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

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

Executive Summary

Patricia Tillmann
National Wildlife Federation

Funded by the North Pacific Landscape Conservation Cooperative

December 2013

* email: tillmannp@nwf.org ** email: glick@nwf.org
Executive Summary

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, 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 (CO₂) 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 CO₂ increased** to ~394 parts per million (ppm)³ in October 2013 from the pre-industrial value of 278 ppm,³ higher than any level in the past 650,000 years.⁵ By 2100, the atmospheric concentration of CO₂ is projected to exceed 400 ppm and may exceed 1000 ppm, depending on future greenhouse gas emissions.⁶,⁷ As the level of CO₂ increases, ecosystem productivity and carbon storage may also increase, particularly in combination with warmer temperatures and sufficient moisture and nutrients.⁸,⁹

- **Annual average temperatures increased** ~1-2°F (~0.6-1°C) from coastal British Columbia to northwestern California over the 20th century¹⁰,¹¹ and 3.4°F (~1.9°C) in Alaska from 1949 to 2009.¹² 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.¹³,¹⁴,¹⁵ 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).¹⁶,¹⁷,¹⁸ 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.\textsuperscript{19,20,21} 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).\textsuperscript{22} These temperature increases will lengthen the growing season and frost-free season,\textsuperscript{23,24,25,26,27} 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.\textsuperscript{28,29,30}

- **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 20\textsuperscript{th} century, depending on the time period studied.\textsuperscript{31} Over the 21\textsuperscript{st} 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),\textsuperscript{32} and more intense rain possible.\textsuperscript{33,34,35,36,37,38} This shift has already been observed in northwest California, where winter and early spring precipitation increased and fall precipitation decreased from 1925 to 2008.\textsuperscript{39} 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.\textsuperscript{40,41,42,43,44} More frequent or intense floods may increase landslides and remove soil nutrients from forest ecosystems.\textsuperscript{45,46}

- **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.\textsuperscript{47,48} By altering the behavior, growth, development, and survival of existing species, novel climates may disrupt existing species relationships and modify current community composition.\textsuperscript{49} Novel or no-analog communities, which have not been observed historically or currently, may develop, potentially challenging existing management and conservation practice.\textsuperscript{50}

**Impacts of climate change on terrestrial systems**

Increases in CO\textsubscript{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.\textsuperscript{51} 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.\textsuperscript{52,53,54}

Much of the NPLCC region currently experiences little drought,\textsuperscript{55} but changes in potential evaporation and increases in drought and drought stress are projected for the 21\textsuperscript{st} century.\textsuperscript{56,57,58} 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). In Washington, average water deficit for lodgepole pine is projected to increase 432% by the 2080s (vs. 1980-1999). 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). However, fog patterns may change in northwest California, altering the annual contribution of fog water and risk of water stress in coast redwood ecosystems. 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. Drought stress typically increases fire risk and may reduce the ability of trees to repel insect attacks and disease, which may promote prairie expansion where they border affected forests. Conversely, trees weakened by insect infestation or disease often are more prone to drought stress.

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

The length of the growing season increased $12 \pm 4$ days globally since the 1960s, at least two days per decade in the western United States since 1948, and up to 6.97 days per decade in southcentral and southeast Alaska from 1949 to 1997. However in high-elevation areas of the Cascade Mountains, little change in the length of the growing season was observed from 1950 to 1999. 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. 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, with increases of 20 to 40 days projected for Alaska by 2100 (vs. 1961-1990), particularly in coastal areas. 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. 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. However, moisture and nutrient limitations such as those associated with drier summers may forestall or prevent significant productivity gains. Fewer freeze events and a longer frost-free season may benefit deer and moose by increasing food availability, 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.).

**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. When fires occur, they are severe (severity is the degree to which fire alters a site). The region’s prairies, grasslands, oak woodlands, savanna, and northwest California are characterized by more frequent (6-50 years), low to moderate severity fire. 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. 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.

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. In the Pacific Northwest, area burned is projected to increase 78% by 2050, relative to 2000. 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. Extreme fire danger is expected to increase zero to twelve days in the southern NPLCC region. In northern California, the probability of large fires (> 500 acres, > 202 ha) is projected to increase 15% to 90% by 2100 (vs. 1961-1990), 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). However, declines in area burned are projected for some coastal areas, including an 8% decline in overall area burned in the Humboldt Ranger Unit (2 x CO₂ vs. present climate). Given the wetness of British Columbia’s coastal climate, fires in that region should continue to be rare. 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. Trees weakened by fire are also more susceptible to insect attacks.

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. 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. 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). 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). Combined with increased overwintering survival and higher drought stress in trees, this could increase the overall population of spruce bark beetle over time.

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. 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. 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. This is approximately double the historic average impact of 18% to 50% from 1590 to 2011. 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). 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).\textsuperscript{133} 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.\textsuperscript{134}

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.\textsuperscript{135}

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.\textsuperscript{136,137} 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 20\textsuperscript{th} century dehardened roots too early, proving lethal to many trees especially at lower elevations.\textsuperscript{138,139,140,141} 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).\textsuperscript{142} 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.\textsuperscript{143} Where conditions prove unsuitable, western redcedar, which appears more resistant to decline, may begin to replace yellow-cedar.\textsuperscript{144} Western hemlock, mountain hemlock, and shore pine may enter the assemblage as well.\textsuperscript{145}

The most detailed projections suggest the largest areas with increased risk of mountain pine beetle outbreak are outside the NPLCC region.\textsuperscript{146,147,148} 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.\textsuperscript{149} 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.\textsuperscript{150} 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.\textsuperscript{151,152,153}

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.\textsuperscript{154,155,156} 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,\textsuperscript{157} may increase fuel loads,\textsuperscript{158,159} and affect ecosystem processes,\textsuperscript{160,161} all of which influence the growth, productivity, and composition of terrestrial habitats and species.\textsuperscript{162,163} 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.\textsuperscript{164,165} Conversely, fire, drought and heat stress can increase a tree’s susceptibility to infestation and infection.\textsuperscript{166}

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).\textsuperscript{167} Future landslide patterns are expected to mimic peak flow regimes in rain-dominant and mixed rain-snow watersheds.\textsuperscript{168} For example,
projections for reduced snow in the Pacific Northwest’s currently mixed rain-snow watersheds may reduce landslides, provided overall precipitation remains unchanged.169

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.170,171

Damage or destruction of trees due to windstorms, known as windthrow, is projected to mimic current patterns in southeast Alaska.172 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.173 On Kuiu Island, windthrow has affected 20% of forests.174 North-facing slopes, wetland forests, and cedar forests are least prone to windthrow.175

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.176 The possibility of a warmer, drier climate, particularly in summer, may increase soil water stress.177 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.178 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.179 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).180 In the Pacific Northwest, mid-21st century soil conditions may mimic those of approximately 6,000 years ago, when fires were more frequent.181
Current and potential carbon (C) storage in the NPLCC region’s forests is among the highest in the world.\textsuperscript{182} 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,\textsuperscript{183} and 312 to 430 Mg C per hectare in the soils of Oregon’s Cascade and Coast Ranges.\textsuperscript{184}

Due to the combined influences of fire, insect infestations, and other disturbances,\textsuperscript{185} 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).\textsuperscript{186} The loss was projected even with fire suppression included in the simulation.\textsuperscript{187} 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).\textsuperscript{188} At the same time, 18\% of live vegetation carbon and 7\% of soil carbon is expected to be lost in California.\textsuperscript{189} 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.\textsuperscript{190,191} 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.\textsuperscript{192,193}

**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.\textsuperscript{194} 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).\textsuperscript{195} 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.\textsuperscript{196}

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).\textsuperscript{197} 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.\textsuperscript{198} Temperate and marine coniferous forests are expected to expand in southcentral and southeast Alaska and may serve as biome refugia in a changing climate.\textsuperscript{199,200}

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.\textsuperscript{201} Western hemlock and western redcedar may expand their overall range while maintaining most or all of their current range.\textsuperscript{202} The same may occur for Douglas-fir,\textsuperscript{203,204} although a 4\% decline in overall habitat and shifts inland away from coasts have also been projected.\textsuperscript{205,206} Western larch may expand to newly climate suitable areas of British Columbia’s southern Coast Mountains.\textsuperscript{207} 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.\textsuperscript{208,209,210} In western Washington for example, subalpine fir is considered vulnerable to insect disturbance and disease as well as warmer summers and reduced snowpack.\textsuperscript{211,212}

Where heat stress induces tree mortality, shifts to shrub- and grass-dominated landscapes may occur in northwestern North America.\textsuperscript{213} 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.\textsuperscript{214,215} Since the 1800s, nearly 90\% of British Columbia’s coastal Garry-oak woodlands have been lost, largely to land use change.\textsuperscript{216} Recent losses may be recovered due to increased climatic habitat suitability in Oregon, British Columbia and especially Washington.\textsuperscript{217,218} 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.\textsuperscript{219}

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.\textsuperscript{220,221,222,223} 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.\textsuperscript{224,225} 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.\textsuperscript{226} Similarly, treeline advance may increase the loss of grasslands isolated on Oregon’s Coast Range peaks.\textsuperscript{227} 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.\textsuperscript{228} However, complex mountain terrains create microclimates, and these general trends may not hold true where microclimates support continued subalpine habitats.\textsuperscript{229,230} 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.\textsuperscript{231} 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.\textsuperscript{232} Frost damage may also increase if earlier snowmelt triggers shoot growth before the last frost.\textsuperscript{233}

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.\textsuperscript{234} 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.\textsuperscript{235} 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.\textsuperscript{236} 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.\textsuperscript{237} Gray-crowned rosy-finches 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.\textsuperscript{238} 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.\textsuperscript{239} 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).\textsuperscript{240} 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.\textsuperscript{241} 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.\textsuperscript{242}

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 21\textsuperscript{st} century (vs. 2000-2009).\textsuperscript{243} 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.\textsuperscript{244} All three species show small range shifts northward, and Lewis’s woodpecker is using more of its northern range.\textsuperscript{245} Northern flickers laid their eggs 1.15 days earlier for every degree warmer at their Pacific Northwest breeding grounds.\textsuperscript{246} 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.\textsuperscript{247}

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).\textsuperscript{248,249,250} Warming temperatures, particularly combined with more rain and less snow, are expected to enhance sachem skipper persistence.\textsuperscript{251} 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.\textsuperscript{252} 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. 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. 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. 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. 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. 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. 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 CO₂ will likely continue to increase and exacerbate climate change effects for the foreseeable future, adaptation has emerged as an appropriate response to the unavoidable impacts of climate change. Adaptive actions reduce a system’s vulnerability, increase its capacity to withstand or be resilient to change, and/or transform systems to a new state compatible with likely future conditions.

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

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. 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. 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.”
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.” 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.

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. 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. 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. 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). 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).

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.

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. 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. For both tribes, these projects are part of larger, multi-year efforts to plan for and respond to climate change.

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

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

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.

<table>
<thead>
<tr>
<th>Location</th>
<th>Summer / Warm Season*</th>
<th>Winter / Cool Season**</th>
<th>Time Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near Juneau, Alaska</td>
<td>1.67 (4.24)</td>
<td>+5.7%</td>
<td>2.17 inches (5.51 cm)</td>
</tr>
<tr>
<td>Coastal British Columbia</td>
<td>30-year: 0.14 (3.50)</td>
<td>-8 to -13%</td>
<td>30-year: -0.24 (-6.08)</td>
</tr>
<tr>
<td></td>
<td>100-year: 0.036 (0.91)</td>
<td></td>
<td>100-year: 0.13 (3.39)</td>
</tr>
<tr>
<td>Pacific Northwest†</td>
<td>0.39 (0.99)</td>
<td>-14%</td>
<td>2.47 (6.27)</td>
</tr>
<tr>
<td>Northwest California</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

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).


9 Pojar (2010)


For the Pacific Northwest, Mote (2003). Information on average seasonal temperature change in California is not available, although information on maximum and minimum seasonal temperature change is available in Chapter III.2.


Pojar (2010)


For B.C., B.C. 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.


Cayan et al. (2008)


46 Grimm et al. (2012); Peng et al. (2008); Peterman & Bachelet (2012)

47 Ackerly (2012)


50 Williams & Jackson (2007)


52 Allen et al. (2010); Dale et al. (2008); Grimm et al. (2012); Peng et al. (2008); Peterman & Bachelet (2012); Ryan et al. (2012)


Coops et al. (2010)


Ryan et al. (2012)


Limm & Dawson (2010)

Pojar et al. (2010); Shafer et al. (2010)


Shafer et al. (2010)


Running & Mills (2009)

Jezierski et al. (2010)

Arora & Boer (2005)

Wolken et al. (2011)

Ackerly (2012)

Coops et al. (2010); Ryan et al. (2012)


Wolken et al. (2011)


Shafer et al. (2001)


Fried et al. (2004)

Pojar (2010)

Littell et al. (2010); Prichard et al. (2009); Rogers et al. (2011); Ryan et al. (2012)


Shafer et al. (2010)

Berg & Anderson (2006); Kelly et al. (2007)


Berg et al. (2006);


Berg et al. (2006)

Kliejunas (2011); Sturrock et al. (2011)


Stone et al. (2008)


Ibid.

Ibid.

Lee et al. (2013); Stone et al. (2008)

Shafer et al. (2010)

Hennon et al. (2012); Shafer et al. (2010)


D’Amore & Hennon (2006); Hennon et al. (2012)


Hennon et al. (2012)

Ibid.

D’Amore et al. (2009); Hennon et al. (2012)

Hennon et al. (2012)

Bentz et al. (2010); Littell et al. (2010); Shafer et al. (2010)


168 Pike et al. (2010)

169 Dale et al. (2008)

170 Pike et al. (2010)


172 Pojar (2010)


175 Nowacki & Kramer (1998)


177 Peterman & Bachelet (2012); Shafer et al. (2001)

178 Coops et al. (2010); Shafer et al. (2001)

179 Coops et al. (2010); Peterman & Bachelet (2012)

180 Coops et al. (2010)

181 Whitlock et al. (2003)

182 Pojar (2010); Shafer et al. (2010)

183 Pojar (2010)


185 Ryan et al. (2012)

186 Rogers et al. (2011)

187 Rogers et al. (2011)

188 Lenihan et al. (2008a)


190 Pojar (2010)


192 Coops et al. (2010); Kareiva et al. (2012); Shafer et al. (2001)


Coops & Waring (2011b)

Lenihan et al. (2008a); Rogers et al. (2011); Shafer et al. (2010)

Frost & Sweeney (2000)

Bachelet et al. (2005)


Gray & Hamann (2013)

Coops & Waring (2011b); Pojar (2010)

Coops & Waring (2011b)


Coops et al. (2010); Littell et al. (2010)


Aubry et al. (2011)


Bachelet et al. (2011)

Pojar (2010)


Pojar (2010)

Cocking et al. (2012)


256 Jeziorski et al. (2010); Kelly et al. (2007)


260 Carroll (2010)


267 Glick et al. (2009)


269 Vose et al. (2012)

Millar et al. (2012)


Conservation Biology Institute (n.d.)


Ray (n.d.); Viles (2013)


Littell et al. (2010); Millar et al. (2012); Stein et al. (2012); Vose et al. (2012)

Stein et al. (2012)

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

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

Prepared by:
Patricia Tillmann and Patty Glick

December 2013

Funding for this project was provided by the North Pacific Landscape Conservation Cooperative.

Partner: University of Washington Climate Impacts Group.

National Wildlife Federation
Pacific Regional Center – Seattle

2100 Westlake Ave. N., Suite 107
Seattle, Washington 98109

(206) 285-8707
(206) 285-8698 fax