vs. 1971-2000).[441] The loss was projected even with fire suppression included in the simulation.[442] Statewide projections for California are similar: the state may gain 5.5% in new ecosystem carbon (321 million Mg C) under a cooler-wetter scenario or lose 2.2% of total carbon stocks (129 million Mg C) under a warm-dry scenario (2070-2099 vs. 1961-1990).[443] At the same time, 18% of live vegetation carbon and 7% of soil carbon is expected to be lost in California.[444] British Columbia's peatlands as well as the state of Alaska may become carbon sources by 2100, while British Columbia's wet coastal, subalpine, and interior forests will continue to be carbon sinks if stand-replacing disturbances remain rare.[445,446] Projected changes in soil conditions and carbon storage will affect plant growth in the NPLCC region, as well as atmospheric levels of carbon dioxide and other greenhouse gases.[447,448]

Habitat loss and transition

Forests will remain the dominant habitat type, but their distribution and composition may change significantly due to range shifts, expansions, and contractions of many tree species. Changes to oak woodland, savanna, prairie and grassland habitat, and loss of high-elevation habitat are also expected.

Some species are already experiencing suboptimal climate conditions and declining habitat suitability, which has increased vulnerability to current and projected climate change in some cases. Fifteen forest tree species common to western North America are, on average, living farther south or lower in elevation than the locations where climate is now optimal for species success.[449] Higher elevation species such as subalpine fir and noble fir were termed highly vulnerable to the climatic changes in 1976-2006 (vs. 1950-1975), while Alaska yellow-cedar was considered vulnerable in 25% of its baseline range and whitebark pine remained well suited to the climate conditions of 1976-2006 (vs. 1950-1975).[450] Vulnerability in this case refers to a lower probability of occurrence in 1976-2006 compared to 1950-1975: a tree species is considered vulnerable where its modeled baseline range (1950-1975) is modeled as climatically unsuitable (i.e., modeled absent instead of present) for 15 years or more of the 1976 to 2006 timeframe.[451]

General shifts in forest composition are projected for northwest California (evergreen conifer to mixed evergreen forest) and southwest Oregon (temperate to subtropical species including maple, madrone, and oak).[452] This area currently comprises the southern range limit for Pacific silver fir, yellow-cedar and Engelmann spruce and the northern range limit for coast redwood, Jeffrey pine, and Shasta red fir.[453] Temperate and marine coniferous forests are expected to expand in southcentral and southeast Alaska and may serve as biome refugia in a changing climate.[454,455]

Range shifts, expansions, and contractions are also expected for specific tree species. In western North America, observed geographic lags (the distance between the current location of a tree or tree species range and the location of its optimal climate conditions) are projected to double by the 2020s and double again by the 2050s, with especially large lags for northern and coastal populations of Alaska yellow-cedar, Sitka spruce, Pacific silver fir, western hemlock, and western redcedar.[456] Western hemlock and western redcedar may expand their overall range while maintaining most or all of their current range.[457] The same may occur for Douglas-fir,[458,459] although a 4% decline in overall habitat and shifts inland away from coasts have also been projected.[460,461] Western larch may expand to newly climate suitable areas of British Columbia's southern Coast Mountains.[462] However, most of these projections do not account for biological and ecological processes (e.g., fire, insect outbreaks, disease, soil conditions, mortality, growth) that affect tree establishment and survival in both climatically suitable and unsuitable locations.[463,464,465] In western Washington for example, subalpine fir is considered vulnerable to insect disturbance and disease as well as warmer summers and reduced snowpack.[466,467]

Where heat stress induces tree mortality, shifts to shrub- and grass-dominated landscapes may occur in northwestern North America.[468] Oak woodland, prairie, savanna, and grassland were maintained historically by fire and controlled burns by First Nations and Native Americans in the southern NPLCC region.[469,470] Since the 1800s, nearly 90% of British Columbia's coastal Garry-oak woodlands have been lost, largely to land use change.[471] Recent losses may be recovered due to increased climatic habitat suitability in Oregon, British Columbia and especially Washington.[472,473] Or, habitat loss may increase as competition limits post-fire establishment, which is occurring currently with California black oak and Douglas-fir in northwest California.[474]

In high-elevation areas of the NPLCC region, some treelines are advancing upslope in response to warming temperatures, some treelines are retreating, and tree establishment in subalpine meadows is increasing.[475,476,477,478] Upward movements of Pacific silver fir, western hemlock, and other mid-elevation trees are expected as higher elevations become more suitable, which is projected to extirpate or push subalpine trees, meadows and shrubs higher in elevation and reduce alpine and tundra habitat region-wide.[479,480] For example, trees and shrubs are projected to replace alpine and tundra habitats in much of southcentral and southeast Alaska, with a 75% to 90% loss of tundra to boreal and temperate forest projected statewide.[481] Similarly, treeline advance may increase the loss of grasslands isolated on Oregon's Coast Range peaks.[482] In the Olympic Mountains of Washington, Pacific silver fir is projected to move upslope, replacing mountain hemlock and subalpine meadow and leaving room for western hemlock to establish in areas previously dominated by Pacific silver fir.[483] However, complex mountain terrains create microclimates, and these general trends may not hold true where microclimates support continued subalpine habitats.[484,485] For example, the persistence of mountain hemlock in western Washington is considered vulnerable to warmer summers, reduced snowpack, and associated declines in habitat affinity, but microhabitat variability may provide refugia.[486] Where mountain hemlock remains, growth and productivity may increase as warmer, less snowy conditions become more common, although drought stress would continue to reduce productivity in southern Oregon and at low-elevation distribution limits.[487] Frost damage may also increase if earlier snowmelt triggers shoot growth before the last frost.[488]

Projected habitat losses and transitions will tend to be exacerbated where insect disturbance (especially bark beetles) and disease are prevalent or co-occur with drought stress, which when combined can make trees more susceptible to fire as they weaken, dry out, and die. Conversely, large vegetation shifts, such as those from forest to woodland or alpine tundra to forest, are expected to significantly alter historic fire regimes.[489] Habitat losses and transitions affect terrestrial fauna, and are also affected by changes in the phenology, range, and composition of bird, invertebrate, and mammal communities.

Phenology, range shifts, and community composition.

Expected changes to the phenology, range, and composition of bird, invertebrate, and mammal communities will benefit some species and disadvantage others, as well as increase the possibility of novel species assemblages.

Over half (57%) of western U.S. forest birds restricted to a single habitat type show medium to high vulnerability to climate change.[490] Medium vulnerability birds include large flycatchers that feed on aerial insects and birds in riparian or humid forests susceptible to increased drought and more frequent fires.[491] For example in Washington, the olive-sided flycatcher and black-backed woodpecker may benefit from increased forest fire intensity, while flammulated owl, western grebe, Clark’s grebe, black-necked stilt, American avocet, long-billed curlew, and black tern are at high risk from changing fire, temperature, and precipitation regimes.[492] Gray-crowned rosy-finch and American pipit may move north to more suitable habitats, while northern shrike, snowy owl, and common redpoll may cease overwintering as temperatures rise or face more competition from increased winter resident populations.[493] Rosy-finches and white-tailed ptarmigan are expected to decline or be extirpated as alpine habitats in Washington and Alaska shrink, while Alaska’s blue grouse may benefit as its Sitka spruce-western hemlock habitat moves upslope.[494] In central Oregon, habitat suitability for winter wrens and song sparrows is expected to increase slightly, yet a scenario of minor warming and 5% reduced fecundity (reproductive success) resulted in 61% and 27% population declines, respectively, by 2100 (vs. 1990).[495] Thirty-six percent (36%; 128 of 358) of examined bird taxa in California are vulnerable to climate change, with grassland and oak woodland taxa being least vulnerable.[496] Indeed, the projected northward expansion of prairie-oak habitat may support northward movements of ash-throated flycatcher, blue-gray gnatcatcher, white-tailed kite, western scrub jay, slender-billed white-breasted nuthatch, lark sparrow, and western meadowlark.[497]

Several birds in the NPLCC region are altering migratory and breeding patterns in response to climate change. Requiring 138 ice-free days to fledge their young, Alaska’s trumpeter swans have already extended their breeding season in response to longer growing and ice-free seasons and are projected to shift their range northward and westward over the 21st century (vs. 2000-2009).[498] While Wilson’s phalarope has shortened its stay in British Columbia, Swainson’s thrush and yellow warbler are arriving earlier and leaving later, with Swainson’s thrush spending approximately ten more days in coastal areas during the breeding season.[499] All three species show small range shifts northward, and Lewis’s woodpecker is using more of its northern range.[500] Northern flickers laid their eggs 1.15 days earlier for every degree warmer at their Pacific Northwest breeding grounds.[501] The mismatch between peak prey availability and egg-laying date observed for other species was not observed here, suggesting earlier egg-laying could benefit individuals provided spring temperatures are sufficiently high.[502]

Edith's checkerspot butterfly and the sachem skipper, two butterflies found in Washington, Oregon, and California, are shifting their ranges northward, as well as upward (Edith's checkerspot) and expanding across the Cascade Mountains (sachem skipper).[503,504,505] Warming temperatures, particularly combined with more rain and less snow, are expected to enhance sachem skipper persistence.[506] In Oregon and California, the propertius duskywing butterfly has evolved to prefer certain oak species over others and was unable to colonize less preferable oak species under simulated climate change.[507]

Milder, less snowy winters are projected to further isolate habitat for the snow-dependent wolverine, potentially benefit moose, mountain goat and deer populations due to increases in forage, and may benefit or strain Canada lynx, which already compete with coyote and cougar for food and habitat, depending on the response of key prey species such as snowshoe hare to climate change.[508,509,510] Some small, northern mammals such as masked shrew may fare better as prey availability increases, while others such as the Wrangell Island red-backed vole may lose habitat if warmer, drier conditions prevail in clearcuts and second-growth forests that currently meet their high moisture requirements.[511,512] A red squirrel population in southwest Yukon advanced breeding by 18 days (6 days per generation) from 1989 to 2001 in response to increasing food abundance (3.7 days per generation) and spring temperatures.[513] Highly suitable northern spotted owl habitat is projected to increase 2.52% and shift 15.2 miles (24.4 km) north-northeast by 2061-2090 (vs. 1961-1990 range centroid), where prey species such as woodrat may grow more abundant over time.[514] Competition with non-native barred owl may make this range unavailable in the interim, or the northern spotted owl may prove more resilient to competition due to climate change.[515]

Combined with projected changes in forest, woodland, prairie, and high-elevation habitat, novel communities – species combinations foreign to an area currently or historically – may develop in the NPLCC region. Indeed, significantly more mammal species are projected to be gained than lost from four western U.S. national parks (Glacier, Yellowstone, Yosemite, Zion), suggesting fundamental changes in community structure as new species are introduced.[516] Such changes will further challenge policy and management frameworks that are just beginning to respond to the effects of a changing climate.

Adaptation to climate change in the NPLCC's terrestrial ecosystems

Given that the atmospheric concentration of CO_2 will likely continue to increase and exacerbate climate change effects for the foreseeable future,[517] adaptation has emerged as an appropriate response to the unavoidable impacts of climate change.[518] Adaptive actions reduce a system's vulnerability,[519] increase its capacity to withstand or be resilient to change,[520,521] and/or transform systems to a new state compatible with likely future conditions.[522,523]

Although uncertainty and gaps in knowledge exist, sufficient information is available to plan for and address climate change impacts now.[524] Implementing strategic adaptation actions early may reduce severe impacts and prevent the need for more costly actions in the future.[525] Adaptation actions may occur in legal, regulatory, or decision-making processes, as well as in on-the-ground conservation activities.[526,527,528,529] Decision-makers may also create or modify laws, regulations, and policies to better incorporate current and projected climate change effects.[530]

Examples of planned or ongoing adaptation efforts in the NPLCC region include:

- In Alaska, the four members of the Prince of Wales Island Tribal Environmental Coalition, the **Organized Village of Kasaan, Craig Tribal Association, Hydaburg Cooperative Association,** and **Klawock Cooperative Association,** are conducting multi-generational interviews to determine if the traditional gathering calendar has changed over time.[531,532] The project applies traditional ecological knowledge to better understand the impacts of climate change on traditionally gathered resources and to inform natural resources decision making.[533] While definitions of traditional ecological knowledge vary, they reflect "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment."[534]
- The **Future Forest Ecosystem Initiative** is "adapting British Columbia's forest and range management framework so that it continues to maintain and enhance the resilience and productivity of B.C.'s ecosystems as our climate changes."[535] In addition to a strategic plan, a scientific council to guide funding decisions, a provincial vulnerability assessment, and a monitoring strategy, the Initiative supports or conducts work on climate change and fire management, climate-based seed transfer, and tree species selection. Extension work includes a seminar series and e-newsletter.[536]
- As part of the WestWide Climate Initiative, Washington's **Olympic National Park** and **Olympic National Forest** worked with the University of Washington **Climate Impacts Group** to assess resource vulnerabilities to climate change and develop adaptation options.[537,538,539] Analysis focused on the four resource areas of most importance to agency resource managers and most likely to be affected by climate change: hydrology and roads, vegetation, wildlife, and fish.[540] Adaptation options are specific to each resource area. For example, options to preserve tree genetic diversity, increase disease resistance in western white pine and whitebark pine, and increase capacity to restore forest lands after disturbance were suggested for the vegetation resource area.[541] This approach was adopted in north-central Washington, where a broad range of scientists, managers, and stakeholders formed the **North Cascadia Adaptation Partnership** (NCAP). The NCAP process identified and assessed the vulnerability of four key resource sectors, namely hydrology and access, vegetation and ecological disturbance, wildlife, and fisheries, in two national forests and two national parks (5.9 million acres, 2.4 million ha).[542,543] Adaptation options were also developed for each sector and include options to address changing landslide and windstorm risk, ecological disturbances (e.g., insects, pathogens, invasive species), and specific habitats and associated species (e.g., alpine and subalpine habitats, low-elevation forests on the western slopes of the Cascade Mountains).[544,545,546]
- In western Oregon's **Willamette Valley,** a landscape-level approach is being used to understand the effects of climate and land use change on wildfire in historic oak-pine savanna. The goal of the project is to identify options for reducing the risk of wildfire and the loss of already imperiled oak-pine savanna ecosystems.[547]
- The **Yurok Tribe**, whose ancestral lands are located in the lower Klamath River watershed and surrounding areas, is collecting and mapping traditional ecological knowledge of changes in the distribution and composition of culturally significant species over time. The information will be used to better understand current and future climate change impacts, and guide future

> management of Yurok ancestral resources.[548] Similarly, the **Karuk Tribe** of the mid-Klamath and Salmon River watersheds is exploring barriers to integrating traditional ecological knowledge into land management, with the goal of prioritizing future resource and land management based on existing barriers and management practices.[549] For both tribes, these projects are part of larger, multi-year efforts to plan for and respond to climate change.[550,551]

Adaptive approaches to addressing climate change impacts will vary by sector and management goal, across space and time, and by the goals and preferences of those engaged in the process.[552] In all cases, adaptation is not a one-time activity, but is instead a continuous process, constantly evolving as new information is acquired and interim goals are achieved or reassessed.[553] Ultimately, successful climate change adaptation supports a system's capacity to maintain its past or current state in light of climate impacts or transform to a new state amenable to likely future conditions.[554]

Table 1. Observed trends and future projections for summer and winter temperature in the NPLCC region.
°F with °C in parentheses

Location	Summer		Winter		Time Periods
	Observed Trends	*Future Projections*	*Observed Trends*	*Future Projections*	
Near Juneau, Alaska	2.2 (1.2)	N/A	6.2 (3.4)	N/A	Trends: 1949-2009 Projections: N/A
Coastal British Columbia	0.31 to 0.74 (0.17 to 0.41)	2.7 to 9.0 (1.5 to 5.0)	0.40 to 0.52 (0.22 to 0.29)	0 to 6.3 (0 to 3.5)	Trends: 1950-2006 Projections: 2050 vs. 1961-1990
Pacific Northwest*	1.93 (1.07)	8.1 (4.5)	3.3 (1.83)	5.9 (3.3)	Trends: 1920-2000 Projections: 2080s vs. 1970-1999
Northwest California	N/A	>2.9 and <12 (>1.6 and <6.4)	N/A	>3.1 and <6.1 (>1.7 and <3.4)	Trends: N/A Projections: 2070-2099 vs.1961-1990

N/A: Specific data is unavailable.
** The Pacific Northwest includes Washington, Idaho, Oregon, and southern British Columbia.*
Sources: Ainsworth & Fritsch (2011, personal communication); B.C. Ministry of Environment (2007); Cayan et al. (2008); Karl, Melillo & Peterson (2009); Mote (2003); Mote and Salathé, Jr. (2010)

Table 2. Observed trends and future projections for average warm and cool season precipitation in the NPLCC region.

Location	Summer / Warm Season*		Winter / Cool Season**		Time Periods
	Observed Trends Inches (cm)	*Future Projections*	*Observed Trends* Inches (cm)	*Future Projections*	
Near Juneau, Alaska	1.67 (4.24)	+5.7%	2.17 inches (5.51 cm)	N/A	Trends: 1981-2010 vs. 1971-2000 Projections: 2099 vs. 2000
Coastal British Columbia	30-year: 0.14 (3.50) 100-year: 0.036 (0.91)	-8 to -13%	30-year: -0.24 (-6.08) 100-year: 0.13 (3.39)	+6%	Trends: 1971-2004 and 1901-2004 Projections: 2050s vs. 1961-1990
Pacific Northwest†	0.39 (0.99)	-14%	2.47 (6.27)	+8%	Trends: 1920-2000 Projections: 2070-2099 vs. 1970-1999
Northwest California	N/A	N/A	N/A	N/A	N/A

N/A: Specific data is unavailable.
** The definition varies by study area. Alaska's warm season is April to September for observed trends and during the growing season for future projections (time period between last spring freeze and first fall frost), British Columbia's summer is June to August, and the Pacific Northwest summer is July to September.*
*** The definition varies by study area. Alaska's cool season is October to March, British Columbia's winter is December to February, and the Pacific Northwest winter is January to March.*
† *The Pacific Northwest includes Washington, Idaho, Oregon, and southern British Columbia.*
Sources: Ainsworth & Fritsch (2011, personal communication); Alaska Center for Climate Assessment & Policy (2009); B.C. Ministry of Environment (2006); Killam et al. (2010); Mote (2003); Mote and Salathé, Jr. (2010) Pike et al. (2010).

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Executive Summaries for Marine & Coastal, Freshwater, and Terrestrial Systems

Prepared by:
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