

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

Patricia Tillmann* and Patty Glick**
National Wildlife Federation

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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 mischaracterizations 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,^{1,2} 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,⁴ 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 century^{10,11} 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.^{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).²² These temperature increases will lengthen the growing season and frost-free season,^{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.^{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 20th century, depending on the time period studied.³¹ 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),³² and more intense rain possible.^{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 2008.³⁹ 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.^{40,41,42,43,44} More frequent or intense floods may increase landslides and remove soil nutrients from forest ecosystems.^{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.^{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.⁴⁹ Novel or no-analog communities, which have not been observed historically or currently, may develop, potentially challenging existing management and conservation practice.⁵⁰

Impacts of climate change on terrestrial systems

Increases in CO₂ 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.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.^{52,53,54}

Much of the NPLCC region currently experiences little drought,⁵⁵ but changes in potential evaporation and increases in drought and drought stress are projected for the 21st century.^{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).⁵⁹ In Washington, average water deficit for lodgepole pine is projected to increase 432% by the 2080s (vs. 1980-1999).⁶⁰ 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).⁶¹ However, fog patterns may change in northwest California, altering the annual contribution of fog water and risk of water stress in coast redwood ecosystems.^{62,63} 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.^{64,65} Drought stress typically increases fire risk and may reduce the ability of trees to repel insect attacks and disease,^{66,67,68,69,70} which may promote prairie expansion where they border affected forests.⁷¹ Conversely, trees weakened by insect infestation or disease often are more prone to drought stress.⁷²

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

The length of the growing season increased 12 ± 4 days globally since the 1960s,⁷³ at least two days per decade in the western United States since 1948,⁷⁴ and up to 6.97 days per decade in southcentral and southeast Alaska from 1949 to 1997.^{75,76} However in high-elevation areas of the Cascade Mountains, little change in the length of the growing season was observed from 1950 to 1999.⁷⁷ 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.⁷⁸ 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,⁷⁹ with increases of 20 to 40 days projected for Alaska by 2100 (vs. 1961-1990), particularly in coastal areas.⁸⁰ 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 1971-2000.⁸¹ 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.^{82,83} However, moisture and nutrient limitations such as those associated with drier summers may forestall or prevent significant productivity gains.⁸⁴ Fewer freeze events and a longer frost-free season may benefit deer and moose by increasing food availability,^{85,86} 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.).⁸⁷

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.^{88,89,90,91,92,93,94,95,96} When fires occur, typically they are severe (severity is the degree to which fire alters a site).⁹⁷ The region's prairies, grasslands, oak woodlands, savanna, and northwest California are characterized by more frequent (6-50 years), low to moderate severity fire.^{98,99,100} 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.¹⁰¹ 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.¹⁰²

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.^{103,104} In the Pacific Northwest, area burned is projected to increase 78% by 2050, relative to 2000.¹⁰⁵ 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 1971-2000.¹⁰⁶ Extreme fire danger is expected to increase zero to twelve days in the southern NPLCC region.¹⁰⁷ In northern California, the probability of large fires (> 500 acres, > 202 ha) is projected to increase 15% to 90% by 2100 (vs. 1961-1990),¹⁰⁸ 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).^{109,110} However, declines in area burned are projected for some coastal areas,¹¹¹ including an 8% decline in overall area burned in the Humboldt Ranger Unit (2 x CO₂ vs. present climate).¹¹² Given the wetness of British Columbia's coastal climate, fires in that region should continue to be rare.¹¹³ 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.^{114,115,116,117,118} Trees weakened by fire are also more susceptible to insect attacks.¹¹⁹

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.¹²⁰ 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.^{121,122} 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).^{123,124} 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).¹²⁵ Combined with increased overwintering survival and higher drought stress in trees, this could increase the overall population of spruce bark beetle over time.¹²⁶

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.^{127,128} 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 2006.¹²⁹ 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.¹³⁰ This is approximately double the historic average impact of 18% to 50% from 1590 to 2011.¹³¹ 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).¹³² 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).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.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.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.^{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 20th century dehardened roots too early, proving lethal to many trees especially at lower elevations.^{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).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.¹⁴³ Where conditions prove unsuitable, western redcedar, which appears more resistant to decline, may begin to replace yellow-cedar.¹⁴⁴ Western hemlock, mountain hemlock, and shore pine may enter the assemblage as well.¹⁴⁵

The most detailed projections suggest the largest areas with increased risk of mountain pine beetle outbreak are outside the NPLCC region.^{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.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.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.^{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.^{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,¹⁵⁷ may increase fuel loads,^{158,159} and affect ecosystem processes,^{160,161} all of which influence the growth, productivity, and composition of terrestrial habitats and species.^{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.^{164,165} Conversely, fire, drought and heat stress can increase a tree's susceptibility to infestation and infection.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).¹⁶⁷ Future landslide patterns are expected to mimic peak flow regimes in rain-dominant and mixed rain-snow watersheds.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.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,¹⁸³ and 312 to 430 Mg C per hectare in the soils of Oregon's Cascade and Coast Ranges.¹⁸⁴

Due to the combined influences of fire, insect infestations, and other disturbances,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).¹⁸⁶ The loss was projected even with fire suppression included in the simulation.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).¹⁸⁸ At the same time, 18% of live vegetation carbon and 7% of soil carbon is expected to be lost in California.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.^{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.^{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.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).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.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).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.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.^{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.²⁰¹ Western hemlock and western redcedar may expand their overall range while maintaining most or all of their current range.²⁰² The same may occur for Douglas-fir,^{203,204} although a 4% decline in overall habitat and shifts inland away from coasts have also been projected.^{205,206} Western larch may expand to newly climate suitable areas of British Columbia's southern Coast Mountains.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.^{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.^{211,212}

Where heat stress induces tree mortality, shifts to shrub- and grass-dominated landscapes may occur in northwestern North America.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.^{214,215} Since the 1800s, nearly 90% of British Columbia's coastal Garry-oak woodlands have been lost, largely to land use change.²¹⁶ Recent losses may be recovered due to increased climatic habitat suitability in Oregon, British Columbia and especially Washington.^{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.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.^{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.^{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.²²⁶ Similarly, treeline advance may increase the loss of grasslands isolated on Oregon's Coast Range peaks.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.²²⁸ However, complex mountain terrains create microclimates, and these general trends may not hold true where microclimates support continued subalpine habitats.^{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.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.²³² Frost damage may also increase if earlier snowmelt triggers shoot growth before the last frost.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.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.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.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.²³⁷ 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.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.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).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.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.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 21st century (vs. 2000-2009).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.²⁴⁴ All three species show small range shifts northward, and Lewis's woodpecker is using more of its northern range.²⁴⁵ Northern flickers laid their eggs 1.15 days earlier for every degree warmer at their Pacific Northwest breeding grounds.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.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).^{248,249,250} Warming temperatures, particularly combined with more rain and less snow, are expected to enhance sachem skipper persistence.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.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.^{253,254,255} 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.^{256,257} 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.²⁵⁸ 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.²⁵⁹ 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.²⁶⁰

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.²⁶¹ 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,²⁶² adaptation has emerged as an appropriate response to the unavoidable impacts of climate change.²⁶³ Adaptive actions reduce a system’s vulnerability,²⁶⁴ increase its capacity to withstand or be resilient to change,^{265,266} and/or transform systems to a new state compatible with likely future conditions.^{267,268}

Although uncertainty and gaps in knowledge exist, sufficient information is available to plan for and address climate change impacts now.²⁶⁹ Implementing strategic adaptation actions early may reduce severe impacts and prevent the need for more costly actions in the future.²⁷⁰ Adaptation actions may occur in legal, regulatory, or decision-making processes, as well as in on-the-ground conservation activities.^{271,272,273,274} Decision-makers may also create or modify laws, regulations, and policies to better incorporate current and projected climate change effects.²⁷⁵ 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.^{276,277} 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.²⁷⁸ 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.”²⁷⁹

- 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.”²⁸⁰ 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.²⁸¹
- 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.^{282,283,284} 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.²⁸⁵ 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.²⁸⁶ 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).^{287,288} 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).^{289,290,291}
- 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.²⁹²
- 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.²⁹³ 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.²⁹⁴ For both tribes, these projects are part of larger, multi-year efforts to plan for and respond to climate change.^{295,296}

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.²⁹⁷ 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.²⁹⁸ 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.²⁹⁹

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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List of frequently used acronyms and abbreviations

AOGCM	Atmosphere-Ocean General Circulation Model
AR4	4 th Assessment Report (produced by IPCC)
AR5	5 th Assessment Report (produced by IPCC)
BC	Province of British Columbia, Canada
BP	Before Present
CA	State of California, United States
CE	Common Era
CGCM	Coupled Global Climate Model, Canada
CIG	Climate Impacts Group, University of Washington, United States
CMIP	Coupled Model Intercomparison Project
CNRM	Centre National de Recherches Météorologiques, France
CO ₂	Carbon Dioxide
CRCM	Canadian Regional Climate Model
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
DGVM	Dynamic General Vegetation Model / Dynamic Global Vegetation Model
ENSO	El Niño-Southern Oscillation
EPA	Environmental Protection Agency, United States
GCM	Global Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory, United States
GHG	Greenhouse Gas
GISS	Goddard Institute for Space Studies, United States
HadCM3	Hadley Centre Climate Model, Version 3, United Kingdom
IPCC	Intergovernmental Panel on Climate Change
LCC	Landscape Conservation Cooperative
LEK	Local Ecological Knowledge
MIROC	Model for Interdisciplinary Research on Climate, Japan
MoE	Ministry of Environment, British Columbia
NASA	National Aeronautics and Space Administration, United States
NCAR	National Center for Atmospheric Research, United States
NIES	National Institute of Environmental Studies, Japan
NPLCC	North Pacific Landscape Conservation Cooperative
NPP	Net Primary Productivity

O ₂	Oxygen
OCAR	Oregon Climate Assessment Report (produced by OCCRI)
OCCRI	Oregon Climate Change Research Institute
OR	State of Oregon, United States
PCIC	Pacific Climate Impacts Consortium, British Columbia, Canada
PCM	Parallel Climate Model, United States
PDO	Pacific Decadal Oscillation
PET	Potential Evapotranspiration
PNW	Pacific Northwest
SRES	Special Report on Emissions Scenarios
TEK	Traditional Ecological Knowledge
WA	State of Washington, United States
WACCIA	Washington Climate Change Impacts Assessment (produced by CIG)

I. Introduction

This report compiles existing knowledge on known and potential climate change effects on terrestrial ecosystems within the geographic extent of the North Pacific Landscape Conservation Cooperative (NPLCC) and from surrounding areas where context is needed. The report also includes a menu of policy and management responses to adapt to climate change in terrestrial environments, culled from published science, government reports and publications from non-profit organizations. The NPLCC was established by the U.S. Department of Interior (Secretarial Order 3289) and is one of twenty-two Landscape Conservation Cooperatives (LCCs) planned for the United States, Canada, and Mexico. LCCs are member-directed conservation partnerships among State and Federal agencies, Tribes, nongovernmental organizations, universities, existing partnership efforts, and other conservation entities. Other key partners of the NPLCC are the three regional Climate Science Centers (CSCs) within the geographic are of the NPLCC: the Alaska, Northwest, and Southwest CSCs. The CSCs deliver basic climate change impact science for their region, prioritizing fundamental science, data, and decision-support activities based principally on the needs of the LCCs. LCCs link the science with conservation delivery. Thus, LCCs are management-science partnerships that inform resource management actions and provide needed tools. They provide a forum for identifying common science questions and needs for the defined landscapes, across organization lines. More specifically, LCCs generate applied science to inform conservation actions related to climate change, habitat fragmentation, and other landscape-level stressors and resource issues. The mission of the NPLCC is to promote development, coordination, and dissemination of science to inform landscape-level conservation and sustainable resource management in the face of a changing climate and related stressors. For more information on NPLCC activities, please see <http://www.northpacificlcc.org/> (accessed December 2, 2013).

The NPLCC

The NPLCC region extends from southcentral Alaska to northwest California and comprises approximately 204,000 square miles (530,000 square kilometers, km²) in seven western U.S. states and Canadian provinces (Figure 1).¹ There are four biogeoclimatic rainforest zones in the region, each distinguished by their subregional climate, vegetation, soils, and disturbance regimes.² From north to south, they are the subpolar zone, perhumid zone, seasonal zone, and warm zone.³

The region is characterized by strong linkages among its marine, freshwater, and terrestrial ecosystems, key species such as salmon that connect those ecosystems, and strong cultures that depend upon healthy, resilient habitats. The total amount of coastline is approximately 38,200 miles (~ 61,500 km)⁴ and encompasses picturesque waterways such as Alaska's Inside Passage and Puget Sound in the Pacific Northwest. The region's coastal waters and lands provide an array of ecosystem services including commercial and Subsistence harvest, recreational fishing and gathering opportunities, and protection from storms and flooding.

¹ US FWS (2010b). Within the Yukon Territory (YT; 186,272 mi², 482,443 km²), land within the NPLCC region is in southwest YT, the Kluane National Park and Preserve (8,487 miles², 21, 980 km²; ~4.6% of total area in YT).

² Alaback and Pojar (1997)

³ Alaback and Pojar (1997)

⁴ US FWS (2010b)

The inland extent of the NPLCC is delineated according to the Pacific Flyway, ecoregions, and the crests of several mountain ranges and, from the coast, stretches inland up to 150 miles (~240 km); therefore only the lower extent of many of the larger river watersheds such as the Copper River Watershed, Stikine Watershed, Fraser Basin, Columbia River Basin, and Klamath Basin are included within the area. These watersheds provide fresh water for millions of people and wildlife, are a key sediment source for the region's many estuarine ecosystems, and support vast tracts of temperate forest ecosystems.

Public lands make up approximately 78 percent, or 159,000 square miles (412,000 km²) of the NPLCC, with 82,000 square miles (212,000 km²) of Federal lands in the U.S. portion of the NPLCC and 77,000 square miles (200,000 km²) of Crown lands in the Canadian portion of the NPLCC.⁵ Temperate coniferous and boreal forests dominate the landscape – these temperate rainforests are among the last-remaining, intact forests of their kind in the world.⁶ Old-growth forests in the region provide habitat, sequester carbon, provide clean water, and modulate water flow.⁷ Oak woodlands, prairies, and grasslands are rich in endemic species; thirty-two plant taxa are endemic or nearly endemic to Pacific Northwest prairies.⁸ The connection among the region's marine, freshwater, and terrestrial ecosystems is evident in these forests – the same salmon that return from the sea to their natal freshwater habitats also nourish the forest, provide food for iconic species such as grizzly bear, and are critical to the Way of Life for many Tribes, First Nations, and Native Alaskans.

Organization of Report

The Executive Summary summarizes the major points of this compilation and identifies the most frequently and repeatedly cited needs and potential priorities for science and traditional ecological knowledge in the NPLCC region. The Introduction and Methodology (Chapters I and II, respectively), provide a framework within which to consider the information included in this report by reviewing the project's purpose, key information about the NPLCC, and the methods used to acquire, analyze, and compile the information in this report. Key findings are found in Chapters III-IX, which begins with a review of carbon dioxide concentrations, temperature, and precipitation, then presents information on major climate impacts for the terrestrial environment and implications for ecosystems, habitats, and species. Each of these chapters covers historical baselines, observed trends, and future projections for the topics presented. Chapter X is comprised of three appendices, which cover the common and scientific names of the species mentioned in the report, a primer on SRES scenarios and climate modeling, and a second primer on major climate patterns in the NPLCC region. Chapter XI is the Bibliography.

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⁵ US FWS (2010b)

⁶ DellaSala (2011), Olson et al. (2001)

⁷ Franklin et al. (2006, p. 97)

⁸ Sinclair et al. (2006, p. 29). Bunchgrass Prairies. In: *Restoring the Pacific Northwest: The Art and Science of Ecological Restoration in Cascadia*.

Peterson (U.S. Forest Service), Dr. Dominique Bachelet (Conservation Biology Institute), Dr. Jessica Halofsky (UW Pacific Wildland Fire Sciences Lab), Ms. Lara Whitely Binder (CIG), and Mr. Michael Case (UW Landscape Ecology & Conservation Lab), whose thorough review improved this report.

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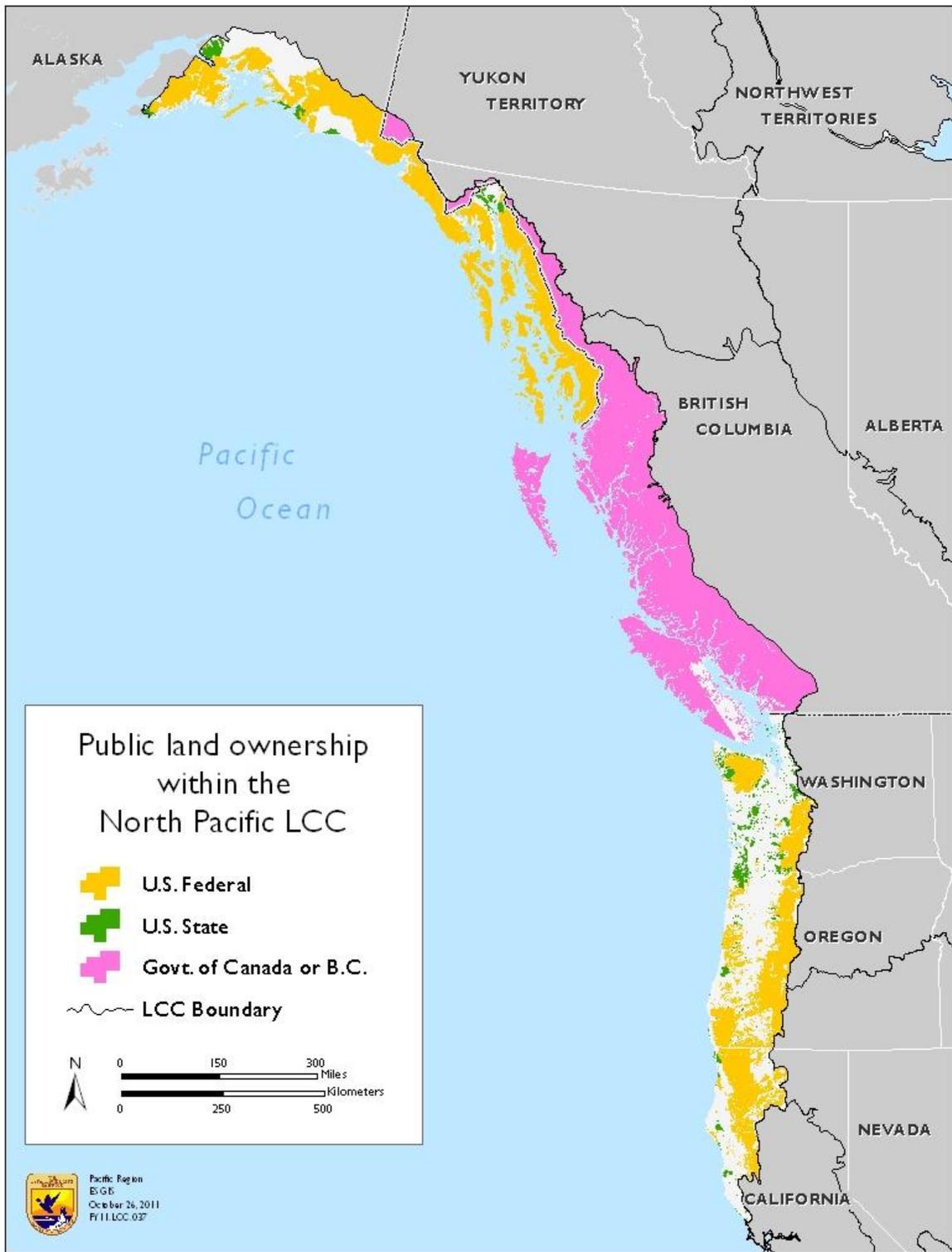


Figure 1. Public land ownership within the North Pacific Landscape Conservation Cooperative (NPLCC). *Source: U.S. Fish and Wildlife Service (2011).* This is a preliminary land ownership map, including only federal, state, and provincial lands. At a later date, the map will be updated to include Native Alaskan, First Nations, and Tribal lands. Lands owned by other entities (e.g. NGOs, private property) may be included as well.

II. Methodology

This report is intended as a reference document – a science summary – for the North Pacific Landscape Conservation Cooperative (NPLCC). The report compiles findings on climate change impacts and adaptation approaches in terrestrial ecosystems within the NPLCC region. The report is intended to make scientific information on climate change impacts within the NPLCC region accessible and useful for natural and cultural resource managers and others. It was produced by National Wildlife Federation under a grant from the NPLCC (FWS Agreement Number F11AP00032).

Two companion reports compiling similar information on marine and coastal ecosystems, and freshwater aquatic and riparian ecosystems were also completed under a separate grant. Together, these three reports provide information on climate change effects and adaptation approaches for the NPLCC region’s three broad ecosystem types: marine, freshwater, and terrestrial.

Approach

This report focuses on the NPLCC region, although information from surrounding areas and, in some instances, global information is presented for context or where more region-specific information is limited or unavailable. We draw 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 (see next section) and seminal papers addressing climate change impacts and adaptation options for the terrestrial environment in the NPLCC region, as well as resources providing information on broader regional and global trends and projections where relevant. Reference lists from these sources provided a starting point for acquiring additional depth and nuance on climate change impacts to the NPLCC’s terrestrial ecosystems, habitats, and species, and adaptation approaches. Only resources published before October 31, 2013 are included in this report.

For topics lacking information in synthesis documents, seminal papers, and their reference lists, we searched scientific literature databases (e.g., Academic Search Premier, ScienceDirect) to find additional resources. Search terms were broad. For example, to find information on altered nutrient cycling, we used combinations of the search terms “nutrient cycling,” “nutrient*,” “carbon,” “nitrogen,” phosphorus,” “soil nutrient*,” “climat*,” “climate change,” “terrestrial,” “forest*,” “alpine,” “subalpine,” “savanna*,” “woodland,” “observed trend*,” “observed change*,” and “projection*.”

Finally, we asked reviewers to identify key references for the NPLCC region missing in the draft report, then reviewed those references in preparation of the final report.

Because the report strives 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. Given the extensive use of verbatim material, in order to improve readability while providing appropriate source attributions, citation footnotes include the phrase “Verbatim from” or “Nearly verbatim from” when the passages are drawn verbatim, or near verbatim, from the cited source. For figures and tables, the phrases “Reproduced from” and “Modified from” are used when the figure or table is drawn completely or largely from the cited source. In general, verbatim and near verbatim materials are found in the main chapters of the report, while the Executive Summary, Boxes, sidebars, and Case Studies reflect our synthesis of multiple sources.

This report was reviewed by climate change scientists and subject-matter experts with the U.S. Forest Service and University of Washington. Please see the Acknowledgements for a list of reviewers.

Description of Synthesis Documents Utilized

This report draws from primary sources as well as synthesis reports. In synthesis reports, we accepted information as it was presented. Readers are encouraged to refer to the primary sources utilized in those synthesis reports for more information. In most cases, we include the page number in the synthesis report for reference. In cases where a primary source is referenced in a secondary source, we have indicated it in the footnote. The global, regional, state, and provincial level synthesis reports drawn from include:

- *Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4): Climate Change 2007.* (2007).
- *Global Climate Change Impacts in the United States.* 2009.
- *Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector.* 2012. We drew from the Abstract, Executive Summary, Chapters 2 (Effects of climatic variability and change) and 4 (Adaptation and Mitigation), and Appendix 1 (Regional Summaries).
- *Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment.* 2012. We drew from Chapters 2 (impacts of climate change on biodiversity), 3 (impacts of climate change on ecosystem structure and functioning), 4 (impacts of climate change on ecosystem services), 5 (impacts of climate change on already stressed biodiversity, ecosystems, and ecosystem services), and 6 (adaptation to impacts of climate change on biodiversity, ecosystems, and ecosystem services).
- *A Risk Assessment of Climate Change and the Impact of Forest Diseases on Forest Ecosystems in the Western United States and Canada.* 2011.
- [*Compendium of Forest Hydrology and Geomorphology in British Columbia: Climate Change Effects on Watershed Processes in British Columbia.*](#) 2010. We drew from Chapter 19.
- *Environmental Trends in British Columbia: 2007.* We drew from the section on climate change.
- *Climatic Change*, Volume 102, Numbers 1-2. September 2010. This volume published the findings of the Washington Climate Change Impacts Assessment (WACCIA).
- *Washington Climate Change Impacts Assessment ([WACCIA](#)).* 2009. We drew from Chapters 1 (future climate in the Pacific Northwest), 2 (regional climate modeling), 7 (forest ecosystems), and 11 (preparing for climate change).
- *Climate Change and Forest Biodiversity: A Vulnerability Assessment and Action Plan for National Forests in Western Washington.* 2011.
- *Oregon Climate Assessment Report ([OCAR](#)).* 2010. We drew from Chapters 1 (climate change in land and marine environments), 5 (vegetation), and 7 (fish and wildlife).
- *2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008.*
- [*Third Assessment*](#) of the California Climate Change Center. 2012. We drew from the brochure synthesizing the assessments results, as well as individual reports on future climate scenarios, climate change impacts on California vegetation, consequences of climate change for native plants and conservation, fire and climate change in California, and decision-making under uncertainty.
- *Preliminary review of adaptation options for climate-sensitive ecosystems and resources.* 2008.
- *Strategies for Managing the Effects of Climate Change on Wildlife and Ecosystems.* 2008.
- *Responding to climate change in National Forests: a guidebook for developing adaptation options.* 2011.

III. Carbon Dioxide, Temperature, & Precipitation

1. Carbon dioxide (CO₂) concentrations – global observed trends and future projections

Observed Trends

- **Overall change:** Atmospheric CO₂ concentrations in October 2013 were approximately 394 parts per million (ppm),⁹ very likely higher than any level in the past 650,000 years¹⁰ and 42% higher than the pre-industrial value (278 ppm).¹¹ Current CO₂ concentrations are about 4.0% higher than the 2005 concentration reported by the IPCC's Fourth Assessment Report (AR4: 379 ± 0.65 ppm).¹² From 2000-2004, the actual emissions trajectory was close to that of the high-emissions A1F1 scenario.¹³ *Note: Most studies cited in this report use the emissions scenarios developed for the AR4. Therefore, the comparisons made here refer to the AR4 instead of the recently released 5th Assessment Report from the IPCC. Please see Box 1 for additional information.*
- **Annual growth rates**
 - 1960-2005: CO₂ concentrations grew 1.4 ppm per year, on average.¹⁴
 - 1995-2005: CO₂ concentrations grew 1.9 ppm per year, on average.¹⁵ This is the most rapid rate of growth since the beginning of continuous direct atmospheric measurements, although there is year-to-year variability in growth rates.¹⁶
 - 2000-2004: the emissions growth rate (>3%/yr) exceeded that of the highest-emissions IPCC scenario (A1F1).¹⁷
 - 2012: the annual mean global CO₂ rate of growth was 2.42 ppm.¹⁸
- **Contribution from fire:** Currently, all sources of fire (landscape and biomass) cause CO₂ emissions equal to 50% of those stemming from fossil-fuel combustion (2 to 4 Petagrams of carbon per year, Pg C year⁻¹ versus 7.2 Pg C year⁻¹) (1 Pg = 1,000,000,000,000,000).¹⁹ Of the fire-related emissions, burning related to deforestation, a net CO₂ source, contributes about 0.65 Pg C year⁻¹.²⁰ In contrast, the regrowth of vegetation and the production of black carbon (which

⁹ NOAA. (2013). *Global Greenhouse Gas Reference Network: Trends in Atmospheric Carbon Dioxide: Global*. Earth System Research Laboratory: Global Monitoring Division.

¹⁰ Jansen et al. (2007, p. 435). Palaeoclimate. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.

¹¹ Forster et al. (2007, p. 141). *Changes in Atmospheric Constituents and in Radiative Forcing*.

¹² Forster et al. (2007, p. 141)

¹³ Raupach et al. (2007). *Global and regional drivers of accelerating CO₂ emissions*.

¹⁴ IPCC. (2007c, p. 2). Summary for Policymakers. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.

¹⁵ IPCC. (2007c, p. 2)

¹⁶ IPCC. (2007c, p. 2)

¹⁷ Raupach et al. (2007)

¹⁸ NOAA. (2013)

¹⁹ Verbatim from Bowman et al. (2009, p. 483). *Fire in the Earth system*. Bowman et al. cite IPCC (2007), van der Werf et al. (2006), and Andreae & Merlet (2001) for this information.

²⁰ Nearly verbatim from Bowman et al. (2009, p. 483)

is a by-product of burning, with a long residence time in soils) are sinks of atmospheric CO₂ and may be expanded with targeted management.²¹

Future Projections

- Even if greenhouse gas emissions are held at year 2000 levels today, the history of past greenhouse gas emissions will contribute to unavoidable warming in the future.²²
- Compared to the concentration in 2005 (~379 ppm), the atmospheric concentration of CO₂ is projected to increase over the period 2000-2100 across all six SRES scenarios,²³ from a low of about 600 ppm under the A1T, B1, and B2 scenarios to a high of about 1000 ppm in the A1F1 scenario.²⁴ In the Representative Concentration Pathways (RCPs), the atmospheric concentration of CO₂ is also projected to increase to 421 ppm in RCP2.6, 538 ppm in RCP4.5, 670 ppm in RCP 6.0, and 936 ppm in RCP8.5.²⁵ By 2100, emissions peak and then decline in the RCP2.6 (a mitigation scenario), stabilize in RCP4.5, and do not peak in RCP6.0 and RCP8.5.²⁶
- *Note: Most projections in this report are based on climate modeling and a number of emissions scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES, see Box 1 and Appendix 3. Major Climate Patterns in the NPLCC: ENSO and PDO for further information).²⁷ A few studies use the Representative Concentration Pathways (RCPs), developed in support of the IPCC's 5th Assessment Report (AR5).*

²¹ Verbatim from Bowman et al. (2009, p. 483). Bowman et al. cite Lehmann et al. (2008) for this information.

²² Verbatim from Klausmeyer et al. (2011, p. 1). *Landscape-scale indicators of biodiversity's vulnerability to climate change*. Klausmeyer et al. cite IPCC (2007) for this information.

²³ Meehl et al. (2007, p. 803). Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. This information was extrapolated from Figure 10.26 in the cited report by the authors of this report.

²⁴ Meehl et al. (2007, p. 803). This information was extrapolated from Figure 10.26 in the cited report by the authors of this report.

²⁵ IPCC (2013a). Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

²⁶ IPCC (2013a)

²⁷ IPCC. (2007b). *Synthesis Report*.

Box 1. The Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathways (RCPs).

Changes in greenhouse gas (GHG, e.g. carbon dioxide, CO₂) and sulfate aerosol emissions are based on different assumptions about future population growth, socio-economic development, energy sources, and technological progress. Because we do not have the advantage of perfect foresight, a range of assumptions about each of these factors are made to bracket the range of possible futures, i.e. scenarios. Most studies cited in this report use the scenarios developed for the AR4, known as the IPCC Special Report on Emissions Scenarios or SRES scenarios. A few studies use the Representative Concentration Pathways (RCPs), developed in support of the AR5. Therefore, SRES scenarios are described in detail and RCPs are discussed only briefly. All scenarios are assumed to be equally valid, with no assigned probabilities of occurrence. While the scenarios cover multiple GHGs and multiple drivers are used to project changes, this report focuses on CO₂ because it is the major driver of climate change impacts and is tightly coupled with many ecological processes.

SRES scenarios are grouped into scenario “families” for modeling purposes. Forty individual emissions scenarios are grouped into six families: A1F1, A1B, A1T, A2, B1, and B2. The “A” families are more economic in focus than the “B” families, which are more environmentally focused. The A1 and B1 families are more global in focus compared to the more regional A2 and B2:

- The A1 scenarios (A1F1, A1B, and A1T) assume rapid economic growth, a global population that peaks in mid-century, and rapid introduction of new and more efficient technologies. They are differentiated by assumptions about the dominant type of energy source: the fossil-intensive A1F1, non-fossil intensive A1T, and mixed energy source A1B scenarios. These correspond to high-, medium-high, and low- emissions scenarios, respectively.
- The B1 scenario assumes the same population as A1, but with more rapid changes toward a service and information economy. This is a low-emissions scenario.
- The B2 scenario describes a world with intermediate population and economic growth, emphasizing local solutions to sustainability. Energy systems differ by region, depending on natural resource availability. This is a medium-low emissions scenario.
- The A2 scenario assumes high population growth, slow economic development, and slow technological change. Resource availability primarily determines the fuel mix in different regions. This is a high-emissions scenario.

SRES Scenario	Cumulative CO ₂ emissions (GtC), 1990-2100	Population Growth Rate	Economic Development Rate	Fuels used
A1F1	2182.3	Peaks in mid-21 st century	Rapid	Fossil fuel intensive
A1B	1492.1	Peaks in mid-21 st century	Rapid	Mixed energy sources
A1T	1061.3	Peaks in mid-21 st century	Rapid	Non-fossil fuel intensive
A2	1855.3	High	Slow	Determined by resource availability
B2	1156.7	Intermediate	Intermediate	Determined by resource availability
B1	975.9	Peaks in mid-21 st century	Rapid – toward service & information economy	Non-fossil fuel intensive

RCPs facilitate coordination of new and integrated scenarios of climate, emissions, and socioeconomics. Four RCPs were developed to reflect a range of possible 21st century climate policies: RCP2.6 (421 ppm CO₂; mitigation scenario), RCP4.5 and RCP6.0 (538 ppm CO₂ and 670 ppm CO₂, respectively; emissions stabilization scenarios), and RCP8.5 (936 ppm CO₂; very high greenhouse gas emissions). By 2100, emissions peak and then decline in RCP2.6, stabilize in RCP4.5, and do not peak in RCP6.0 and RCP8.5.

Sources: CIESIN (2000); CIG (2008); IPCC (2000, Chapters 4.3 & 5.1); IPCC (2007b, 2013a, 2013b, 2013c)

2. Temperature

Observed Trends

Global

- In 2010, the combined land and ocean global surface temperature was 58.12°F (14.52°C; NCDC dataset).²⁸ This is tied with 2005 as the warmest year on record, at 1.12°F (0.62°C) above the 20th century average of 57.0°F (13.9°C; NCDC dataset).²⁹ The range associated with this value is plus or minus 0.13°F (0.07°C; NCDC dataset).³⁰
 - From 1850 through 2006, 11 of the 12 warmest years on record occurred from 1995 to 2006.³¹
 - In 2010, Northern Hemisphere combined land and ocean surface temperature was the warmest on record: 1.31°F (0.73°C) above the 20th century average (NCDC dataset).³²
- From 1906 to 2005, global average surface temperature increased $\sim 1.34^\circ\text{F} \pm 0.33^\circ\text{F}$ ($0.74^\circ\text{C} \pm 0.18^\circ\text{C}$).³³
 - From the 1910s to 1940s, an increase of 0.63°F (0.35°C) was observed.³⁴ Then, about a 0.2°F (0.1°C) decrease was observed over the 1950s and 1960s, followed by a 0.99°F (0.55°C) increase between the 1970s and the end of 2006 (Figure 3).³⁵
- The 2001-2010 decadal land and ocean average temperature trend was the warmest decade on record for the globe: 1.01°F (0.56°C) above the 20th century average (NCDC dataset).³⁶
 - From 1906-2005, the decadal trend increased $\sim 0.13^\circ\text{F} \pm 0.04^\circ\text{F}$ ($0.07^\circ\text{C} \pm 0.02^\circ\text{C}$) per decade.³⁷ From 1955-2005, the decadal trend increased $\sim 0.24^\circ\text{F} \pm 0.05^\circ\text{F}$ ($0.13^\circ\text{C} \pm 0.03^\circ\text{C}$) per decade.³⁸
- Warming has been slightly greater in the winter months from 1906 to 2005 (December to March in the northern hemisphere; June through August in the southern hemisphere).³⁹ Analysis of long-term changes in daily temperature extremes show that, especially since the 1950s, the number of very cold days and nights has decreased and the number of extremely hot days and warm nights has increased.⁴⁰

²⁸ NOAA. *State of the Climate Global Analysis 2010 (website)*. (2011b)

²⁹ NOAA. (2011b)

³⁰ NOAA. (2011b)

³¹ IPCC. *Climate Change 2007: Synthesis Report: Summary for Policymakers*. (2007g, p. 2)

³² NOAA. *State of the Climate Global Analysis 2010 (website)*. (2011b)

³³ Trenberth et al. *Climate Change 2007: The Physical Science Basis: Observations: Surface and Atmospheric Climate Change*. (2007, p. 252)

³⁴ Trenberth et al. (2007, p. 252)

³⁵ Trenberth et al. (2007, p. 252)

³⁶ NOAA. (2011b)

³⁷ Trenberth et al. (2007, p. 237)

³⁸ Trenberth et al. (2007, p. 237)

³⁹ Trenberth et al. (2007, p. 252)

⁴⁰ Nearly verbatim from Trenberth et al. (2007, p. 252)

Southcentral and Southeast Alaska

- Annual average temperature has increased 3.4°F (~1.9°C) over the last fifty years, while winters have warmed even more, by 6.3°F (3.5°C).⁴¹ The time period over which trends are computed is not provided. However, compared to a 1960s-1970s baseline, the average temperature from 1993 to 2007 was more than 2°F (1.1°C) higher.⁴²
 - Annual average temperature increased 3.2°F (1.8°C) in Juneau over 1949-2009.⁴³
From 1971 to 2000, temperatures in Anchorage increased by 2.26°F (1.27°C).⁴⁴
- From 1949 to 2009, winter temperatures increased the most, followed by spring, summer, and autumn temperatures.⁴⁵ For example, in Juneau, winter temperatures increased by 6.2°F (3.4°C), spring temperatures increased by 2.9°F (1.6°C), summer temperatures increased by 2.2°F (1.2°C), and autumn temperatures increased 1.4°F (0.8°C).⁴⁶
- A comparison of official data from the National Climatic Data Center (NCDC) for 1971-2000 and unofficial National Weather Service (NWS) data for 1981-2010 for Juneau, Alaska indicates average annual, warm season (April – September), and cold season (October – March) temperatures have increased from 1971-2000 to 1981-2010 (Table 3):⁴⁷
 - Annual: +0.6°F (+0.33°C), from 41.5°F (5.28°C) to 42.1°F (5.61°C).⁴⁸
 - April-September: +0.2°F (+0.1°C), from 50.9°F (10.5°C) to 51.1°F (10.6°C).⁴⁹
 - October-March: +0.8°F (+0.444°C), from 32.1°F (0.0556°C) to 32.9°F (0.500°C).⁵⁰

Western British Columbia

- Observed trends in the annually averaged daily minimum, mean, and maximum temperatures from 1950 to 2006 are available for four stations along the BC coast (Table 4).⁵¹

⁴¹ Karl, Melillo and Peterson. *Global Climate Change Impacts in the United States*. (2009, p. 139). The report does not provide a year range for this information. The authors cite Fitzpatrick et al. (2008) for this information.

⁴² Karl, Melillo and Peterson. (2009, p. 139). See the figure entitled *Observed and Projected Temperature Rise*.

⁴³ Alaska Climate Research Center. *Temperature Change in Alaska (website)*. (2009)

⁴⁴ Alaska Center for Climate Assessment and Policy. *Climate Change Impacts on Water Availability in Alaska (presentation)*. (2009, p. 4)

⁴⁵ Alaska Climate Research Center. (2009)

⁴⁶ Alaska Climate Research Center. (2009)

⁴⁷ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

⁴⁸ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

⁴⁹ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

⁵⁰ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

⁵¹ B.C. Ministry of Environment (MoE). *Environmental Trends in British Columbia: 2007: Climate Change*. (2007, p. 7)

Table 3. Annual and seasonal temperature trends for Juneau, AK over two thirty-year time periods.

		1971-2000* °F (°C)	1981-2010* °F (°C)	Absolute Change °F (°C)	Percent Change [†]
Annual	Average	41.5 (5.28)	42.1 (5.61)	+0.6 (+0.33)	+1.45
	Average maximum	47.6 (8.67)	48.1 (8.94)	+0.5 (+0.27)	+1.05
	Average minimum	35.3 (1.83)	36.1 (2.28)	+0.8 (+0.45)	+2.27
Warm season (April – Sept)	Average	50.9 (10.5)	51.1 (10.6)	+0.2 (+0.1)	+0.393
	Average maximum	58.2 (14.6)	58.3 (14.6)	+0.1 (0.06)	+0.172
	Average minimum	43.5 (6.39)	44.0 (6.67)	+0.5 (+0.28)	+1.15
Cold season (Oct – March)	Average	32.1 (0.0556)	32.9 (0.500)	+0.8 (+0.444)	+2.49
	Average maximum	37.0 (2.78)	37.7 (3.17)	+0.7 (+0.39)	+1.89
	Average minimum	27.2 (-2.67)	28.1 (-2.17)	+0.9 (+0.50)	+3.31

*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 official data for 1981-2010 are scheduled for release by NCDC in July 2011. The table was created by the authors of this report and approved by Tom Ainsworth and Rick Fritsch on June 10, 2011.

†Percent change reflects the relative increase or decrease from 1971-2000 to 1981-2010.

Table 4. Trends in the average daily minimum, mean, and maximum temperatures per decade in °F (°C) in southern coastal British Columbia, 1950-2006.

	Temperature	Annual	Winter	Spring	Summer	Autumn
Abbotsford Airport, near Vancouver	Minimum	0.72 (0.40)	1.58 (0.88)	0.86 (0.48)	0.58 (0.32)	0.23 (0.13)
	Average	0.59 (0.33)*	0.52 (0.29)*	0.68 (0.38)*	0.74 (0.41)*	0.27 (0.15)*
	Maximum	0.20 (0.11)	1.13 (0.63)	-0.41 (-0.23)	1.21 (0.67)	-0.76 (-0.42)
Comox Airport, east Vancouver Island	Minimum	0.58 (0.32)*	0.40 (0.22)*	0.79 (0.44)*	0.65 (0.36)*	0.38 (0.21)*
	Average	0.41 (0.23)*	0.40 (0.22)*	0.50 (0.28)*	0.45 (0.25)*	0.22 (0.12)*
	Maximum	0.23 (0.13)*	0.31 (0.17)*	0.23 (0.13)	0.27 (0.15)	0.11 (0.06)
Port Hardy Airport, NE Vancouver Island	Minimum	0.38 (0.21)*	0.43 (0.24)*	0.50 (0.28)*	0.45 (0.25)*	0.04 (0.02)
	Average	0.34 (0.19)*	0.49 (0.27)*	0.36 (0.20)	0.31 (0.17)	0.07 (0.04)
	Maximum	0.27 (0.15)*	0.52 (0.29)*	0.41 (0.23)*	0.14 (0.08)	0.05 (0.03)
Victoria Airport, near Victoria	Minimum	0.40 (0.22)*	0.36 (0.20)*	0.63 (0.35)*	0.45 (0.25)*	0.20 (0.11)*
	Average	0.45 (0.25)*	0.40 (0.22)*	0.58(0.32)*	0.52 (0.29)*	0.22 (0.12)*
	Maximum	0.43 (0.24)*	0.52 (0.29)*	0.43 (0.24)*	0.49 (0.27)*	0.18 (0.10)

Note: Asterisks indicate a statistically significant difference, meaning there is at least a 95% probability that the trend is not due to chance.

Source: Adapted from B.C. MoE.(2007, Table 1, p. 7-8) by authors of this report.

Pacific Northwest (Figure 2)

- Average 20th century warming was 1.64°F (0.91°C; the linear trend over the 1920-2000 period, expressed in degrees per century).⁵²
- Warming over the 20th century varied seasonally, with average warming in winter being the largest (+3.3°F, +1.83°C), followed by summer (+1.93°F, +1.07°C), spring (+1.03°F, +0.57°C), and autumn (+0.32°F, +0.18°C).⁵³ Data reflect the linear trend over the 1920-2000 period, expressed in degrees per century; data for summer are significant at the 0.05 level.⁵⁴
- Increases in maximum and minimum temperatures in the cool (October-March) and warm (April-September) seasons from 1916 to 2003 and from 1947 to 2003 have been observed (Table 4).⁵⁵

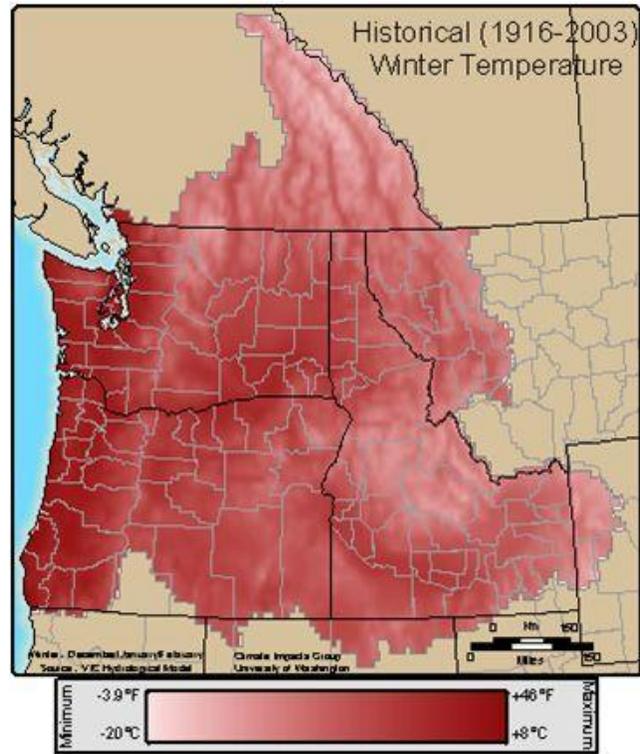


Figure 2. Historical average (1916-2003) winter temperature in the Pacific Northwest.
Source: Downloaded with permission from the Climate Impacts Group. August 13, 2011.
(<http://ces.washington.edu/cig/maps/index.shtml>).

- When comparing the 1981-2010 climate normals (i.e., the 30-year average) to the 1971-2000 climate normals, both maximum and minimum temperatures are about 0.5°F (~0.3°C) warmer on average in the new normals across the United States.⁵⁶ The averaged annual statewide increases in maximum and minimum temperatures observed over this period are:
 - **Maximum:** +0.3 to +0.5°F (~+0.2-0.3°C) in Washington and Oregon.⁵⁷
 - **Minimum:** +0.3 to +0.5°F (~+0.2-0.3°C) in Washington and +0.1 to +0.3°F (~+0.06-0.3°C) in Oregon.⁵⁸

⁵² Mote. *Trends in temperature and precipitation in the Pacific Northwest during the Twentieth Century*. (2003, Fig. 6, p. 276)

⁵³ Mote (2003, Fig. 6, p. 276)

⁵⁴ Mote (2003, Fig. 6, p. 276)

⁵⁵ Hamlet et al. *Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States*. (2007, Table 1, p. 1475).

⁵⁶ NOAA. *NOAA Satellite and Information Service: NOAA's 1981-2010 Climate Normals (website)*. (2011a)

⁵⁷ NOAA. (2011a, Fig. 1)

⁵⁸ NOAA. (2011a, Fig. 2)

Northwestern California

- PRISM data (a climate-mapping system) suggest that most of the Six Rivers National Forest area, located in northwestern California, experienced increases in mean annual temperature of about 1.8°F (1°C) between the 1930s and 2000s, although some coastal areas have seen a slight decrease in temperature.⁵⁹ Average temperatures at the Orleans station increased approximately 2°F (1.1°C) in the period from 1931 to 2009 (1931 baseline: ~56.2°F, or ~13 °C).⁶⁰ The trend is driven by a highly significant increase in mean minimum (i.e., nighttime) temperature, which rose by almost 4°F (2.2°C) between 1931 and 2009 (1931 baseline: ~42°F, or ~5.5°C).⁶¹ *Note: For a figure showing mean annual temperature and annual temperature seasonality from 1971 to 2000, please see Figure S1 in the link included in the footnote.*⁶²
- When comparing the 1981-2010 climate normals (i.e., the 30-year average) to the 1971-2000 climate normals, both maximum and minimum temperatures are about 0.5°F (~0.3°C) warmer on average in the new normals across the United States.⁶³ The averaged annual increase in maximum and minimum temperatures in California observed over this period are:
 - **Maximum:** +0.3 to +0.5°F (~+0.2-0.3°C).⁶⁴
 - **Minimum:** +0.3 to +0.5°F (~+0.2-0.3°C).⁶⁵

Table 5. Regional-scale maximum and minimum temperature trends during 1916-2003 and 1947-2003 for the cool season (October-March) and warm season (April-September) in the Pacific Northwest. (°F per century with °C per century in parentheses; trends extrapolated from 1916-2003 and 1947-2003 data records)

Source: Modified from Hamlet et al. (2007, Table 1, p. 1475) by authors of this report.

Maximum temperature	October-March	1916-2003	1.82 (1.01)
		1947-2003	3.47 (1.93)
	April-September	1916-2003	0.40 (0.22)
		1947-2003	2.68 (1.49)
Minimum temperature	October-March	1916-2003	3.01 (1.67)
		1947-2003	4.09 (2.27)
	April-September	1916-2003	2.43 (1.35)
		1947-2003	3.47 (1.93)

⁵⁹ Butz and Safford. *A summary of current trends and probable future trends in climate and climate-driven processes for the Six Rivers National Forest and surrounding lands (pdf)*. (2010, p. 1). Butz and Safford refer the reader to Figure 1 in the cited report.

⁶⁰ Nearly verbatim from Butz and Safford. (2010, p. 1). Butz and Safford refer the reader to Figure 1 in the cited report. For the 1931 baseline, please see Figure 2 in the cited report.

⁶¹ Nearly verbatim from Butz and Safford. (2010, p. 1). Butz and Safford refer the reader to Figure 2 in the cited report.

⁶² Ackerly et al. *The geography of climate change: implications for conservation biogeography (Supplemental Information)*. (2010). http://onlinelibrary.wiley.com/store/10.1111/j.1472-4642.2010.00654.x/asset/supinfo/DDI_654_sm_Data_S1andFig_S1-S8.pdf?v=1&s=93f8310b31bb81d495bae87579a8d7f4d710ca3e (accessed 6.8.2011).

⁶³ NOAA. (2011a)

⁶⁴ NOAA. (2011a, Fig. 1)

⁶⁵ NOAA. (2011a, Fig. 2)

Future Projections

Note: The studies presented here differ in the baseline used for projections. Baselines include 1980-1999 (IPCC), 1961-1990 (BC, CA), 1970-1999 (WA, OR), 1971-2000 (CA) and 1960-1970s (AK).

Global (1980-1999 baseline)

- Even if greenhouse gas (GHG) concentrations were stabilized at year 2000 levels, an increase in global average temperature would still occur: 0.67°F (0.37°C) by 2011-2030, 0.85°F (0.47°C) by 2046-2065, 1.01°F (0.56°C) by 2080-2099, and 1.1°F (0.6°C) by 2090-2099 (all compared to a 1980-1999 baseline).^{66,67}
- Global average temperatures are projected to increase at least 3.2°F (1.8°C) under the B1 scenario and up to 7.2°F (4.0°C) under the A1F1 scenario by 2090-2099 compared to a 1980-1999 baseline.⁶⁸ The range of projected temperature increases is 2.0°F (1.1°C) to 11.5°F (6.4°C) by 2090-2099, compared to a 1980-1999 baseline (Figure 3).⁶⁹
- A study by Arora et al. (2011) suggests that limiting warming to roughly 3.6°F (2.0°C) by 2100 is unlikely since it requires an immediate ramp down of emissions followed by ongoing carbon sequestration after 2050.⁷⁰
- Loarie et al. (2009) present a new index of the velocity of temperature change (kilometers per year, km/yr), derived from spatial gradients (°C/km) and multimodel ensemble forecasts of rates of temperature increase (°C/yr) in the twenty-first century.⁷¹ This index represents the instantaneous local velocity along Earth's surface needed to maintain constant temperatures, and has a global mean of 0.42 km/yr (2000-2100; average of 16 GCMs run with A1B).⁷²
- In climate simulations for the IPCC A2 and B1 emission scenarios, novel climates arise by 2100 AD, primarily in tropical and subtropical regions (Box 2).⁷³

Southcentral and Southeast Alaska (1960s-1970s baseline)

- By 2020, compared to a 1960-1970s baseline, average annual temperatures in Alaska are projected to rise 2.0°F to 4.0°F (1.1-2.2°C) under both the low-emissions B1 scenarios and higher-emissions A2 scenario.⁷⁴
- By 2050, average annual temperatures in Alaska are projected to rise 3.5°F to 6°F (1.9-3.3°C) under the B1 scenario, and 4°F to 7°F (2.2-3.9°C) under the A2 scenario (1960-1970s baseline).⁷⁵ Later in the century, increases of 5°F to 8°F (2.8-4.4°C) are projected under the

⁶⁶ IPCC. (2007g, p. 8). See Figure SPM.1 for the information for 2090-2099.

⁶⁷ Meehl et al. (2007). Data for 2011-2030, 2046-2065, 2080-2099, and 2180-2199 were reproduced from Table 10.5 on p. 763. Data for 2090-2099 were obtained from p. 749.

⁶⁸ IPCC. (2007g, p. 8). See Figure SPM.1.

⁶⁹ IPCC. (2007, Table SPM.3, p. 13). AOGCMs are Atmosphere Ocean General Circulation Models.

⁷⁰ Nearly verbatim from Arora et al. *Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases*. (2011)

⁷¹ Verbatim from Loarie et al. (2009, p. 1052). *The velocity of climate change*.

⁷² Nearly verbatim from Loarie et al. (2009, p. 1052)

⁷³ Nearly verbatim from Williams & Jackson (2007, p. 475)

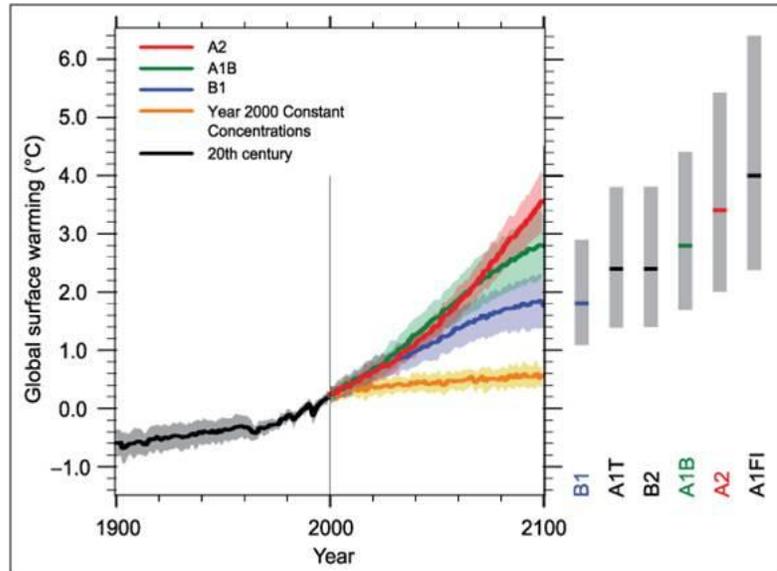
⁷⁴ Karl, Melillo and Peterson. (2009, p. 139). See the figure titled *Observed and Projected Temperature Rise* (section on Regional Impacts: Alaska)

⁷⁵ Karl, Melillo and Peterson. (2009, p. 139)

B1 scenario, and increases of 8°F to 13°F (4.4-7.2°C) are projected under the A2 scenario (1960-1970s baseline).⁷⁶

- On a seasonal basis, Alaska is projected to experience far more warming in winter than summer, whereas most of the United States is projected to experience greater warming in summer than in winter.⁷⁷
- No data were found for mean temperatures associated with the ranges reported here.

Figure 3. Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ± 1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the **likely** range assessed for the six SRES marker scenarios. The assessment of the best estimate and **likely** ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. {Figures 10.4 and 10.29} *Source: Reproduced from IPCC. (2007, Fig. SPM.5, p. 14) by authors of this report.*



Western British Columbia (1961-1990 baseline)

- Along the North Coast by the 2050s, annual air temperature is projected to increase 2.5°F (1.4°C) compared to a 1961-1990 baseline (multi-model average; scenarios not provided).⁷⁸ Along the South Coast, annual air temperature is projected to increase 2.7°F (1.5°C) compared to a 1961-1990 baseline (multi-model average; scenarios not provided).⁷⁹ The North Coast extends from the border with Alaska to just north of Vancouver Island; the South Coast extends to the Washington border.⁸⁰
- Along the North Coast by 2050, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
 - In winter, temperatures are projected to increase 0°F to 6.3°F (0-3.5°C), and
 - In summer, temperatures are projected to increase 2.7°F to 5.4°F (1.5-3°C).⁸¹

⁷⁶ Karl, Melillo and Peterson. (2009, p. 139)

⁷⁷ Karl, Melillo and Peterson. (2009, p. 28)

⁷⁸ Pike et al. *Compendium of forest hydrology and geomorphology in British Columbia: Climate Change Effects on Watershed Processes in British Columbia.* (2010, Table 19.3, p. 711).

⁷⁹ Pike et al. (2010, Table 19.3, p. 711)

⁸⁰ Please see the map available at <http://pacificclimate.org/resources/publications/mapview> (accessed 3.16.2011).

⁸¹ B.C. Ministry of Environment. *Alive and Inseparable: British Columbia's Coastal Environment: 2006.* (2006, Table 10, p. 113). The authors make the following note: From data in the Canadian Institute for Climate Studies,

- Along the South Coast by 2050, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
 - In winter, temperatures are projected to increase 0°F to 5.4°F (0-3°C), and
 - In summer, temperatures are projected to increase 2.7°F to 9.0°F (1.5-5°C).⁸²

Pacific Northwest (1970-1999 baseline)

- Average annual temperature could increase beyond the range of year-to-year variability observed during the 20th century as early as the 2020s.⁸³ Annual temperatures, averaged across all climate models under the A1B and B1 scenarios, are projected to increase as follows (1970-1999 baseline):
 - By the 2020s: 2.0°F (1.1°C), with a range of 1.1°F to 3.4°F (0.61-1.9°C),
 - By the 2040s: 3.2°F (1.8°C), with a range of 1.6°F to 5.2°F (0.89-2.89°C), and
 - By the 2080s: 5.3°F (~3.0°C), with a range of 2.8°F to 9.7°F (1.56-5.4°C).⁸⁴
- Seasonal temperatures, averaged across all models under the B1 and A1B scenarios, are projected to increase as described in Table 6 (compared to a 1970-1999 baseline).
- In another look at the Pacific Northwest by the 2080s, temperatures are projected to increase 2.7 to 10.4 °F (1.5-5.8 °C), with a multi-model average increase of 4.5°F (2.5°C) under the B1 scenario and 6.1°F (3.4°C) under the A1B scenario (1970-1999 baseline).⁸⁵

Table 6. Projected multi-model average temperature increases, relative to the 1970-1999 mean. (°F with °C in parentheses) *Source: Modified from Mote and Salathé, Jr. (2010, Fig. 9, p. 42) by authors of this report. Please see Figure 9 in the cited report for the range of each average shown below.*

	2020s		2040s		2080s	
	B1	A1B	B1	A1B	B1	A1B
Winter (Dec-Feb)	2.0 (1.1)	2.2 (1.2)	2.9 (1.6)	3.4 (1.9)	4.9 (2.7)	5.9 (3.3)
Spring (March-May)	1.8 (1.0)	1.8 (1.0)	2.5 (1.4)	3.1 (1.7)	3.8 (2.1)	5.0 (2.8)
Summer (June-Aug)	2.3 (1.3)	3.1 (1.7)	3.4 (1.9)	4.9 (2.7)	5.4 (3.0)	8.1 (4.5)
Fall (Sept-Nov)	1.8 (1.0)	2.0 (1.1)	2.7 (1.5)	3.6 (2.0)	4.3 (2.4)	6.1 (3.4)

Northwestern California (1961-1990 and 1971-2000 baselines)

- Compared to a 1961-1990 baseline under the B1 and A2 scenarios, California-wide annual average temperatures are projected to increase as follows:
 - By 2050: 1.8 to 5.4 °F (1-3 °C), and
 - By 2100: 3.6 to 9 °F (2-5 °C).⁸⁶

University of Victoria (www.cics.uvic.ca) study of model results from eight global climate modelling centres. A total of 25 model runs using the eight models were used to determine the range of values under different IPCC emission scenarios (Nakicenovic and Swart 2000).

⁸² B.C. Ministry of Environment. (2006, Table 10, p. 113). The authors make the following note: From data in the Canadian Institute for Climate Studies, University of Victoria (www.cics.uvic.ca) study of model results from eight global climate modelling centres. A total of 25 model runs using the eight models were used to determine the range of values under different IPCC emission scenarios (Nakicenovic and Swart 2000).

⁸³ Verbatim from CIG. *Climate Change Scenarios: Future Northwest Climate (website)*. (2008)

⁸⁴ CIG. *Climate Change: Future Climate Change in the Pacific Northwest (website)*. (2008, Table 3)

⁸⁵ Mote, Gavin and Huyer. *Climate change in Oregon's land and marine environment*. (2010, p. 21)

- In northwestern California, regional climate models project mean annual temperature increases of 3.1 to 3.4°F (1.7-1.9°C) by 2070 (no baseline provided).⁸⁷ In contrast, Ackerly et al. (2010) project a mean annual temperature increase of more than 3.6°F (2°C) but less than 5.4°F (3°C) by 2070-2099 (Figure 4; 1971-2000 baseline).⁸⁸
 - By 2070, mean diurnal (i.e., daily) temperature range is projected to increase by 0.18 to 0.36°F (0.1-0.2°C) based on two regional climate models.⁸⁹ No baseline was provided.
- In northern California, Cayan et al. (2008) project average annual temperature increases of 2.7°F (1.5°C) or 4.9°F (2.7°C) under the B1 scenario (PCM and GFDL models, respectively) and 4.7°F (2.6°C) or 8.1°F (4.5°C) (PCM and GFDL models, respectively) under the A2 scenario by 2070-2099 (1961-1990 baseline).⁹⁰
- Seasonally, the projected impacts of climate change on thermal conditions in northwestern California will be warmer winter temperatures, earlier warming in the spring, and increased summer temperatures.⁹¹ Average seasonal temperature projections in northern California are as follows (1961-1990 baseline):⁹²
 - Winter projections:
 - 2005-2034: at least ~0.18°F (0.1°C; A2, PCM model) and up to 2.5°F (1.4°C; A2, GFDL model).
 - 2035-2064: at least 1.6°F (0.9°C; A2, PCM model) and up to 4.3°F (2.4°C; B1, PCM model).
 - 2070-2099: at least 3.1°F (1.7°C; B1, PCM model) and up to 6.1°F (3.4°C; A2, GFDL model).
 - Summer projections:
 - 2005-2034: at least ~1°F (0.6°C; B1, PCM model) and up to 3.8°F (2.1°C; A2, GFDL model).
 - 2035-2064: at least ~2.0°F (1.1°C; B1, PCM model) and up to 6.1°F (3.4°C; A2, GFDL model).
 - 2070-2099: at least 2.9°F (1.6°C; B1, PCM model) and up to ~12°F (6.4°C; A2, GFDL model).
- Coastal regions are likely to experience less pronounced warming than inland regions.⁹³

⁸⁶ California Natural Resources Agency. *2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008*. (2009, p. 16-17). Figure 5 (p. 17) indicates projections are compared to a 1961-1990 baseline.

⁸⁷ Nearly verbatim from Port Reyes Bird Observatory. *Projected effects of climate change in California: Ecoregional summaries emphasizing consequences for wildlife. Version 1.0 (pdf)*. (2011, p. 8)

⁸⁸ Ackerly et al. (2010, Fig. S2, p. 9). Ackerly et al. use bias-corrected and spatially downscaled future climate projections from the CMIP-3 multi-model dataset. Data are downscaled to 1/8th degree spatial resolution (see p. 2).

⁸⁹ Nearly verbatim from Port Reyes Bird Observatory. (2011, p. 8). This data was based on two regional climate models presented in Stralberg et al. (2009).

⁹⁰ Cayan et al. *Climate change scenarios for the California region*. (2008, Table 1, p. S25)

⁹¹ Nearly verbatim from Port Reyes Bird Observatory. (2011, p. 8)

⁹² Cayan et al. (2008, Table 1, p. S25)

⁹³ Nearly verbatim from California Natural Resources Agency. (2009, p. 16)

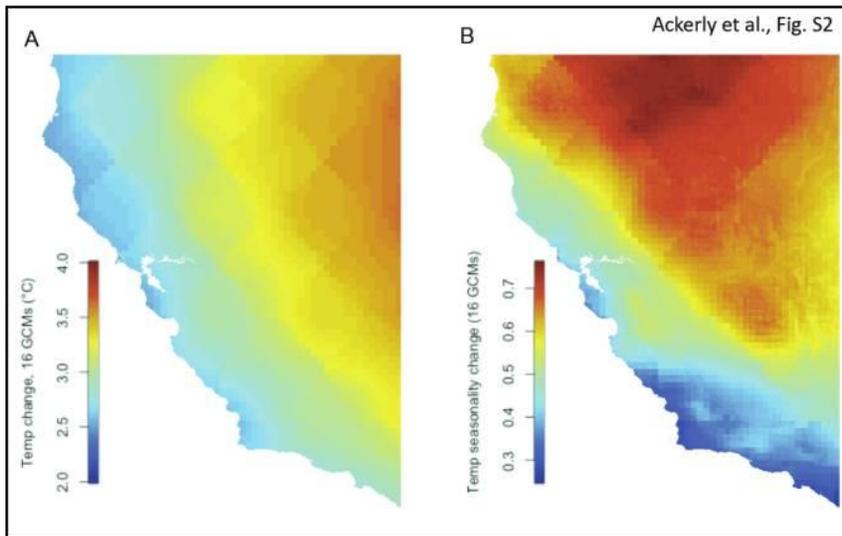


Figure 4. Changes in (A) mean annual temperature and (B) temperature seasonality, averaged over 16 GCMs, A1B scenario, for 2070-2099 (1971-2000 baseline). *Source: Reproduced from Ackerly et al. (2010, Fig. S2, p. 9) by authors of this report.* *Note: Temperature seasonality is the standard deviation of monthly means. Lower values indicate temperature varies less throughout the year, i.e. temperature is more constant throughout the year in blue areas than in yellow and red areas.*

Box 2. Novel Climates

Novel climate conditions are likely to alter the magnitude and direction of existing species relationships, leading to changes in community composition and food web processes (e.g., energy and material flow). Novel or no-analog communities, those with no historic or current precedent in an area, are possible.

What are novel climates?

Novel climates are future climates that exceed the historical range, variability, or composition of climate in a given area. For example, in a historically warm and wet climate that experiences little drought, transition to a hot and dry climate with frequent drought may be considered novel.

Where might novel climates develop?

Novel climates are likely to develop in lowland Amazonia, the southeastern U.S., the African Sahara and Sahel, the eastern Arabian Peninsula, southeast Indian and China, the IndoPacific, and northern Australia. Novel climate might also develop in the western U.S., central Asia, and Argentina, while temperate and high latitudes are at low risk for developing novel climates by 2080-2099 (vs. 1980-1999; IPCC AR4 ensemble GCMs, A2 and B1 emissions scenarios). *Likely* climates are projected by more than half the ensemble models; *might* climates are projected by less than half the ensemble models.

California's current coastal and montane climates are projected to be replaced by climates currently located to the south or east by 2100. Desert and Central Valley climates are projected to expand. Under a higher emissions scenario, some coastal and high Sierra Nevada climates are projected to disappear (2070-2099 vs. 1971-2000; CNRM, GFDL, PCM1, and CCSM3; A2 and B1).

Sources: Ackerly (2012), Staudinger et al. (2012), Williams & Jackson (2007)

3. Precipitation

Observed Trends

Note: Please see Box 3 for information on extreme precipitation in the NPLCC region.

Global (see also: projections below)

- Atmospheric moisture amounts are generally observed to be increasing after about 1973 (prior to which reliable atmospheric moisture measurements, i.e. moisture soundings, are mostly not available).⁹⁴
- Most of the increase is related to temperature and hence to atmospheric water-holding capacity,⁹⁵ i.e. warmer air holds more moisture.

Southcentral and Southeast Alaska

- In southeast Alaska from 1949 to 1998, mean total annual precipitation was at least 39 inches (1000 mm).⁹⁶ The maximum annual precipitation over this period was 219 inches (5577 mm) at the Little Port Walter station on the southeast side of Baranof Island about 110 miles (177 km) south of Juneau.⁹⁷
- In southcentral Alaska from 1949 to 1998, mean total annual precipitation was at least 32 inches (800 mm) and up to 39 inches (1000 mm).⁹⁸
- A comparison of official data from the National Climatic Data Center (NCDC) for 1971-2000 and unofficial National Weather Service (NWS) data for 1981-2010 for Juneau, Alaska indicates annual, warm season, and cold season precipitation increased.⁹⁹ The official NCDC record indicates average snowfall increased from 1971-2000 to 1981-2010, but the local NWS database indicates average snowfall decreased over the same time periods (Table 7, see notes).¹⁰⁰ In addition:
 - The date of first freeze occurred, on average, one day earlier over 1981 to 2010 than over 1971 to 2000, on October 3 instead of October 4.¹⁰¹
 - The date of last freeze occurred two days earlier, on average, over 1981 to 2010 than over 1971 to 2000, on May 6 instead of May 8.¹⁰²

⁹⁴ Nearly verbatim from Trenberth et al. *The changing character of precipitation*. (2003, p. 1211). The authors cite Ross and Elliott (2001) for this information.

⁹⁵ Nearly verbatim from Trenberth et al. (2003, p. 1211).

⁹⁶ Stafford, Wendler and Curtis. *Temperature and precipitation of Alaska: 50 year trend analysis*. (2000, Fig. 7, p. 41).

⁹⁷ Stafford, Wendler and Curtis. (2000, Fig. 7, p. 41)

⁹⁸ Stafford, Wendler and Curtis. (2000, Fig. 7, p. 41)

⁹⁹ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

¹⁰⁰ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

¹⁰¹ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

Western British Columbia

- Annual and seasonal precipitation trends over thirty, fifty, and 100-year time periods in the Georgia Basin and remaining coastal regions of B.C. within the NPLCC region are summarized in Table 8.¹⁰³ The Georgia Basin includes eastern Vancouver Island and a small portion of the mainland east of Vancouver Island; the coastal region includes all remaining areas in B.C. within the NPLCC region.¹⁰⁴

Table 7. Annual and seasonal precipitation and date of freeze trends for Juneau, AK over two thirty-year time periods.

		1971-2000* inches (cm)	1981-2010* inches (cm)	Absolute Change inches (cm)	Percent Change [†]
Annual and date of freeze trends	Total annual precipitation (including melted snow)	58.33 (148.2)	62.17 (157.9)	+3.84 (+9.75)	+6.58
	Average snowfall (Jan-Dec, NWS/Juneau)	93.0 [#] (236)	86.8 (220)	-6.2 (-16)	-6.7
	Average snowfall (Jan-Dec, NCDC/Asheville)	84.1 [#] (214)	N/A*	N/A	N/A
	Date of first freeze, on average	October 4	October 3	One day earlier	N/A
	Date of last freeze, on average	May 8	May 6	Two days earlier	N/A
Warm season (April – Sept)	Average seasonal precipitation (mostly rain)	26.85 (68.20)	28.52 (72.44)	+1.67 (+4.24)	+6.22
	Average snowfall (NWS/Juneau)	1.0 (2.5)	1.1 (2.8)	+0.1 (+0.3)	+10
	Average snowfall (NCDC/Asheville)	1.0 (2.5)	N/A*	N/A	N/A
Cold season (Oct – March)	Average seasonal precipitation	31.48 (79.96)	33.65 (85.47)	+2.17 (+5.51)	+6.89
	Average snowfall (NWS/Juneau)	92.0 [#] (234)	85.7 (218)	-6.3 (-16)	-6.8
	Average snowfall (NCDC/Asheville)	83.1 [#] (211)	N/A*	N/A	N/A

*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 official data for 1981-2010 are scheduled for release by NCDC in July 2011. The table was created by the authors of this report and approved by Tom Ainsworth and Rick Fritsch on June 10, 2011.

†Percent change reflects the relative increase or decrease from 1971-2000 to 1981-2010.

#Two values for average snowfall for 1971-2000 are reported due to differences between the locally held National Weather Service (NWS) database in Juneau and the official NWS database in Asheville, North Carolina. Differences represent the quality assurance processing and filtering that occurs at the National Climatic Data Center (NCDC) in Asheville (the source of official U.S. climate data) as well as missing data in the NCDC record. The Juneau office of the NWS is investigating the discrepancy.

¹⁰² This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

¹⁰³ Pike et al. *Compendium of forest hydrology and geomorphology in British Columbia: Climate Change Effects on Watershed Processes in British Columbia*. (2010, Table 19.1, p. 701)

¹⁰⁴ Pike et al. (2010, Fig. 19.1, p. 702)

Table 8. Historical trends precipitation in 30-, 50-, and 100-year periods, calculated from mean daily values as seasonal and annual averages.

(inches per month per decade, with millimeters per month per decade in parentheses)

Source: Modified from Pike et al. (2010, Table 19.1, p. 701) by authors of this report.

	<i>Time period</i>	<i>Coastal B.C.</i>	<i>Georgia Basin</i>
Annual	30-year: 1971-2004	0.064 (1.63)	-0.017 (-0.42)
	50-year: 1951-2004	0.040 (1.01)	-0.017 (-0.43)
	100-year: 1901-2004	0.089 (2.25)	0.047 (1.20)
Winter (Dec-Feb)	30-year: 1971-2004	-0.24 (-6.08)	-0.32 (-8.06)
	50-year: 1951-2004	-0.12 (-3.06)	-0.21 (-5.35)
	100-year: 1901-2004	0.13 (3.39)	0.070 (1.78)
Summer (June-Aug)	30-year: 1971-2004	0.14 (3.50)	-0.071 (-1.80)
	50-year: 1951-2004	0.083 (2.11)	-0.011 (-0.27)
	100-year: 1901-2004	0.036 (0.91)	0.034 (0.93)

Pacific Northwest¹⁰⁵

- Annual precipitation increased 12.9% (6.99"; 17.76cm) from 1920 to 2000.¹⁰⁶
- Observed relative increases were largest in the spring (+37%; +2.87"; 7.29cm), followed by winter (+12.4%; 2.47"; 6.27cm), summer (+8.9%; +0.39"; 0.99cm), and autumn (+5.8%; +1.27"; 3.22cm) from 1920 to 2000.¹⁰⁷ The spring trend (April-June) is significant at the $p < 0.05$ level.¹⁰⁸
- From about 1973 to 2003, clear increases in the variability of cool season precipitation over the western U.S. were observed.¹⁰⁹
- *Note: For the reader interested in trends in mean temperature, maximum temperature, minimum temperature, and precipitation annually, seasonally, and monthly, an online mapping tool produced by the Office of the Washington State Climatologist is available at <http://www.climate.washington.edu/trendanalysis/> (accessed 6.8.2011).*

Northwestern California

- Annual precipitation increased 2 to 6 inches (~5-15cm) from 1925 to 2008.¹¹⁰ There also appears to be a shift in seasonality of precipitation: an increase in winter and early spring precipitation and a decrease in fall precipitation from 1925 to 2008.¹¹¹
- From 1925 to 2008, the daily rainfall totals show a shift from light rains to more moderate and heavy rains that is especially evident in northern regions.¹¹² The increase in precipitation intensity over this time period is similar to results from other regions of the United States.¹¹³

¹⁰⁵ In this report, the Pacific Northwest refers to Washington, Oregon, Idaho, and in some cases, southern British Columbia.

¹⁰⁶ Mote. *Trends in temperature and precipitation in the Pacific Northwest during the Twentieth Century.* (2003, p. 279)

¹⁰⁷ Mote. (2003, p. 279)

¹⁰⁸ Mote. (2003, p. 279)

¹⁰⁹ Hamlet and Lettenmaier. *Effects of 20th century warming and climate variability on flood risk in the western U.S.* (2007, p. 15)

¹¹⁰ Killam et al. *California rainfall is becoming greater, with heavier storms.* (2010, p. 2)

¹¹¹ Killam et al. (2010, p. 4)

Future Projections

Note: The studies presented here differ in the baseline used for projections. Baselines include 1961-1990 (BC, CA) and 1970-1999 (WA, OR).

Note: Please see Box 3 for information on extreme precipitation in the NPLCC region.

Global

- Global precipitation patterns are projected to follow observed recent trends, increasing in high latitudes and decreasing in most subtropical land regions.¹¹⁴ Overall, precipitation may be more intense, but less frequent, and is more likely to fall as rain than snow.¹¹⁵
- *Note: There is greater confidence overall in projected temperature changes than projected changes in precipitation given the difficulties in modeling precipitation¹¹⁶ and the relatively large variability in precipitation (both historically and between climate model scenarios) compared with temperature.*

Southcentral and Southeast Alaska (1961-1990 and 2000 baseline)

- Climate models project increases in precipitation over Alaska.¹¹⁷ Simultaneous increases in evaporation due to higher air temperatures, however, are expected to lead to drier conditions overall, with reduced soil moisture.¹¹⁸
- The University of Alaska – Fairbanks Scenarios Network for Alaska Planning (SNAP) has web-based mapping tools for viewing current and future precipitation under the B1, A1B, and A2 scenarios for the 2000-2009, 2030-2039, 2060-2069, and 2090-2099 decades (baseline not

Box 3. Trends and projections for extreme precipitation in the NPLCC region.

Trends. In the Pacific Northwest (WA, OR, ID, southern B.C.), trends in extreme precipitation are ambiguous. Groisman et al. (2004) find no statistical significance in any season in the Pacific Northwest (1908-2000). Madsen and Figdor (2007) find a statistically significant increase of 18% (13-23%) in the Pacific states (WA, OR, CA), a statistically significant increase of 30% (19-41%) in Washington, and a statistically significant decrease of 14% (-4 to -24%) in Oregon (1948-2006). In southern British Columbia and along the North Coast, Vincent and Mekis (2006) report some stations showed significant increases in very wet days (the number of days with precipitation greater than the 95th percentile) and heavy precipitation days ($\geq 0.39''$, 1.0cm). A limited number of stations also showed significant decreases.

Projections. Precipitation patterns in the Northwest are expected to become more variable, resulting in increased risk of extreme precipitation events, including droughts. In northern California, daily extreme precipitation occurrences (99.9 percentile) are projected to increase from 12 occurrences (1961-1990) to 25 (+108%) or 30 (+150%) occurrences by 2070-2099 under A2 simulations in the PCM and GFDL models, respectively.

Sources: Capalbo et al. (2010); Cayan et al. (2008); Groisman et al. (2004); Madsen & Figdor (2007); Mote, Gavin, & Huyer (2010); Vincent & Mekis (2006)

¹¹² Nearly verbatim from Killam et al. (2010, p. 3)

¹¹³ Nearly verbatim from Killam et al. (2020, p. 3-4)

¹¹⁴ Nearly verbatim from IPCC. (2007g, p. 8)

¹¹⁵ Karl, Melillo and Peterson. (2009, p. 24)

¹¹⁶ CIG. (2008) The authors cite the IPCC AR4, Chapter 8 of the Working Group I report, for this information.

¹¹⁷ Karl, Melillo and Peterson. (2009, p. 139)

¹¹⁸ Verbatim from Karl, Melillo and Peterson. (2009, p. 139). The authors cite Meehl et al. (2007) for this information.

provided). Tools are available at <http://www.snap.uaf.edu/web-based-maps> (accessed 3.16.2011).¹¹⁹

Western British Columbia (1961-1990 baseline)

- By the 2050s, annual precipitation is projected to increase 6% (range not provided) along the B.C. coast compared to a 1961-1990 baseline (multi-model average; scenarios not provided).¹²⁰
- Along the North Coast by the 2050s, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
 - In winter, precipitation is projected to increase 6%¹²¹ (0 to +25%),¹²²
 - In spring, precipitation is projected to increase 7% (range not provided),
 - In summer, precipitation is projected to decrease 8%¹²³ (-25 to +5%),¹²⁴ and
 - In fall, precipitation is projected to increase 11% (range not provided).¹²⁵
- Along the South Coast by the 2050s, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
 - In winter, precipitation is projected to increase 6%¹²⁶ (-10 to +25%),¹²⁷
 - In spring, precipitation is projected to increase 7% (range not provided),¹²⁸
 - In summer, precipitation is projected to decrease 13%¹²⁹ (-50 to 0%),¹³⁰ and
 - In fall, precipitation is projected to increase 9% (range not provided).¹³¹

Pacific Northwest (1970-1999 baseline)

- Annual average precipitation is projected to increase as follows (1970-1999 baseline):
 - By 2010-2039, precipitation is projected to increase 1% (-9 to +12%),
 - By 2030-2059, precipitation is projected to increase increase 2% (-11 to +12%), and
 - By 2070-2099, precipitation is projected to increase 4% (-10 to +20%).¹³²
- Winter projections are as follows (1970-1999 baseline):
 - In 2010-2039 and 2030-2059, 58 to 90% of models project increases in precipitation.¹³³

¹¹⁹ Maps are also available for current and future mean annual temperature, date of thaw, date of freeze up, and length of growing season. The scenario and decadal options are the same as those described for precipitation.

¹²⁰ Pike et al. (2010, Table 19.3, p. 711)

¹²¹ Pike et al. (2010, Table 19.3, p. 711)

¹²² B.C. Ministry of Environment. (2006, Table 10, p. 113). B.C. Ministry of Environment makes the following note: "From data in the Canadian Institute for Climate Studies, University of Victoria (www.cics.uvic.ca) study of model results from eight global climate modelling centres. A total of 25 model runs using the eight models were used to determine the range of values under different IPCC emission scenarios (Nakicenovic and Swart 2000)."

¹²³ Pike et al. (2010, Table 19.3, p. 711)

¹²⁴ B.C. Ministry of Environment. (2006, Table 10, p. 113)

¹²⁵ Pike et al. (2010, Table 19.3, p. 711)

¹²⁶ Pike et al. (2010, Table 19.3, p. 711)

¹²⁷ B.C. Ministry of Environment. (2006, Table 10, p. 113)

¹²⁸ Pike et al. (2010, Table 19.3, p. 711)

¹²⁹ Pike et al. (2010, Table 19.3, p. 711)

¹³⁰ B.C. Ministry of Environment. (2006, Table 10, p. 113)

¹³¹ Pike et al. (2010, Table 19.3, p. 711)

¹³² The range of precipitation reported here was obtained from the Climate Impacts Group. It can be found in a document titled *Summary of Projected Changes in Major Drivers of Pacific Northwest Climate Change Impacts*. A draft version is available online at http://www.ecy.wa.gov/climatechange/2010TAGdocs/20100521_projecteddrrivers.pdf (last accessed 1.5.2011).

- In 2070-2099, an 8% increase in precipitation is projected (small decrease to +42%; 1.2 inches; ~3cm).¹³⁴
- Summer precipitation is projected to decrease 14% by the 2080s, although some models project decreases of 20 to 40% (1.2-2.4 inches; 3-6cm) compared to a 1970-1999 baseline.¹³⁵
- These regionally averaged precipitation projections reflect all B1 and A1B simulations, along with the weighted reliability ensemble average (REA, an average that gives more weight to models that perform well in simulating 20th century climate).¹³⁶

Northwestern California (1961-1990 baseline)

- Annual average precipitation is projected to decrease 12 to 35% by mid-century, with further decreases expected by 2070-2099 compared to a 1961-1990 baseline.¹³⁷ Over 2005-2034, small to moderate decreases are projected compared to a 1961-1990 baseline.¹³⁸ These projections are based on six climate models using the A2 and B1 emissions scenarios.¹³⁹

Information Gaps

Regional predictions of changes in precipitation intensity–duration relationships remain a significant knowledge gap in British Columbia, particularly for durations shorter than 24 hours.¹⁴⁰ Information on seasonal temperature projections in California is needed.

¹³³ Mote and Salathé Jr. *Future climate in the Pacific Northwest*. (2010, p. 43-44)

¹³⁴ Mote and Salathé Jr. (2010, p. 43-44)

¹³⁵ Mote and Salathé Jr. (2010, p. 42)

¹³⁶ Mote and Salathé Jr. (2010, p. 39)

¹³⁷ California Natural Resources Agency. (2009, p. 17-18)

¹³⁸ California Natural Resources Agency. (2009, p. 17-18)

¹³⁹ California Natural Resources Agency. (2009, p. 17-18)

¹⁴⁰ Verbatim from Pike et al. (2011, p. 727)

IV. Climate Impacts on Terrestrial Environments

The responses of terrestrial ecosystems to a changing climate have many dimensions.¹⁴¹ Key environmental consequences of climate change are increased temperature, longer growing seasons, less snow, and more frequent drought.¹⁴² Climate variability and climate changes alter the frequency, intensity, timing, and/or spatial extent of disturbances.¹⁴³ Natural disturbances, impacted by climate, include insects, disease, introduced species, fires, droughts, hurricanes, landslides, wind storms, and ice storms.¹⁴⁴ Climate change has directly affected and will continue to affect the global hydrologic cycle and thus the quality, quantity, and timing of streamflows from forests.¹⁴⁵

Natural disturbances are fundamental to ecosystem structure and function.¹⁴⁶ As agents of change, shifting disturbance regimes and patterns could become as important as increasing temperatures and changing levels of precipitation.¹⁴⁷ When ecosystems experience more than one disturbance, the compounded effects can lead to new domains (i.e., a new long-term condition resulting from a second disturbance occurring before a system has recovered from an initial disturbance event) or surprises.¹⁴⁸ Under climate change, these compounded interactions may be unprecedented and unpredictable.¹⁴⁹ They are likely to appear slowly and be difficult to detect because trees live for so long.¹⁵⁰ Furthermore, climate change has been shown to exacerbate the effects of other stressors.¹⁵¹

Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations including global and regional synthesis reports (see Methodology), the following major climate-driven impacts on terrestrial ecosystems in the NPLCC region have been identified:

1. Altered hydrology, fog regimes, and drought regimes
2. Altered growing season and freeze and thaw patterns
3. Altered fire regimes
4. Altered insect, pathogen, and disease regimes
5. Altered patterns of landslides, ice and wind storms, and avalanches

¹⁴¹ Verbatim from Field et al. (2007, p. 2). *Feedbacks of terrestrial ecosystems to climate change*.

¹⁴² Verbatim from Ryan et al. (2012, p. 32)

¹⁴³ Verbatim from Joyce et al. (2001, p. 499)

¹⁴⁴ Verbatim from Joyce et al. (2001, p. 498)

¹⁴⁵ Verbatim from Furniss et al. (2011, p. 12). *Water, climate change, and forests: Watershed stewardship for a changing climate*.

¹⁴⁶ Verbatim from Pojar (2010, p. 21). Pojar cites Parminter (1998) for this information.

¹⁴⁷ Verbatim from Pojar (2010, p. 25)

¹⁴⁸ Nearly verbatim from Dale et al. (2008, p. 729). Dale et al. cite Paine et al. (1998) for this information.

¹⁴⁹ Verbatim from Dale et al. (2008, p. 729)

¹⁵⁰ Verbatim from Dale et al. (2008, p. 729)

¹⁵¹ Nearly verbatim from Staudt et al. (2012, p. 5-1)

These five impacts will be discussed in the order listed. The following structure will be used to discuss all impacts, with the exception of altered hydrology, fog regimes, and drought regimes, for which we focus on fog and drought regimes. Hydrologic impacts are summarized, and the reader is referred to a companion report for further detail:

- **Understanding the causes** – a description of the physical, chemical, and/or biological dynamics and processes contributing to each impact, with the exception of the section on altered growing season and freeze and thaw patterns.
- **Observed Trends** – observed changes, compared to the historical baseline, for southcentral and southeast Alaska, western British Columbia, western Washington, western Oregon, and northwest California. For context, summary information on observed changes globally or for western North America is also provided.
- **Future Projections** – projected direction and/or magnitude of future change for southcentral and southeast Alaska, western British Columbia, western Washington, western Oregon, and northwest California. For context, summary information on future projections globally or for western North America is also provided.
- **Information Gaps** – information and research needs identified in the literature, as well as our summary of the sections missing information in this chapter.

1. Altered hydrology, fog regimes, and drought regimes

The key hydrologic changes for the NPLCC's terrestrial ecosystems are reduced snowpack and earlier snowmelt, more intense rain, and increased drought. Observed trends and future projections for changes in snowpack, snowmelt, and intense rain are covered in a companion report and summarized in Box 3 and the sidebar below.¹⁵² Changes in fog and drought regimes are covered in this section.

Water is essential for sustaining forest, stream, wetland, and lake ecosystems and a wide range of human activities.¹⁵³ Climatic warming will affect forest ecosystems primarily through effects on precipitation (i.e., snow versus rain).¹⁵⁴

A climatic moisture deficit occurs when the monthly precipitation is less than the evaporative demand for the month; conversely, if precipitation is greater than the evaporative demand, a moisture surplus occurs.¹⁵⁵

Understanding forest water cycling, fog regimes, and drought regimes

Climate change will have both indirect and direct effects on forest water cycling.¹⁵⁶ Indirect effects are associated with changes in atmospheric CO₂, increased temperature, altered soil water availability, climate-mediated changes in species composition, and changes in disturbance regimes or management and policy decisions that alter forest structure and composition (i.e., non-climate stressors).¹⁵⁷ Indirect effects of climate change on forest water cycling work primarily through effects on forest evapotranspiration (ET), the combination of evaporation of water from plant and ground surfaces and transpiration.¹⁵⁸ Besides elevated atmospheric CO₂ concentration, some of the most important variables affecting forest ET are temperature, humidity, water availability, and species distributions.¹⁵⁹ Direct effects are associated with more rainfall and more intense storms.¹⁶⁰ These in turn increase base flows in streams (particularly intermittent streams), increase flood risk,

Summary: Snowpack, Snowmelt, and Intense Rain

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. While annual precipitation may not change significantly, more cool season and less warm season precipitation is projected, with more intense rainfall possible. 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.

Sources: Allan et al. (2010); Coxson & Curteanu (2002); Dale et al. (2008); Grimm et al. (2012); Peng et al. (2008); Peterman & Bachelet (2012); Ryan et al. (2012); Tillmann & Siemann (2011b) and many references therein; USGS (2002)

¹⁵² Tillmann & Siemann (2011b)

¹⁵³ Verbatim from B.C. Ministry of Forests, Mines, and Lands (2010, p. 97)

¹⁵⁴ Nearly verbatim from Vose et al. (2012, p. vi). *Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector.*

¹⁵⁵ Verbatim from Pike et al. (2010, p. 713)

¹⁵⁶ Verbatim from Ryan et al. (2012, p. 47). *Effects of climatic variability and change.*

¹⁵⁷ Nearly verbatim from Ryan et al. (2012, p. 47)

¹⁵⁸ Verbatim from Ryan et al. (2012, p. 47)

¹⁵⁹ Verbatim from Ryan et al. (2012, p. 47)

¹⁶⁰ Nearly verbatim from Ryan et al. (2012, p. 47)

accelerate erosion, and increase the potential for both landslides and increased interstorm periods and drought, along with climate-related changes in infiltration rate owing to extreme wildfire.¹⁶¹

Low-altitude fog and clouds provide important terrestrial water subsidies to many ecosystems around the world including neotropical montane cloud forests and coastal grasslands and forests of the western United States.¹⁶² By reducing transpiration rates, low clouds provide an atmospheric mechanism for redwood water conservation during the dry summer season.¹⁶³ The most likely effect of fog decline is a heightened drought sensitivity for coastally restricted plants.¹⁶⁴ In these ecosystems and others (i.e., neotropical montane cloud forests, western U.S. coastal grasslands and forests), plants gain access to fog and cloud moisture through root uptake of coalesced water that drips to the soil or by direct foliar uptake of water retained by the plant crowns following interception.¹⁶⁵ Unlike root uptake of water that occurs only when significant fog or cloud inundation causes drip to the soil, foliar uptake allows plants to immediately capture any atmospheric water subsidy that wets foliage but may otherwise never reach the ground.¹⁶⁶

Increases in the frequency, duration, and/or severity of drought and heat stress associated with climate change could fundamentally alter the composition, structure, and biogeography of forests in many regions.¹⁶⁷ Droughts occur in nearly all forest ecosystems.¹⁶⁸ Drought is a critical predisposing factor that leads to both wildfires and major insect outbreaks.¹⁶⁹ Drought effects are influenced by soil texture and depth, exposure, species present, life stage, and the frequency, duration, and severity of drought.¹⁷⁰ The primary immediate response of trees to drought is to reduce net primary production (NPP) and water use, which are both driven by reduced soil moisture and stomatal conductance.¹⁷¹ Under extended severe drought conditions, plants die.¹⁷² Seedlings and saplings usually die first and can succumb under moderate drought conditions.¹⁷³ Deep rooting, stored carbohydrates, and nutrients in large trees make them susceptible only to longer, more severe droughts.¹⁷⁴ Secondary effects also occur.¹⁷⁵ When reductions in NPP are extreme or sustained over multiple growing seasons, increased susceptibility to

¹⁶¹ Verbatim from Ryan et al. (2012, p. 47)

¹⁶² Verbatim from Limm & Dawson (2010, p. 1121). *Polystichum munitum* (Dryopteridaceae) varies geographically in its capacity to absorb fog water by foliar uptake within the redwood forest ecosystem. Limm & Dawson cite Grubb & Whitmore (1966), Cavelier & Goldstein (1989), Cavelier et al. (1996), and Holder (2004) for information on neotropical montane cloud forests and Azevedo & Morgan (1974), Ingraham & Matthews (1995), Corbin et al. (2005), Williams et al. (2008), Fischer et al. (2009), and Ewing et al. (2009) for information on the western United States.

¹⁶³ Verbatim from Johnstone & Dawson (2010, p. 4537). *Climatic context and ecological implications of summer fog decline in the coast redwood region.*

¹⁶⁴ Verbatim from Johnstone & Dawson (2010, p. 4537). Johnstone & Dawson cite Fischer et al. (2009) for this information.

¹⁶⁵ Verbatim from Limm & Dawson (2010, p. 1121)

¹⁶⁶ Verbatim from Limm & Dawson (2010, p. 1121). Limm & Dawson cite Múnne-Bosch (2009) for this information.

¹⁶⁷ Verbatim from Allan et al. (2010, p. 660)

¹⁶⁸ Verbatim from Joyce et al. (2001, p. 501). Joyce et al. cite Hanson and Weltzin (2000) for this information.

¹⁶⁹ Verbatim from Shafer et al. (2010, p. 186)

¹⁷⁰ Verbatim from Dale et al. (2008, p. 727). *Climate change and forest disturbances.*

¹⁷¹ Verbatim from Joyce et al. (2001, p. 501)

¹⁷² Verbatim from Joyce et al. (2001, p. 501)

¹⁷³ Verbatim from Joyce et al. (2001, p. 501)

¹⁷⁴ Verbatim from Joyce et al. (2001, p. 501)

¹⁷⁵ Verbatim from Dale et al. (2008, p. 727)

insects or disease is possible, especially in dense stands.¹⁷⁶ Drought can also reduce decomposition processes leading to a buildup of organic matter on the forest floor.¹⁷⁷ The consequences of a changing drought regime depend on annual and seasonal changes in climate and whether a plant's current drought adaptations offer resistance and resilience to new conditions.¹⁷⁸ Elevated CO₂ concentrations may increase a plant's water-use efficiency, which in turn may enhance its tolerance of drought conditions.¹⁷⁹ Alternatively, a small increase in growing season temperature could increase evaporative demand, triggering moisture stress.¹⁸⁰ Further, if high temperature coincides with drought stress in forests, carbon starvation and mortality can occur more quickly than if these factors did not coincide.¹⁸¹

Observed Trends

Global

Although episodic mortality occurs in the absence of climate change, studies suggest that at least some of the world's forested ecosystems already may be responding to climate change and raise concern that forests may become increasingly vulnerable to higher background tree mortality rates and die-off in response to future warming and drought, even in environments that are not normally considered water-limited.¹⁸²

Western North America

In places in the U.S. with seasonal snowpack, there is high certainty that warming has caused profound changes in snowpack, seasonality of discharge, and frequency of soil freezing, with profound consequences for both terrestrial and aquatic ecosystems.¹⁸³

Southcentral and Southeast Alaska

For most of Alaska, water lost through potential evapotranspiration typically exceeds the rate of incoming precipitation during the peak of the growing season, leading to an overall water deficit during this time.¹⁸⁴

Western British Columbia

Under current climatic conditions, the coastal zones (i.e., Coastal Western Hemlock) experience little or no drought throughout the year.¹⁸⁵ The eastside of Vancouver Island (i.e., the Coastal Douglas-fir zone) and the more inland areas of the Mountain Hemlock zone exhibit some areas with drought stress.¹⁸⁶

¹⁷⁶ Verbatim from Joyce et al. (2001, p. 501). Joyce et al. cite Negron (1998) for this information.

¹⁷⁷ Verbatim from Joyce et al. (2001, p. 501)

¹⁷⁸ Verbatim from Joyce et al. (2001, p. 501)

¹⁷⁹ Verbatim from Shafer et al. (2011, p. 213). Shafer et al. cite Polley (1997) for this information.

¹⁸⁰ Verbatim from Dale et al. (2008, p. 727)

¹⁸¹ Verbatim from Ryan et al. (2012, p. 49). Ryan et al. cite Adams et al. (2009) for this information.

¹⁸² Nearly verbatim from Allen et al. (2010, p. 660). *A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests.*

¹⁸³ Nearly verbatim from Grimm et al. (2012, p. 3-31). *Impacts of climate change on ecosystem structure and functioning.*

¹⁸⁴ Verbatim from O'Brien & Loya (n.d., p. 2). *Climate Change Impacts on Water Availability in Alaska.* O'Brien & Loya refer the reader to Figure 1a in the cited report for this information.

At two locations on the east coast of Vancouver Island in predominantly Douglas-fir forests from 1951 to 2002, the soil water storage capacity varied from 3.1 inches (78 millimeters, mm) at the poorest site to 10.2 inches (260 mm) at the best site.¹⁸⁷ Thus, summer water availability (May to July rainfall plus 60% of the water storage capacity of the root zone) ranged from 6.89 to 11.6 inches (175 to 295 mm) for the sites investigated.¹⁸⁸ The calculated May to July potential evaporation for 1951 to 2002 varied from a low of 6.02 inches (153 mm) in 1993 to a high of 11.0 inches (279 mm) in 1951, with a mean of 8.58 ± 1.1 inches (218 ± 28 mm).¹⁸⁹ The better the growing site, the smaller the number of years when the evaporative demand is greater than summer water availability and the smaller the number of years with soil water restrictions to evaporation in early summer.¹⁹⁰ For example, sites with shallower root zones were frequently under moisture stress early in the summer and this was reflected in lower growth.¹⁹¹

Pacific Northwest

Large annual snowfall levels in the maritime climate of the west slope of the Washington-Oregon Cascades and British Columbia-Alaska Coast Mountains depresses snowline and results in a wide distribution of alpine and subalpine vegetation.¹⁹²

Northwest California

Fog is clearly a dominant climatic factor on the California coast, and long-term reductions likely have and may continue to impact the water and carbon economy of redwoods and other coastal endemic species.¹⁹³ Based on direct hourly measurements of cloud ceiling heights from 1951 to 2008 from central Oregon to southern California, fog frequency (i.e., the summer daily average computed from hourly records at two stations) is greatest (40-44%) in northern and central California and declines below 30% toward Oregon and southern California.¹⁹⁴ By using a long-term index of daily maximum land temperatures, Johnstone & Dawson (2010) infer a 33% reduction in fog frequency since the early 20th century.¹⁹⁵ More specific information on historical fog variability is also available:

- From 1951 to 1975, fog frequency varied around a mean of 44%, followed by a gradual decline through the 1980s and 1990s culminating in a record minimum of 27% in 1997.¹⁹⁶ The past decade has seen a partial recovery to pre-1977 levels with an average frequency of 42%.¹⁹⁷

¹⁸⁵ Verbatim from Coops et al. (2010, p. 519). *Assessing the impact of current and projected climates on Douglas-fir productivity in British Columbia, Canada, using a process-based model (3-PG)*.

¹⁸⁶ Verbatim from Coops et al. (2010, p. 519). Coops et al. refer the reader to Figures 4C and 4D in the cited article for this information.

¹⁸⁷ Nearly verbatim from Spittlehouse (2003, p. 679). *Water availability, climate change and the growth of Douglas-fir in the Georgia Basin*.

¹⁸⁸ Nearly verbatim from Spittlehouse (2003, p. 673)

¹⁸⁹ Nearly verbatim from Spittlehouse (2003, p. 680). Spittlehouse refers the reader to Figure 1 in the cited article for this information.

¹⁹⁰ Verbatim from Spittlehouse (2003, p. 680)

¹⁹¹ Nearly verbatim from Spittlehouse (2003, p. 683)

¹⁹² Verbatim from Rochefort et al. (2006, p. 245)

¹⁹³ Verbatim from Johnstone & Dawson (2010, p. 4537)

¹⁹⁴ Nearly verbatim from Johnstone & Dawson (2010, p. 4534)

¹⁹⁵ Verbatim from Johnstone & Dawson (2010, p. 4533)

¹⁹⁶ Verbatim from Johnstone & Dawson (2010, p. 4535)

¹⁹⁷ Verbatim from Johnstone & Dawson (2010, p. 4535)

- Hourly summer averages indicate that nighttime fog is approximately twice as common as its daytime occurrence.¹⁹⁸
- Seasonally, fog frequency reaches a maximum in early August, with greatest occurrence from June through September.¹⁹⁹
- In summers of extreme anomalies, fog was present 62% of the time in 1951, a frequency 2.3 times greater than the 1997 minimum.²⁰⁰ From 10:00 AM to 9:00 PM local time, the summer of 1951 was fog-free only 13 of 122 days, compared to 62 fogless days in 1997.²⁰¹

These conclusions differ from those reached by observational and modeling studies suggesting increases in northern California coastal fog in response to enhanced greenhouse forcing.²⁰² These observational and modeling studies have proposed that disproportionate radiative heating over interior land areas might lead to increases in the ocean-land pressure gradient and therefore stronger upwelling winds and greater fog frequency.²⁰³ However, as described in the bullets above, Johnstone & Dawson (2010) find direct evidence for moderate fog reductions since 1951, with interannual and multidecadal variations governed largely by ocean-atmosphere circulation and temperature anomalies related to the PDO.²⁰⁴ For example, Johnstone & Dawson's (2010) results show a strong positive relationship between northern California fog and upwelling-favorable winds over the northern limb of the California Current.²⁰⁵

In another study, 34%, on average, of the annual hydrologic input to a northern California coast redwood forest was from fog drip off the redwood trees themselves (interception input) (study period: 1992-1994).²⁰⁶ When trees were absent, the average annual input from fog was only 17%, demonstrating that the trees significantly influence the magnitude of fog water input to the ecosystem.²⁰⁷ In summer, when fog was most frequent, approximately 19% of the water within coast redwood, and approximately 66% of the water within the understory plants came from fog after it had dripped from tree foliage into the soil; for coast redwood, this fog water input comprised 13–45% of its annual transpiration.²⁰⁸

¹⁹⁸ Verbatim from Johnstone & Dawson (2010, p. 4534). Johnstone & Dawson refer the reader to Figure S1 in the cited article for this information.

¹⁹⁹ Verbatim from Johnstone & Dawson (2010, p. 4534). Johnstone & Dawson refer the reader to Figure S2 in the cited article for this information.

²⁰⁰ Nearly verbatim from Johnstone & Dawson (2010, p. 4535). Johnstone & Dawson refer the reader to Figures 2A and 2B in the cited article for this information.

²⁰¹ Nearly verbatim from Johnstone & Dawson (2010, p. 4535)

²⁰² Verbatim from Johnstone & Dawson (2010, p. 4537). Johnston & Dawson cite Bakun (1990) and Lebassi et al. (2009) for information on observational studies and Diffenbaugh et al. (2004) and Snyder et al. (2003) for information on modeling studies.

²⁰³ Nearly verbatim from Johnstone & Dawson (2010, p. 4537)

²⁰⁴ Verbatim from Johnstone & Dawson (2010, p. 4537)

²⁰⁵ Nearly verbatim from Johnstone & Dawson (2010, p. 4537)

²⁰⁶ Nearly verbatim from Dawson (1998, p. 476). *Fog in the California redwood forest: ecosystem inputs and use by plants.*

²⁰⁷ Verbatim from Dawson (1998, p. 476)

²⁰⁸ Verbatim from Dawson (1998, p. 476)

Future Projections

Global

If the recent increase in mortality reports is indeed driven in part by global climate change, far greater chronic forest stress and mortality risk should be expected in coming decades due to the large increases in mean temperature and significant long-term regional drying projected in some places by 2100, in addition to projected increases in the frequency of extreme events such as severe droughts, hot extremes, and heat waves.²⁰⁹

Western North America

Forest ecosystems typically support high infiltration capacities because of large soil pores developed by root systems and soil fauna, so surface runoff is not common compared to other land cover.²¹⁰ However, high-intensity precipitation or snowmelt events can rapidly move water in the soil to the unsaturated zone or ground water, or into the local stream, particularly in steep terrain.²¹¹ Increases in storm intensity projected for the future may increase peak streamflow and flooding through this process.²¹² In addition, increased flooding, erosion, and movement of sediment into streams will be caused by higher rain to snow ratios in mountainous regions (western mountains).²¹³ Increased drought will exacerbate stress complexes that include insects, fire, and invasive species, leading to higher tree mortality, slow regeneration in some species, and altered species assemblages.²¹⁴

Although the effects of elevated CO₂ on evapotranspiration remain uncertain, studies agree that the direct effects will be modest (± 10 percent; study baselines and time periods not provided) compared to the changes expected for other variables that affect evapotranspiration, such as precipitation variability.²¹⁵ Spatially, springtime evapotranspiration in the lower latitudes could be delayed (i.e., come later in the season) while evapotranspiration in the higher latitudes could be advanced (i.e., come earlier in the season).²¹⁶ However, the potential increase in evapotranspiration owing to a lengthened growing season can be constrained by the water availability and drought that often arise late in the growing season.²¹⁷ Water limitations are a direct control on evapotranspiration (lower water availability reduces transpiration), and many regions of the United States have experienced more frequent precipitation extremes, including droughts, over the last 50 years.²¹⁸ Evapotranspiration will also change with changes in canopy density, canopy composition, water demand, and resulting energy partitioning in new

²⁰⁹ Verbatim from Allen et al. (2010, p. 670). Allan et al. cite IPCC (2007a), Jentsch et al. (2007), and Sterl et al. (2008) for this information.

²¹⁰ Verbatim from Ryan et al. (2012, p. 50)

²¹¹ Verbatim from Ryan et al. (2012, p. 50). Ryan et al. cite Brooks et al. (2011), Laio et al. (2001), Troch et al. (2009), and Hwang et al. (n.d.) for this information.

²¹² Verbatim from Ryan et al. (2012, p. 50)

²¹³ Nearly verbatim from Vose et al. (2012, p. v)

²¹⁴ Verbatim from Vose et al. (2012, p. v)

²¹⁵ Verbatim from Ryan et al. (2012, p. 48). Ryan et al. cite Leuzinger & Korner (2010) for information on other variables affecting evapotranspiration.

²¹⁶ Nearly verbatim from Ryan et al. (2012, p. 48)

²¹⁷ Nearly verbatim from Ryan et al. (2012, p. 48). Ryan et al. cite Zhao & Running (2010) for this information.

²¹⁸ Verbatim from Ryan et al. (2012, p. 48). Ryan et al. cite Easterling et al. (2000b), Groisman et al. (2004), Huntington (2006), and Solomon et al. (2007) for this information.

communities, which will occur in response to species changes that accompany climate change, especially if large areas of forests experience mortality.²¹⁹

Southcentral and Southeast Alaska

In many areas the growing season will get longer as average spring and fall temperatures rise above freezing (see Chapter IV.2) for additional information on growing season).²²⁰ As a result, many areas are projected to undergo a transition from being non-evaporative environments (potential evapotranspiration, PET, equal to zero) to areas that are experiencing some amount of evaporation (PET>0) in the future.²²¹ By the end of the century most of Alaska south of the Brooks Range is expected to undergo this transition during the spring thaw, with only extremely high altitude areas remaining unaffected.²²²

One analysis reveals that this water deficit (i.e., PET exceeding precipitation during the peak of the growing season) will become even greater in the future due to significant increases in PET without comparable increases in precipitation (2090-2099 vs. 1961-1990; Echam5, GFDL2.1, MIROC3.2MR, HadCM3, and CGCM3 run under A1B).²²³ Only the colder, high altitude areas of the Alaska Range, Chugach, and Wrangell Mountains are predicted to increase their water storage in June (Figure 5).²²⁴

Western British Columbia

On Vancouver Island, drought along the east coast is expected to increase with elevated temperature and no increase in precipitation.²²⁵

In two locations on the east coast of Vancouver Island in forests currently dominated by Douglas-fir, climate change scenarios for a 1.8-7.2 °F (1-4 °C) increase in mean daily temperature resulted in a 3-10% increase in potential evaporation.²²⁶ The changes in potential evaporation are not large but combined with a reduction in rainfall could result in a significant decrease in tree growth over time.²²⁷ The biggest impact of increased potential evaporation and decreased rainfall will be on sites with a low summer water availability that are already regularly under moisture stress.²²⁸ Sites that have a high summer water

²¹⁹ Verbatim from Ryan et al. (2012, p. 49). Ryan et al. cite Breshears et al. (2005) for this information.

²²⁰ Nearly verbatim from O'Brien & Loya (n.d., p. 3)

²²¹ Nearly verbatim from O'Brien & Loya (n.d., p. 3). O'Brien & Loya refer the reader to Figures 2a and 2d in the cited report for information on non-evaporative environments.

²²² Verbatim from O'Brien & Loya (n.d., p. 3). O'Brien & Loya refer the reader to Figure 2c in the cited report for this information.

²²³ Nearly verbatim from O'Brien & Loya (n.d., p. 2).

²²⁴ Verbatim from O'Brien & Loya (n.d., p. 2).

²²⁵ Verbatim from Coops et al. (2010, p. 519)

²²⁶ Nearly verbatim from Spittlehouse (2003, p. 683). *Note: Regarding the methods used to calculate the projection, Spittlehouse states that climate change scenarios were based on the summary of the output from a number of GCM and emissions scenarios. Graphs of predicted changes in temperature versus precipitation on a seasonal basis for the grid cell containing the Georgia Basin were obtained from CICS (2003). The change in summer potential evaporation was determined by applying increases of 1.8-7.2 °F (1-4 °C) in the temperature and a 10% decrease or 5% increase in precipitation to the May through September daily values of long-term weather data and recalculating evaporation. A 5% reduction in solar radiation was applied to the 7.2 °F (4 °C) increase calculation. The increase in mean May to September air temperature ranged from 1.8-3.6 °F (1-2 °C) in 2020 to 5.4-7.2 °F (3-4 °C) by 2080. Source: Spittlehouse (2003, p. 678)*

²²⁷ Verbatim from Spittlehouse (2003, p. 681)

²²⁸ Verbatim from Spittlehouse (2003, p. 683)

availability may have sufficient water storage capacity to meet the increased potential evaporative demand in most years.²²⁹ Specific results for Douglas-fir productivity and stand volume are available:

- **Douglas-fir productivity:** The growth/available water relationship indicated that the productivity of Douglas-fir could decline by up to 30% in response to the increase in potential evaporation and this would be exacerbated by a reduction in summer precipitation.²³⁰
- **Stand volume:** Change in water availability through a 10% reduction in rainfall or a 6% increase in potential evaporation over the life of the stand could result in a reduction in stand volume by up to 80 cubic meters per hectare at harvest, 10 to 30% of current merchantable volume.²³¹

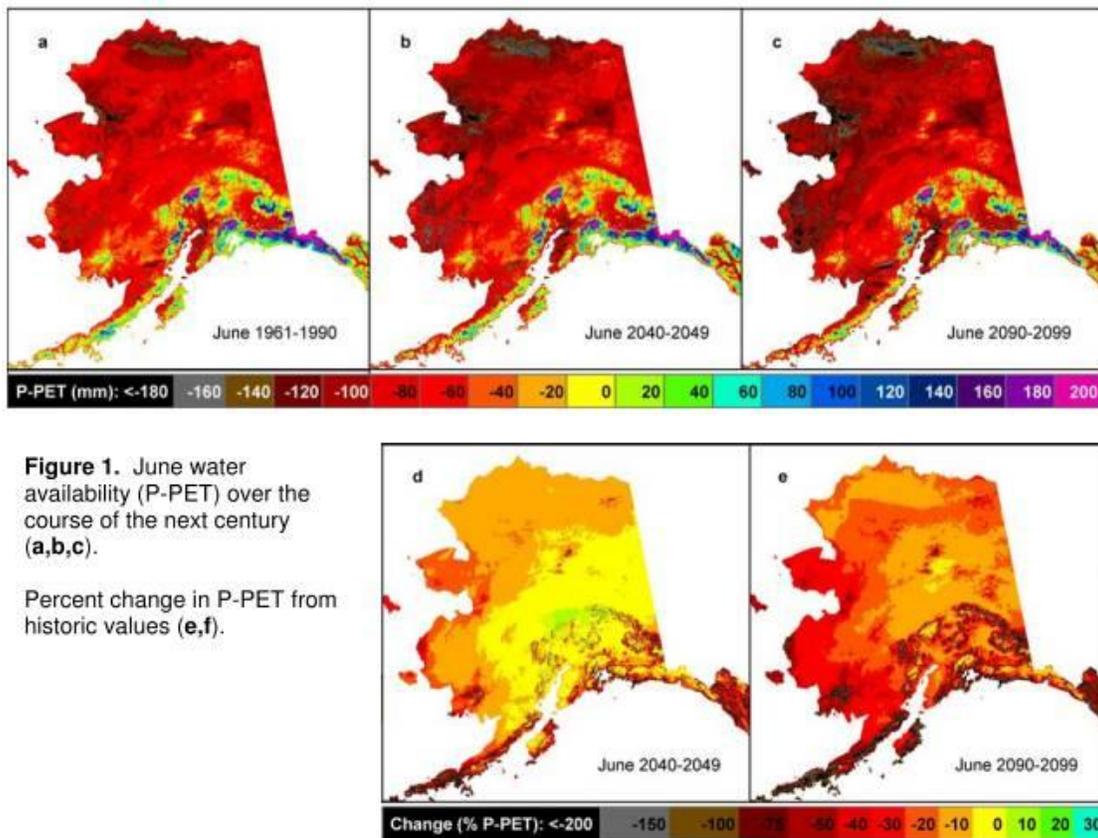


Figure 5. June water availability (Precipitation-Potential Evapotranspiration, P-PET) over the course of the next century (a, b, c). Percent change in P-PET from historic values (e, f).
Source: Reproduced from O'Brien & Loya (n.d., Figure 1, p. 2) by authors of this report.

Western Washington

The area of Washington forest that is severely water-limited will likely increase (relative to 1970-1999) by 32% in the 2020s and an additional 12% increase in both the 2040s and the 2080s (all values relative

²²⁹ Verbatim from Spittlehouse (2003, p. 683)

²³⁰ Verbatim from Spittlehouse (2003, p. 683)

²³¹ Verbatim from Spittlehouse (2003, p. 673)

to 20th century water-limited forests) (Figure 38).²³² These changes are projected to occur on the east side of the Cascade Mountains and west side of the Rocky Mountains in the northern part of the state.²³³ Furthermore, analysis by Littell et al. (2010) of host vulnerability to mountain pine beetle identified a substantial change in the future average water deficit across all sites within the current range of lodgepole pine (Table 9).²³⁴

Table 9. Expected water deficit and precipitation changes for six future scenarios and historical DAYMET-based calculations in the lodgepole pine forests of Washington.

Scenario	Year	Scenario Climate			% Change from 1980-1999			
		Mean water deficit inches (mm)	Annual PPT* inches (mm)	Summer PPT inches (mm)	Mean water deficit (%)	Annual PPT (%)	Summer PPT (%)	# Plots with deficit > 9.84 inches (250 mm)
A1B	2020	5.59 (142)	48.90 (1242)	1.3 (34)	+294	+132	+29	116
	2040	6.97 (177)	76.18 (1935)	0.67 (17)	+367	+206	+15	228
	2080	8.23 (209)	111.5 (2831)	0.47 (12)	+432	+302	+11	442
B1	2020	3.7 (93)	63.15 (1604)	3.5 (88)	+193	+171	+75	27
	2040	4.49 (114)	69.13 (1756)	2.8 (70)	+236	+187	+60	18
	2080	6.22 (158)	86.57 (2199)	1.1 (29)	+326	+235	+25	116
Historical	2000-2003	3.8 (96)	30.2 (767)	2.4 (60)	+199	+82	+51	33
Historical	1980-1999	1.9 (48)	36.9 (937)	4.65 (118)	+100	+100	+100	2

*PPT = precipitation
Source: Reproduced from Littell et al. (2010, Table 2, p. 144) by authors of this report.

Western Oregon

Information needed.

Northwest California

Evidence from several different regions suggests that the major coastal upwelling systems of the world have been growing in upwelling intensity as greenhouse gases have accumulated in the earth’s atmosphere.²³⁵ Thus the cool foggy summer conditions that typify the coastlands of northern California and other similar upwelling regions might, under global warming, become even more pronounced.²³⁶ *For additional information on coastal upwelling, please see a companion report to this one,²³⁷ as future projections for the magnitude and direction of coastal upwelling vary in the scientific literature.*

²³² Verbatim from Littell et al. (2010, p. 138). Littell et al. refer the reader to Figure 3 in the cited article for this information.

²³³ Verbatim from Littell et al. (2010, p. 138)

²³⁴ Nearly verbatim from Littell et al. (2010, p. 143). Littell et al. refer the reader to Table 2 in the cited article for this information.

²³⁵ Verbatim from Bakun (1990, p. 198). *Global climate change and intensification of coastal ocean upwelling.*

²³⁶ Verbatim from Bakun (1990, p. 198)

²³⁷ Tillmann & Siemann (2011a)

Information Gaps

Key information needs include more information on interactions among hydrology, climate change, disturbance and changing species composition and phenology, as well as better projections of future effects on hydrologic processes and water resources, which will require improved hydrologic models that can account for variation in species and stand structures, yet can be readily scaled to larger and more complex landscapes with mixed land uses.²³⁸ Short-term weather forecasts will be needed to predict drought occurrences for existing forests.²³⁹ To understand interactions between forest disturbance and management for drought, new field experiments could test forest sensitivity to specific climate-change projections in combination with changes in the concentration of atmospheric trace gases.²⁴⁰

²³⁸ Nearly verbatim from Ryan et al. (2012, p. 50)

²³⁹ Verbatim from Dale et al. (2008, p. 731)

²⁴⁰ Nearly verbatim from Dale et al. (2008, p. 732)

2. Altered growing season, freeze and thaw patterns

Increases in temperature lengthen the growing season in temperate or cold-deciduous systems.²⁴¹ Changes in the timing and magnitude of summer drought will alter patterns of temperature and moisture within the growing season.²⁴² In regions where drought stress is not important because of high levels of precipitation, or if increases in CO₂ concentration increase water use efficiency and thus reduce water stress, longer growing seasons could result in increased growth.²⁴³ Where drought stress is important, a longer growing season may mean only that plant respiration exceeds photosynthesis for a longer time, which would result in reduced growth.²⁴⁴

A longer growing season may increase the possibility of damage to trees from late frost events.²⁴⁵ Plant sensitivity to cold depends on both long-term historical climate, shaping evolutionary adaptation, and short-term weather events, influencing acclimation.²⁴⁶ Extreme cold can impact plant function in two main ways, either by damage to living tissues or by causing embolisms (air bubbles) in the water-conducting xylem elements.²⁴⁷ While many plants avoid cold by dropping leaves or remaining dormant below ground, woody evergreens continue to function through both cold and dry unfavorable seasons.²⁴⁸

Observed Trends

Global

Extension of the growing season (i.e., by up to 3.6 days per decade over the past 50 years in some areas) accords with the lengthening of 12 ± 4 days derived from satellite data as well as with an advance in the seasonal cycle by 7 days and an increase in amplitude of the annual CO₂ cycle since the 1960s.²⁴⁹ For northern high latitudes (>47.5 °N), warming climate lengthens growing seasons, promoting plant growth.²⁵⁰

²⁴¹ Nearly verbatim from Aber et al. (2001, p. 737). *Forest processes and global environmental change: predicting the effects of individual and multiple stressors*.

²⁴² Verbatim from Beedlow et al. (2013, p. 174)

²⁴³ Verbatim from Aber et al. (2001, p. 737)

²⁴⁴ Verbatim from Aber et al. (2001, p. 737)

²⁴⁵ Verbatim from Ryan et al. (2012, p. 44). Ryan et al. cite Augspurger (2009) and Gu et al. (2008) for this information.

²⁴⁶ Nearly verbatim from Ackerly (2012, p. 5)

²⁴⁷ Verbatim from Ackerly (2012, p. 5). Ackerly cites Sperry and Sullivan (1992), Davis et al. (1999), and Stuart (2007) for this information.

²⁴⁸ Verbatim from Ackerly (2012, p. 5)

²⁴⁹ Nearly verbatim from Walther et al. (2002, p. 389). *Ecological responses to recent climate change*. Walther et al. cite Myneni et al. (1997) for information on the satellite data and Keeling et al. (1996) for information on the advance in the seasonal cycle and increase in amplitude of the annual CO₂ cycle.

²⁵⁰ Verbatim from Zhao & Running (2010, p. 941). *Drought-induced reduction in global terrestrial net primary production from 2000 through 2009*. Zhao et al. cite Chen et al. (2006) for this information.

Western North America

The vegetation growing season, as defined by continuous frost-free air temperatures, has increased by, on average, two days per decade since 1948 in the conterminous United States, with the largest change in the western United States and most of the increase from earlier warming in the spring (Figure 6).²⁵¹ Global daily satellite data, available since 1981, have detected similar changes in earlier onset of spring “greenness” of 10-14 days in 19 years, particularly in temperate latitudes of the Northern Hemisphere.²⁵² *For additional information on changes in the timing of seasonal events, please see Chapter VII.2.*

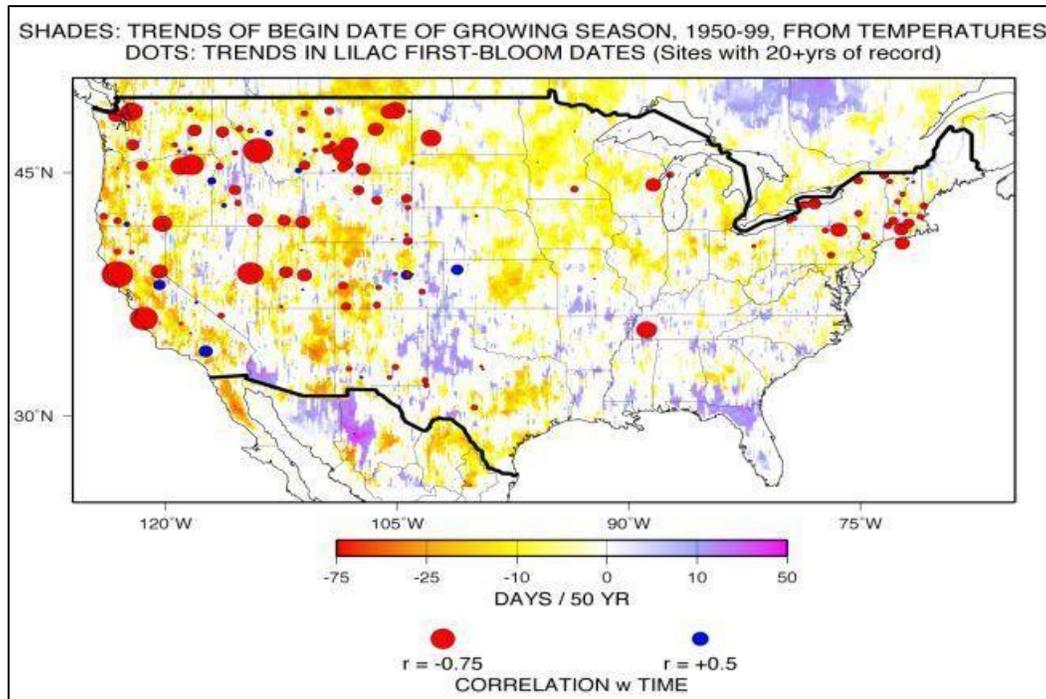


Figure 6. Trends in frost-free growing season length and phenological observation of bud burst.
Source: Reproduced from Running & Mills (2009, Figure 6, p. 8) by authors of this report. Note: Running & Mills cite Cayan et al. (2001) for this figure.

Southcentral and Southeast Alaska

From 1972 to 2000 in Alaska, the duration of the snow-free period increased by 3 to 6 days per decade, and the first week in spring without snow cover shifted to 3 to 5 days earlier per decade.²⁵³

In a study using microwave and optical remote sensing, the springtime thaw event extends over a 12-week period from approximately 7 March (day 66) to 26 May (day 146), with generally earlier occurrence

²⁵¹ Verbatim from Running & Mills (2009, p. 7). *Terrestrial Ecosystem Adaptation*. Running & Mills cite Easterling (2002) and Feng & Hu (2004) for this information. Running & Mills also refer the reader to Figure 6 in the cited report for this information.

²⁵² Verbatim from Running & Mills (2009, p. 7). Running & Mills cite Myneni (2001) and Lucht et al. (2002) for this information.

²⁵³ Verbatim from Jezierski et al. (2010, p. 6). Jezierski et al. cite Dye (2002) for this information.

at lower latitudes and elevations (study period: 1988-2000).²⁵⁴ Boreal forest and tundra areas show respective average thaw dates of approximately 12 April [day 102 ± 8.3 (s)] and 23 April [day 113 ± 5.6 (s)], with considerable overlap among regional biomes.²⁵⁵ Mean annual variability in springtime thaw was on the order of ±7 days, with corresponding impacts to annual productivity of approximately 1% per day.²⁵⁶

In another study, the growing season lengthened between 1.51 days per decade (in Talkeetna) and 6.97 days per decade (in Yakutat) between 1949 and 1997 in the Maritime and Transitional Bioregion, which includes southcentral and southeast Alaska.²⁵⁷ Growing season lengthened by 2.62 days per decade in Anchorage from 1954-1997 and 6.54 days in Juneau from 1950-1997.²⁵⁸

Western British Columbia

Information needed.

Western Washington

Information needed.

Western Oregon

Information needed.

Northwest California

Information needed.

Future Projections

Global

Climate warming because of an increase in the concentration of greenhouse gases in the atmosphere is expected to lengthen the growing season by advancing the date of leaf onset and delaying leaf offset.²⁵⁹ An increase in the mean annual temperature of 1.8 °F (1 °C) is generally expected to lengthen the growing season by approximately 5–10 days in extratropical regions.²⁶⁰ In the northern high latitudes

²⁵⁴ Nearly verbatim from Kimball et al. (2006, p. 8). *Spring thaw and its effect on terrestrial vegetation productivity in the western Arctic observed from satellite microwave and optical remote sensing.*

²⁵⁵ Verbatim from Kimball et al. (2006, p. 8)

²⁵⁶ Verbatim from Kimball et al. (2006, p. 2)

²⁵⁷ Nearly verbatim from Jezierski et al. (2010, p. 8). Jezierski et al. cite Keyser et al. (2000) for this information.

²⁵⁸ Keyser et al. (2000, Table 4, p. 191). *Simulating the effects of climate change on the carbon balance of North American high-latitude forests.*

²⁵⁹ Verbatim from Arora & Boer (2005, p. 39-40). Arora & Boer cite Ahas (1999), Beaubien & Freeland (2000), Schwartz & Reiter (2000), and Ahas et al. (2002) for information on the advances in the date of leaf onset. Arora & Boer cite Menzel & Fabian (1999), Chmielewski & Rötzer (2001), and Defila & Clot (2001) for information on delays in leaf offset.

²⁶⁰ Verbatim from Arora & Boer (2005, p. 40). Arora & Boer cite Matsumoto et al. (2003) and Norby et al. (2003) for this information.

(>47.5 °N), continuing warming may offset the benefits of an earlier spring and decrease carbon sequestration in a drier summer and warmer autumn.²⁶¹

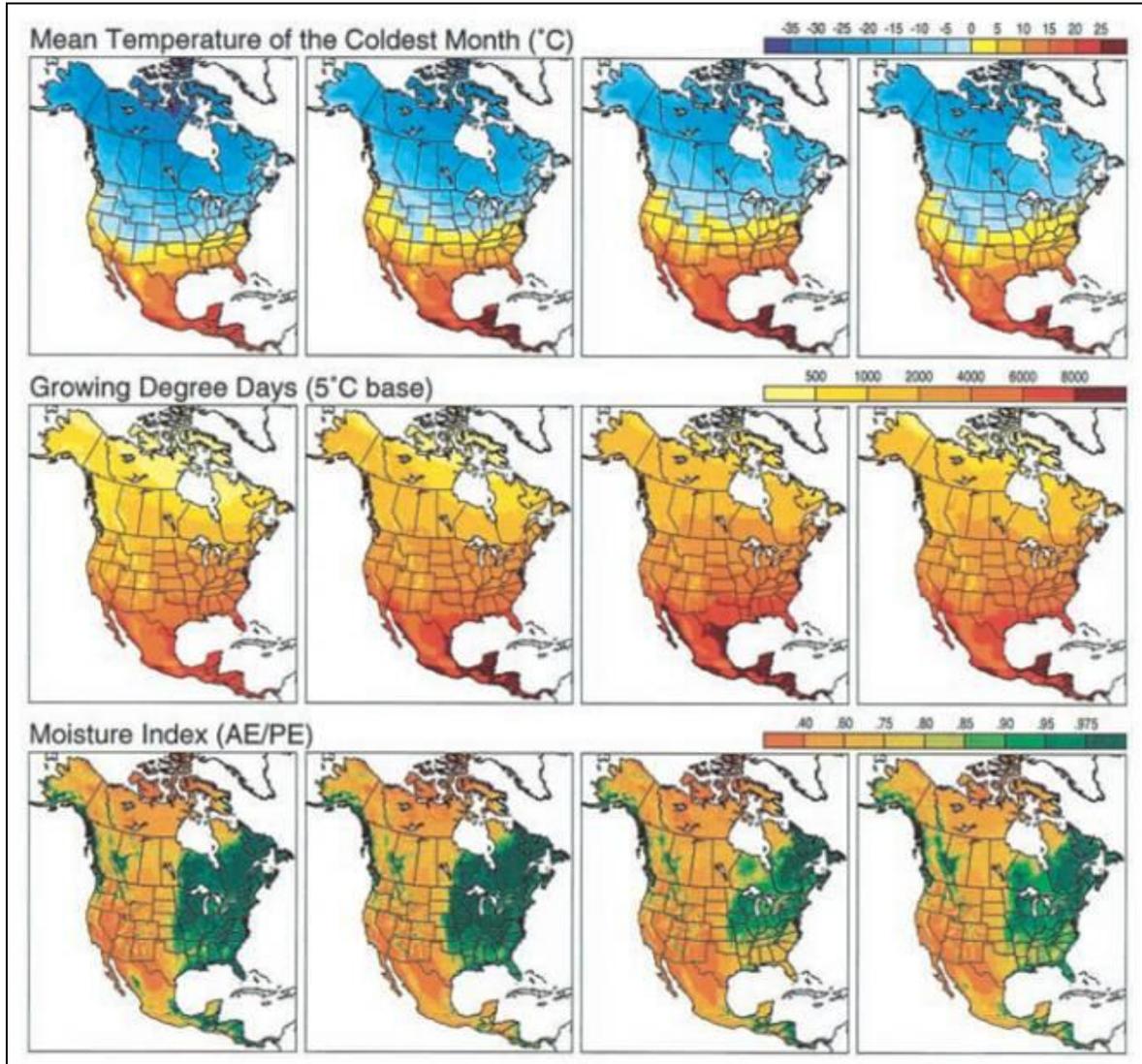


Figure 7. Maps of the three bioclimatic variables: mean temperature of the coldest month (MTCOM) (top), growing degree days (GDD) (middle), and moisture index (bottom). The first panel in each row displays the bioclimatic variable derived from the modern observed 1951-80 climate data set. The following three panels in each row display the bioclimatic variable as calculated from each of the three future-climate scenario data sets (2090-99, 10-year mean, using scenarios generated by HADCM2, CGCM1, and CSIRO and assuming 1% per year compound increase in greenhouse gases and changes in sulfate aerosols based on IPCC IS92a scenario). *Source: Reproduced from Shafer et al. (2001, Fig. 1, p. 204) by authors of this report.*

Western North America

A shift of mean monthly temperatures from below to above freezing does not mean that freezing temperatures will no longer occur.²⁶² However, such a shift will change the duration and magnitude of

²⁶¹ Nearly verbatim from Zhao & Running (2010, p. 941). Zhao et al. cite Angert et al. (2005) and Piao et al. (2008) for this information.

below-freezing temperatures, which will have significant impacts on many species in the western United States.²⁶³

Southcentral and Southeast Alaska

Growing season length is projected to increase, with the largest increase near coasts:²⁶⁴

- **2050:** 10-20 days; and,
- **2100:** 20-40 days²⁶⁵
- *Note: Projections from SNAP are compared to 1961-1990 climate normals (downscaled using PRISM to 2 km resolution) using the five best-performing GCMs of the fifteen used in the IPCC AR4 and run under the A1B scenario.*²⁶⁶

Western British Columbia

By 2080, most of the biogeoclimatic zones in B.C. are predicted to experience longer growing seasons and more favorable temperatures for Douglas-fir (vs. 1961-1990 run with CGCM2 under A2x, an ensemble average of the three A2 runs).²⁶⁷

Pacific Northwest

Driving a shift of the potential ranges of species from west to east is the projected increase in the mean temperature of the coldest month from 0-9 °F (-18 to -13 °C) to 9-18 °F (-13 to -7.8 °C) along the Pacific Northwest coast by 2090-99 compared to 1950-1980 under three GCMs (HADCM2, CGCM1, CSIRO) and the IPCC IS92a scenario (Figure 7).²⁶⁸ Although increased temperatures may not affect some species, many Pacific Northwest tree species have a winter chilling requirement that is optimally achieved with temperatures at or below approximately 9 °F (-13 °C).²⁶⁹ Chilling requirements are found in many Pacific Northwest evergreen conifers, such as Douglas-fir and western hemlock.²⁷⁰

Northwest California

Warming leads to larger areas being relieved from freezing events under the higher emissions A2 scenarios, compared to the B1 scenario (Figure 8; comparing 2070-2099 with 1971-2000 across four GCMs: CCSM3, CNRM, GFDL, and PCM1).²⁷¹ Variation among the four GCMs is relatively minor.²⁷²

²⁶² Verbatim from Shafer et al. (2001, p. 212)

²⁶³ Verbatim from Shafer et al. (2001, p. 212)

²⁶⁴ Wolken et al. (2011, Table 4, p. 19). *Evidence and implications of recent and projected climate change in Alaska's forest ecosystems*. Wolken et al. cite Field & Mortsch (2007) and SNAP for this information.

²⁶⁵ Wolken et al. (2011, Table 4, p. 19). Wolken et al. cite Field & Mortsch (2007) and SNAP for this information.

²⁶⁶ Wolken et al. (2011, p. 5)

²⁶⁷ Nearly verbatim from Coops et al. (2010, p. 521)

²⁶⁸ Nearly verbatim from Shafer et al. (2001, p. 211). Shafer et al. refer the reader to Figure 1 in the cited article.

²⁶⁹ Nearly verbatim from Shafer et al. (2001, p. 211). Shafer et al. cite Kimmins and Lavender (1992) for this information.

²⁷⁰ Nearly verbatim from Shafer et al. (2001, p. 211). Shafer et al. cite McCreary and others (1990) for information on Douglas-fir and Nelson and Lavender (1979) for information on western hemlock.

²⁷¹ Nearly verbatim from Ackerly (2012, p. 15). Ackerly refers the reader to Figures 6, 7, and A4-9 in the cited report for this information.

For northwest California:

- A growing area of the northwest coast is projected to no longer experience freeze events (of < 14 °F, < -10 °C at least once in 30 years) in the future.²⁷³
- Furthermore at the annual time scale, with warming temperatures, narrow bands around the edges of the Mojave desert, along the western slope of the Sierra, and around the Klamath-Siskiyou, where such events (i.e., freezing events of < 14 °F, < -10 °C each year) have occurred historically, will no longer experience them each year.²⁷⁴

Information Gaps

Information on observed trends in growing season and freeze and thaw dates is needed throughout the NPLCC region. Information on future projections for freeze and thaw dates is needed for southcentral and southeast Alaska and western British Columbia. Future projections for growing season are also needed for western British Columbia. Future projections for growing season, freeze dates, and thaw dates is also needed in the Pacific Northwest, as the information presented here discusses winter chilling requirements for conifers. In addition, information on future projections for growing season and thaw dates is needed for northwest California.

²⁷² Verbatim from Ackerly (2012, p. 15)

²⁷³ Nearly verbatim from Ackerly (2012, p. 15)

²⁷⁴ Nearly verbatim from Ackerly (2012, p. 15-16)

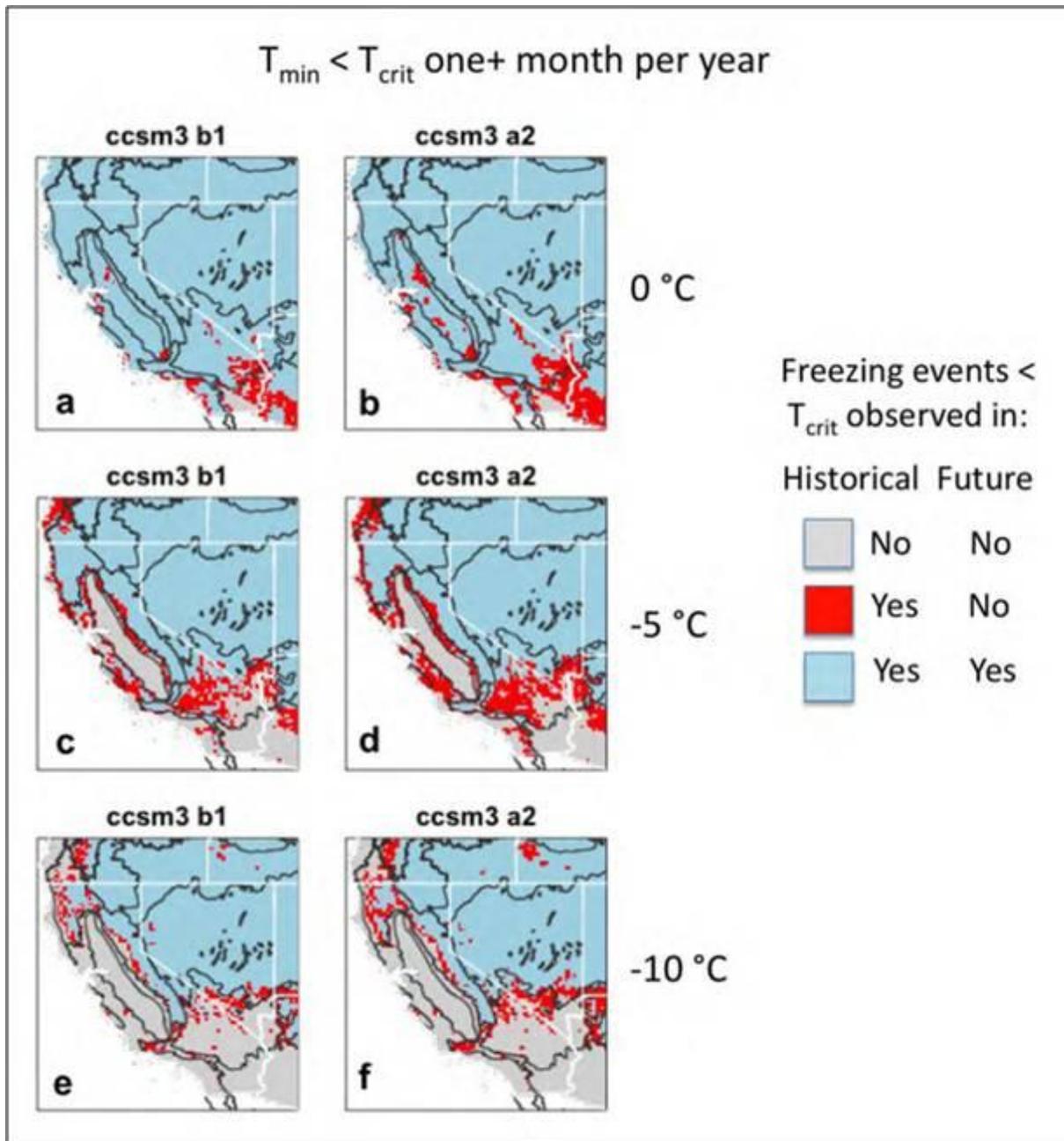


Figure 8. Changes in the distribution of freeze events occurring on average one or more times per year, from the 1971-2000 historical period to the 2071-2100 future projections, for the CCSM3 GCM. (a, b, d): B1 emissions scenario; (c, e, f): A2 emissions scenario. (a-b): Freezing events less than critical temperature ($T_{\text{crit}} = 32\text{ }^{\circ}\text{F}$ ($0\text{ }^{\circ}\text{C}$)); (c-d): $T_{\text{crit}} < 23\text{ }^{\circ}\text{F}$ ($-5\text{ }^{\circ}\text{C}$); (e-f): $T_{\text{crit}} < 14\text{ }^{\circ}\text{F}$ ($-10\text{ }^{\circ}\text{C}$). Blue areas have experienced a freeze less than the indicated T_{crit} values in the past, and are projected to continue to experience these events in the future. Red areas have experienced these in the past, but are not projected to experience these in the future. Gray are areas that have not experienced a freeze at this temperature in the past, and will not in the future either. *Source: Reproduced from Ackerly (2012, Figure 7, p. 17) by authors of this report.*

3. Altered fire regimes

Fire is a worldwide phenomenon that appears in the geological record soon after the appearance of terrestrial plants.²⁷⁵ Fire influences global ecosystem patterns and processes, including vegetation distribution and structure, the carbon cycle, and climate.²⁷⁶ Coastal temperate rainforests from southeast Alaska through to southern Oregon are ecologically distinct from forests of neighboring regions, which have a drier, or more continental, climate and disturbance regimes dominated by fires.²⁷⁷

Fire regime refers to the characteristic role of fire in an ecosystem, especially the extent, intensity, and frequency of fires.²⁷⁸ The frequency, severity, and extent of wildfire are strongly related to climate.²⁷⁹ The interactions between climate and fire are complex.²⁸⁰ While the degree of influence by biophysical and eco-cultural controls over fire are far from clear, the basic understanding of the relationships between fire and climate suggest that burning over the next century may be altered due to three general factors:²⁸¹

1. **Direct effects of changes in fire conditions** such as drought, high temperatures, winds, and their seasonality.²⁸² Warmer temperatures alone would lead to increased fire activity by reducing the moisture content of fuels and increasing litterfall caused by drought stress, as long as ignition sources were not limiting.²⁸³ A concurrent increase in precipitation amount and storm frequency may more than compensate for the increase in temperature by reducing flammability and also fostering changes to a less fire prone or drought sensitive vegetation cover.²⁸⁴ On the other hand, increased rainfall will enhance plant growth and fuel build-up, and an increase in storm frequency will enhance the opportunity for lightning (as described below).²⁸⁵ Different combinations of these factors can result in no change or even a decrease in predicted fire activity, and the exact effect of climate change on fire is likely to vary greatly regionally.²⁸⁶ For example, in mesic forest types (i.e., forest types of moderate moisture, common in the NPLCC region), dry and warm summers exert the strongest climatic influence on forest area burned, depleting fuel moisture and creating favorable conditions for fire spread.²⁸⁷

²⁷⁵ Verbatim from Bowman et al. (2009, p. 481)

²⁷⁶ Verbatim from Bowman et al. (2009, p. 481)

²⁷⁷ Verbatim from Lertzman et al. (2002, p. 5). *Long-term fire regime estimated from soil charcoal in coastal temperate rainforests.*

²⁷⁸ Verbatim from CIG (2004, p. 1)

²⁷⁹ Verbatim from Peterson, Halofsky & Johnson. (2011, p. 249). Peterson, Halofsky & Johnson cite Swetnam & Betancourt (1990), Johnson & Wowchuk (1993), Stocks et al. (1998), Hessler et al. (2004), Gedalof et al. (2005), Heyerdahl et al. (2008), Skinner et al. (2008), Taylor et al. (2008), and Littell et al. (2009) for this information.

²⁸⁰ Verbatim from Bachelet et al. (2005, p. 2244)

²⁸¹ Verbatim from Krawchuk & Moritz (2012, p. 1)

²⁸² Verbatim from Krawchuk & Moritz (2012, p. 1)

²⁸³ Verbatim from Bachelet et al. (2005, p. 2244)

²⁸⁴ Verbatim from Bachelet et al. (2005, p. 2244-5). Bachelet et al. cite Bergeron et al. (2004) for this information.

²⁸⁵ Nearly verbatim from Bachelet et al. (2005, p. 2245). Bachelet et al. cite Lynch et al. (2004) for this information.

²⁸⁶ Verbatim from Bachelet et al. (2005, p. 2245)

²⁸⁷ Nearly verbatim from Shafer et al. (2010, p. 183). Shafer et al. cite Littell et al. (2009a) for this information.

2. **An indirect effect on fire through vegetation** – that is, by climate altering the structure and abundance of biomass to burn.²⁸⁸ Relationships between fire and climate are vegetation and fuel specific.²⁸⁹ Wet conditions during the growing season promote fuel – especially fine fuel (grasses, etc.) – production via the growth of vegetation, while dry conditions during and prior to the fire season increase the flammability of the live and dead vegetation that fuels wildfires.²⁹⁰ Since vegetation is expected to shift with climate change (altered disturbance regimes will themselves alter vegetation), it may then be expected that the relationship between fire and climate on a monthly or seasonal basis will change as well.²⁹¹ In addition, fire mediates the responses of forests to climate change, either by accelerating species turnover or by selecting for fire-adapted species.²⁹² In the same way, changes in species composition may alter fire occurrence by changing the concentration and arrangement of flammable fuels.²⁹³
3. **Through changes in ignition potential** due to shifting spatial or temporal patterns of lightning and human behavior in response to factors such as climate policy and environmental management.²⁹⁴

Understanding fire regimes in the NPLCC region

Fire is a key Earth system process affecting ecosystems, land-surface properties, the carbon cycle, atmospheric chemistry, aerosols and human activities.²⁹⁵ Fire regimes are primarily a product of climate, vegetation, topography, and human activities – factors that interact in a variety of ways and on a range of spatial and temporal scales.²⁹⁶

Key Terms in this Section Fire Regimes

Extent: *the area affected by a fire*

Frequency: *the number of fires during a given amount of time, e.g., every 1000 years*

Fuel: *potentially combustible materials, consisting of surface fuels (e.g., grass, dead leaves, needles) and ladder fuels that carry fire into the canopy (e.g., dead branches, moss, lichens). Fuels may be fine (e.g., dead leaves) or coarse (e.g., tree trunks), responding to changes in air moisture in hours or weeks, respectively.*

Fuel load: *the amount of fuel available for ignition*

Intensity: *also known as magnitude; the rate of heat release along a unit length of fireline, derived from the energy content of the fuel, the mass of fuel consumed, and the rate of spread of the fire; measured in $kW m^{-1}$*

Patch size: *the size of openings created by fire where post-fire regeneration is likely to occur and persist; tends to increase with fire severity*

Predictability: *variation in fire frequency*

Return interval: *the average number of years between consecutive fires in one location*

Seasonality: *when fires occur during the year*

Severity: *the degree to which a site has been altered by fire, typically classified as low, medium, or high severity; the effect of fire on plants. For trees, this is often measured as percentage of basal area removed.*

Sources: Agee (1993), Agee (1998), Bachelet et al. (2007)

²⁸⁸ Verbatim from Krawchuk & Moritz (2012, p. 1)

²⁸⁹ Nearly verbatim from Hessler (2011, p. 395). Hessler cites Littell et al. (2009) for this information.

²⁹⁰ Verbatim from Westerling & Bryant (2008, S233)

²⁹¹ Nearly verbatim from Hessler (2011, p. 395)

²⁹² Verbatim from Gavin et al. (2007, p. 501). Gavin et al. cite Overpeck et al. (1990) for this information.

²⁹³ Verbatim from Gavin et al. (2007, p. 501). Gavin et al. cite Bond and Kelley (2005) for this information.

²⁹⁴ Verbatim from Krawchuk & Moritz (2012, p. 1)

²⁹⁵ Verbatim from Marlon et al. (2008, p. 697). *Climate and human influences on global biomass burning over the past two millennia.*

²⁹⁶ Verbatim from Marlon et al. (2012, p. E535). *Long-term perspective on wildfires in the western USA.*

Information on spatial scale interactions includes:

- **Climate:** Different types of fire regimes are associated with different climates and forest types.²⁹⁷ Climate influences fire at the broadest scales via the annual cycle, weather, and the distribution of vegetation (fuels).²⁹⁸ Fire frequency, size, intensity, seasonality, type, and severity are highly dependent on weather and climate.²⁹⁹ An individual fire results from the interaction of ignition agents (such as lightning, fuel conditions, and topography) and weather (including air temperature, relative humidity, wind velocity, and the amount and frequency of precipitation).³⁰⁰ Drought increases the likelihood of fire, and over the course of decades or centuries, shifts in climate may shift fire regimes.³⁰¹
- **Vegetation and topography:** Topography, winds, and the type, distribution, and structure of vegetation become more important controls on fire at regional-to-local scales.³⁰² Box 4 provides information on the interactive effects of invasive and non-native plants on fire regimes.
- **Human activities:** Humans have a broad influence on fire through intentional or accidental ignitions, exclusion (e.g., suppression and fuel alteration from grazing), and indirectly through climate change.³⁰³

Climate, vegetation change, and human activities can influence fuels across a wide range of spatial and temporal scales resulting in several pathways of possible change in fire regimes.³⁰⁴ Information on the temporal scale interactions includes:

- **Short-term:** Temperature, relative humidity, precipitation, and wind speed all influence how fires burn on short timescales by both influencing the condition of fuels and the amount of heat transfer required for combustion of those fuels.³⁰⁵

More Key Terms in this Section Types of Fire

Crown fire: *a fire burning into the crowns of the vegetation, generally associated with an intense understory fire*

Prescribed fire: *a fire ignited under known conditions of fuel, weather, and topography to achieve specified objectives*

Stand-replacing fire: *a high-severity fire, specifically one that kills trees, thereby creating room for a new stand of trees to grow*

Surface fire: *a fire burning along the surface without significant movement into the understory or overstory, with flame length usually less than 3.28 feet (1 m)*

Understory fire: *a fire burning in the understory, more intense than a surface fire and with flame lengths of 3.28-9.84 feet (1-3 m)*

Wildfire: *a fire that is not meeting land management objectives, may be naturally caused or caused by humans*

Sources: Agee (1993), Agee (1998), Bachelet et al. (2007)

²⁹⁷ Nearly verbatim from CIG (2004, p. 1)

²⁹⁸ Verbatim from Marlon et al. (2012, p. E535)

²⁹⁹ Verbatim from Joyce et al. (2001, p. 500)

³⁰⁰ Verbatim from Joyce et al. (2001, p. 500)

³⁰¹ Verbatim from CIG (2004, p. 1)

³⁰² Verbatim from Marlon et al. (2012, p. E535)

³⁰³ Verbatim from Marlon et al. (2012, p. E535)

³⁰⁴ Verbatim from Hessl (2011, p. 400)

³⁰⁵ Verbatim from Hessl (2011, p. 400). Hessl cites Albin (1976), Anderson (1982), and Rothermel (1983) for this information.

- **Mid-term (weeks to months):** On the timescale of weeks to months, meteorological variables may influence the duration of the fire season, frequency of lightning ignitions, and the abundance of fine fuels.³⁰⁶
- **Long-term (years to decades):** On the scale of years to decades, climate may influence fire regimes by altering net primary productivity, decomposition, vegetation structure, vegetation composition, density, fuel loading, and fuel connectivity across a landscape.³⁰⁷ Shifts between El Niño and La Niña phases or in the decadal-scale climate variability determine drought severity during a particular fire season or years, as well as the accumulation of fuels in previous years.³⁰⁸ This alternation of wet and dry episodes has been shown to be important in shaping the fire regime of the last few centuries, especially in low-elevation conifer forests and grasslands.³⁰⁹
- **Very long-term (centuries or more):** On century and longer time scales (> 100 years), large-scale changes in the climate system caused by variations in the seasonal cycle of insolation (i.e., the amount of solar radiation energy in a given area over a given period of time), atmospheric composition, and atmosphere-ocean interactions emerge as important controls of the fire regime.³¹⁰

Box 4. Interactive effects of invasive or non-native plants on fire regimes.

Disturbance agents such as fire and invasive or non-native plants interact and affect each other in myriad ways. Plant invasions can alter fuel properties, which in turn can affect fire behavior and the overall fire regime. Over time, the fire regime may transition to a new state, which may or may not be stable.

The most direct effects of newly established invasive or non-native plants on fire regimes include:

- **Alter plant tissue flammability & fuel load:** Plants with lower moisture content or that dry quickly in less moist or humid conditions may be more flammable (e.g., grasses). Similarly, plants that decompose quickly or contain more volatile compounds may increase fuel load. Plants with higher moisture content, fewer volatile compounds, or that decompose more slowly may have the opposite effect.
- **Alter fuel continuity:** Fuel continuity may be interrupted or enhanced by plant invaders depending on the type of plant and the existing fire regime. For example, tree invasion of prairie grassland would decrease horizontal continuity by interrupting the grassy landscape, but could increase vertical continuity as crown fuels become more continuous. If tree invasion increases over time, the fire regime could shift from frequent, low severity surface fires to mixed regimes of surface and crown fires to less frequent, higher severity crown fires.
- **Alter packing ratio** (i.e., a measure of fuel bed compactness): A less densely packed fuel load, such as occurs when shrubs invade grasslands, may reduce fire risk. A more densely packed fuel load increases fire risk. However, very dense fuel loads may inhibit combustion under normal conditions or result in a more severe fire under extreme weather conditions (e.g., very dry).

Source: Brooks et al. (2004)

³⁰⁶ Verbatim from Hessl (2011, p. 400). Hessl cites Goldammer & Price (1998) and Wotton & Flannigan (1993) for this information.

³⁰⁷ Verbatim from Hessl (2011, p. 400). Hessl cites Meyn et al. (2007) for this information.

³⁰⁸ Verbatim from Whitlock & Bartlein (2003, p. 483). *Holocene fire activity as a record of past environmental change*.

³⁰⁹ Verbatim from Whitlock & Bartlein (2003, p. 483). Whitlock & Bartlein cite Clark (1988c) and Grissino-Mayer & Swetnam (2000) for information on low-elevation conifer forests, and Clark et al. (2002) for information on grasslands.

³¹⁰ Verbatim from Whitlock & Bartlein (2003, p. 483)

Observed Trends

Global

Using a hybrid, global, monthly burned area dataset, Giglio et al. (2010) estimated the global annual burned area for the years 1997-2008 to vary between 815 million acres and 1065 million acres (330 and 431 million hectares), with the maximum occurring in 1998 and the minimum in 2008 (Table 10).³¹¹

Table 10. 1997-2008 estimated annual area burned globally and in North America. <i>Million acres with million hectares in parentheses</i>					
	Boreal North America		Temperate North America		Global
	<i>Value</i>	<i>% of Global</i>	<i>Value</i>	<i>% of Global</i>	<i>Value</i>
1997	2.2 (0.9)	0.25	1.2 (0.5)	0.14	888.6 (359.6)
1998	11 (4.5)	1.0	2.7 (1.1)	0.26	1066 (431.2)
1999	3.7 (1.5)	0.37	4.4 (1.8)	0.44	1010 (408.7)
2000	1.7 (0.7)	0.18	5.4 (2.2)	0.56	973.1 (393.8)
2001	0.7 (0.3)	0.081	3.0 (1.2)	0.32	919.5 (372.1)
2002	7.9 (3.2)	0.83	3.5 (1.4)	0.36	952.8 (385.6)
2003	4.9 (2.0)	0.58	3.2 (1.3)	0.38	854.0 (345.6)
2004	12 (5.0)	1.4	1.7 (0.7)	0.19	897.0 (363.0)
2005	7.2 (2.9)	0.81	4.2 (1.7)	0.48	881.4 (356.7)
2006	4.7 (1.9)	0.56	5.9 (2.4)	0.70	845.1 (342.0)
2007	3.7 (1.5)	0.41	6.7 (2.7)	0.74	905.1 (366.3)
2008	3.5 (1.4)	0.42	3.7 (1.5)	0.45	814.7 (329.7)
Mean (1997-2008)	5.4 (2.2)	0.59	3.7 (1.5)	0.40	917.3 (371.2)
<i>Source: Modified from Giglio et al. (2010, Table 2, p. 1181) by authors of this report.</i>					

³¹¹ Nearly verbatim from Giglio et al. (2010, p. 1184). *Assessing variability and long-term trends in burned area by merging multiple satellite fire products.*

Western North America

Fire has had both fine and coarse scale (i.e., minute resolution and broad areas, respectively) effects on the forests of western North America, but these effects differed considerably by fire regime.³¹² Drought has a major influence on fire in the United States.³¹³ Analysis of climate reconstructions beginning from 500 and population data show that temperature and drought predict changes in biomass burning up to the late 1800s.³¹⁴ Climate controls on the area burned by wildfire in the western United States are strong, even during the dominant period of fire suppression and exclusion in the last two-thirds of the 20th century.³¹⁵ Roughly 39% (1916–2003) to 64% (1977–2003) of the fire area burned can be related directly to climate:³¹⁶

- **1916–2003:** The relationships are weaker (compared to 1977–2003), but climate explained 25–57% (mean = 39%) of the variability (in wildfire area burned).³¹⁷
- **1977–2003:** A few climate variables explain 33–87% (mean = 64%) of wildfire area burned, indicating strong linkages between climate and area burned.³¹⁸

Most western U.S. ecoprovinces have stronger characteristics of fuel (moisture) or climate (energy) limitation, but the results support the idea that there is a range of vegetation types and seasonal climates that produce fire regimes limited by both fuel and climate.³¹⁹ For example:

- Low precipitation, high temperature, and negative Palmer Drought Severity Index immediately preceding and during the year of fire are associated with increased wildfire area burned in the Cascade Range (as well as the Rocky Mountains and Sierra Nevada), probably because persistent hot temperatures and low humidity are required to dry out fine fuels in these ecoprovinces even when winters are comparatively mild.³²⁰
- For the period 1977–2003, correlations between area burned and seasonal climate suggest the Cascades and Northern Rockies are sensitive primarily to low precipitation during the fire season (summer and growing season).³²¹
- Grass- and shrub-dominated ecoprovinces had positive relationships with antecedent precipitation or Palmer Drought Severity Index.³²²

In the western U.S., historical wildfire observations exhibit an abrupt transition in the mid-1980s from a regime of infrequent large wildfires of short (average of 1 week) duration to one with much more frequent

³¹² Nearly verbatim from Agee (1998, p. 24). *The landscape ecology of Western forest fire regimes*. Agee cites Agee (1993) for information on the scale effects.

³¹³ Verbatim from Bachelet et al. (2007, p. 4). *Wildfires and global climate change: the importance of climate change for future wildfire scenarios in the western United States*. Bachelet et al. cite Siebold & Veblen (2006) and Enfield et al. (2001) for this information.

³¹⁴ Verbatim from Marlon et al. (2012, p. E535)

³¹⁵ Verbatim from Littell et al. (2009, p. 1019)

³¹⁶ Verbatim from Littell et al. (2009, p. 1019)

³¹⁷ Nearly verbatim from Littell et al. (2009, p. 1003)

³¹⁸ Nearly verbatim from Littell et al. (2009, p. 1003)

³¹⁹ Nearly verbatim from Littell et al. (2009, p. 1017)

³²⁰ Nearly verbatim from Littell et al. (2009, p. 1015)

³²¹ Nearly verbatim from Littell et al. (2009, p. 1015–1016)

³²² Verbatim from Littell et al. (2009, p. 1003)

and longer burning (5 weeks) fires.³²³ This transition was marked by a shift toward unusually warm springs, longer summer dry seasons, drier vegetation (which provoked more and longer burning large wildfires), and longer fire seasons.³²⁴ Reduced winter precipitation and an early spring snowmelt played a role in this shift.³²⁵ More specifically, based on comparisons with climatic indices that use daily weather records to estimate land surface dryness, Westerling et al. (2006) attribute this increase in wildfire activity to an increase in spring and summer temperatures by ~1.6 °F (~0.9°C) and a 1- to 4-week earlier melting of mountain snowpacks.³²⁶

Specific observed trends for frequency, area burned, elevation of fire, wildfire duration, length of the wildfire season, and changes associated with the timing of spring and snowmelt are available:

- **Increased frequency and area burned by large wildfires** (> 988 acres; >400 ha): Wildfire frequency was nearly four times the average of 1970 to 1986, and the total area burned by these fires was more than six and a half times its previous level.³²⁷ Increases in wildfire frequency varied regionally:
 - Eighteen percent (18%) of the increase in wildfire frequency occurred in the Sierra Nevada, southern Cascades, and Coast Ranges of northern California and southern Oregon.³²⁸
 - The Northwest; and coastal, central, and southern California each account for 5% and <1%, respectively, of the increase in wildfire frequency.³²⁹
- **Fire was concentrated at mid-elevation:** Increased wildfire frequency since the mid-1980s has been concentrated between 5512 and 8497 feet (1680-2590 meters) in elevation, with the greatest increase centered around 6988 feet (2130 meters).³³⁰ Wildfire activity at these elevations has been episodic, coming in pulses during warm years, with relatively little activity in cool years, and is strongly associated with changes in spring snowmelt timing, which in turn is sensitive to changes in temperature.³³¹
- **Increased duration of wildfire:** The average time between discovery and control for a wildfire increased from 7.5 days from 1970 to 1986 to 37.1 days from 1987 to 2003.³³²
- **Longer wildfire season:** The average season length (the time between the reported first wildfire discovery date and the last wildfire control date) increased by 78 days (64%), comparing 1970 to 1986 with 1987 to 2003.³³³
- **Changes in forest vulnerability and area burned given timing of spring and snowmelt:** Overall, 56% of wildfires and 72% of area burned in wildfires occurred in early snowmelt years (i.e., lower tercile of CT1, the first principal component of the center of mass of annual flow,

³²³ Nearly verbatim from Westerling et al. (2006, p. 942)

³²⁴ Verbatim from Westerling et al. (2006, p. 943)

³²⁵ Verbatim from Westerling et al. (2006, p. 943)

³²⁶ Nearly verbatim from Running (2006, p. 927)

³²⁷ Nearly verbatim from Westerling et al. (2006, p. 941)

³²⁸ Nearly verbatim from Westerling et al. (2006, p. 941). Westerling et al. refer the reader to fig. S2 in the cited article for this information.

³²⁹ Nearly verbatim from Westerling et al. (2006, p. 941)

³³⁰ Nearly verbatim from Westerling et al. (2006, p. 941)

³³¹ Verbatim from Westerling et al. (2006, p. 941)

³³² Verbatim from Westerling et al. (2006, p. 941)

³³³ Verbatim from Westerling et al. (2006, p. 941)

which is a regional proxy for interannual variability in the arrival of spring snowmelt), whereas only 11% of wildfires and 4% of area burned occurred in late (i.e., upper tercile CT1) snowmelt years (time period: 1970-2002).³³⁴ In a measure of forest vulnerability to changes in the timing of spring, the Northern Rockies and Northern California display the greatest vulnerability by this measure—the same forests accounting for more than three-quarters of increased wildfire frequency since the mid-1980s.³³⁵

Published studies suggest that bark beetle outbreaks can affect fuels and fire behavior.³³⁶ The types of change, however, depend on the research question addressed, time since outbreak, and fuels or fire characteristic of interest, suggesting that generalizations about the effects of bark beetle-caused tree mortality on fire characteristics are unwarranted.³³⁷ Although many studies reported that beetle outbreaks were not as important as other factors in driving fire behavior, extent, or severity, the impact of beetle-killed trees can become significant when compared with unattacked stands.³³⁸ One conceptual framework developed from the literature describes responses of different fuels and fire behavior characteristics as a function of time since outbreak (Figure 9).³³⁹

Table 11. Observed trends in biomass burned, area burned, and fire frequency across North America, with a focus on western North America, from 3,000 years ago to the present.

Time Period	Biomass burned / Area burned	Fire frequency	Sources
3 thousand years ago to 1900	Slight decline over past 3 thousands years, with a minimum from 1400-1700 across North America	Forest fires peak from 950-1250 and in the 1800s across North America Regular, widespread fire from 1600-1900 across North America	Marlon et al. (2012)
1916-2003, 1977-2003	~39% (1916–2003) to 64% (1977–2003) related directly to climate	N/A	Littell et al. (2009)
1987-2003 vs. 1970-1986	1987-2003 total was 6.5 times the 1970-1986 total 72% burned in early snowmelt years vs. 4% in late snowmelt years (1970-2002)	Average increased nearly 4 times, with 5% of the increase in the Northwest and 18% of the increase in the Sierra Nevada, southern Cascades and Coast Ranges of northern California and southern Oregon. Fire season 78 days longer (64%) 56% of fires occurred in early snowmelt years vs. 11% in late snowmelt years (1970-2002)	Westerling et al. (2006)

Table created by authors of this report.

³³⁴ Nearly verbatim from Westerling et al. (2006, p. 942)

³³⁵ Nearly verbatim from Westerling et al. (2006, p. 942). Westerling et al. refer the reader to Fig. 4 in the cited article for information on the measure, which uses the “percentage difference in the moisture deficit for early versus late snowmelt years scaled by the fraction of forest cover in each grid cell” (see p. 942 in cited article).

³³⁶ Nearly verbatim from Hicke et al. (2012, p. 88). *Effects of bark beetle-caused tree mortality on wildfire.*

³³⁷ Verbatim from Hicke et al. (2012, p. 88)

³³⁸ Verbatim from Hicke et al. (2012, p. 88)

³³⁹ Nearly verbatim from Hicke et al. (2012, p. 88)

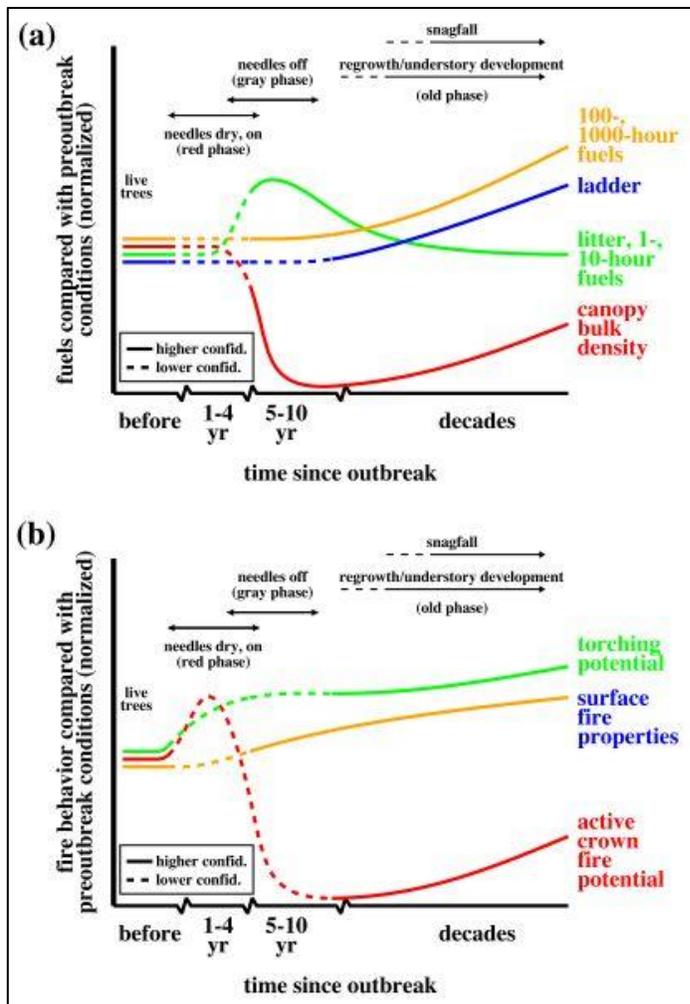


Figure 9. Conceptual framework of (a) fuels characteristics and (b) fire behavior relative to preoutbreak conditions for red, gray, and old (snagfall and regrowth) phases. Surface fire properties include reaction intensity, rate of spread, and flame length. For postoutbreak phases, solid lines indicate higher confidence in responses based on Fig. 3, and dashed lines indicate lower confidence (more disagreement, fewer studies, or knowledge gaps).

Source: Reproduced from Hicke et al. (2012, Figure 2, p. 84) by authors of this report.

Southcentral and Southeast Alaska

Results from soil charcoal analysis indicate that the upland forests of white and Lutz spruce on the western Kenai Peninsula have a relatively inactive history of fire (time period: last ~2,500 years).³⁴⁰ Soil charcoal data suggest that upland forests of white and Lutz spruce have not on average burned for 600 years (time-since-fire range 90 to ~1500 years, at 22 sites) and that the mean fire interval was 400-600 years.³⁴¹ However, fire activity was particularly high near Paradox Lake, possibly due to spread of fires that originated in extensive expanses of lowland black spruce forest to the east, where earlier fire history studies have estimated a mean fire return interval of approximately 79 years.³⁴² Fire activity was notably low west of the Caribou Hills where forests have not burned for 700–1100 years.³⁴³ The topography was more dissected and better drained in this area which may possibly limit the spread of fire.³⁴⁴

Dendrochronological evidence indicated that spruce beetle outbreaks occurred on average every 50 years in these forests.³⁴⁵ It would thus appear that 10 or more spruce beetle outbreaks can occur for every cycle of fire in these forests.³⁴⁶ However, a trend of warmer summers coupled with an increasing human population and associated sources of ignitions may create a greater fire risk in all fuel types than was present during the

³⁴⁰ Nearly verbatim from Berg & Anderson (2006, p. 280). *Fire history of white and Lutz spruce forests on the Kenai Peninsula, Alaska, over the last two millennia as determined from soil charcoal.*

³⁴¹ Verbatim from Berg & Anderson (2006, p. 275)

³⁴² Verbatim from Berg & Anderson (2006, p. 282). Berg & Anderson cite De Volder (1999) for this information.

³⁴³ Verbatim from Berg & Anderson (2006, p. 282)

³⁴⁴ Verbatim from Berg & Anderson (2006, p. 282)

³⁴⁵ Verbatim from Berg & Anderson (2006, p. 275)

³⁴⁶ Verbatim from Berg & Anderson (2006, p. 275)

time period covered by the study (i.e., approximately 2500 years).³⁴⁷ Further, the presence of over 1,060,000 acres (429,000 hectares) of forest with spruce recently killed by spruce beetles on the Kenai Peninsula has raised the specter of catastrophic wildfire.³⁴⁸

Western British Columbia

In a study of long-term fire regime estimated from soil charcoal in coastal temperate rainforests in the Clayoquot and Fraser Valleys, time since the most recent fire (TSF) was more widely distributed in the Clayoquot Valley (290-12,220 calendar years; median: 1300 cal. yrs.) than in the Fraser Valley (50-9,220 cal yrs; median: 1550 cal yrs).³⁴⁹ There is no significant difference in median TSF between the two study areas.³⁵⁰ A larger proportion of sites have burned in the last 1000 years in the Clayoquot Valley (42%) than in the Fraser Valley (17%), although a larger proportion of sites in the Clayoquot Valley (23%) than in the Fraser Valley (6%) have not burned since the early Holocene (7000 cal. yrs. Before Present, BP).³⁵¹ With the assumption that dates from the same site that were separated by less than 300 years represented wood burned in the same event, the Fraser Valley sites had a median fire interval of 1,200 years and the Clayoquot Valley a median fire interval of 2,380 years.³⁵²

The maximum TSF for each study area represents nearly the entire period of time since deglaciation, which began roughly 13,000 cal. years BP.³⁵³ These are the longest documented TSF's that Lertzman et al. (2002) are aware of for any forest worldwide.³⁵⁴ Fire is not just rare on the ecological time scale of the dynamics of populations, but is rare on the biogeographic time scale of the shaping of rainforest communities and ecosystems.³⁵⁵ This rarity of fire has supported the development of ecosystems characterized by great age, massiveness, and the ubiquity of late-seral species and structures at both stand and landscape scales.³⁵⁶ However, these overall summary analyses mask substantial spatial and temporal variation in fire incidence.³⁵⁷ For the Clayoquot Valley, information on area burned in the lower valley (< 656 feet, < 200 m; soil charcoal radiocarbon dating) and near Clayoquot Lake is available, as is information on the number and frequency of fires near the lake (lake data based on lake sediment, tree-ring records, and soil-charcoal records):

- **Time since last fire in the lower Clayoquot Valley:** The estimates of time since last fire ranged from 64 to approximately 12,220 years.³⁵⁸ Approximately 45% of the sites have burned in the last 1000 years, whereas 20% of the sites have not burned for over 6000 years.³⁵⁹

³⁴⁷ Nearly verbatim from Berg & Anderson (2006, p. 275)

³⁴⁸ Verbatim from Berg & Anderson (2006, p. 275)

³⁴⁹ Nearly verbatim from Lertzman et al. (2002, p. 9). Lertzman et al. refer the reader to Figure 6 in the cited article for this information.

³⁵⁰ Nearly verbatim from Lertzman et al. (2002, p. 9-10)

³⁵¹ Verbatim from Lertzman et al. (2002, p. 10)

³⁵² Nearly verbatim from Lertzman et al. (2002, p. 10). Lertzman et al. refer the reader to Table 1 and Figure 6 in the cited article for this information.

³⁵³ Verbatim from Lertzman et al. (2002, p. 10). Lertzman et al. cite Booth (1987) for this information.

³⁵⁴ Nearly verbatim from Lertzman et al. (2002, p. 10)

³⁵⁵ Verbatim from Lertzman et al. (2002, p. 11)

³⁵⁶ Verbatim from Lertzman et al. (2002, p. 11)

³⁵⁷ Nearly verbatim from Lertzman et al. (2002, p. 11)

³⁵⁸ Verbatim from Gavin et al. (2003b, p. 194). *Holocene fire history of a coastal temperate rain forest based on soil charcoal radiocarbon dates*. Gavin et al. refer the reader to Figure 6 in the cited article for this information.

- **Area burned near Clayoquot Lake:** Soil-charcoal radiocarbon dates revealed that 37% of the charcoal source area had not burned over the last 1800 years.³⁶⁰ Based on polygon boundaries, 63% of the area within ~1640 feet (500 m) of the lake burned at least once during AD 200 – present, and 22% burned at least once during AD 1200 – present.³⁶¹
- **Number and frequency of fire near Clayoquot Lake:** The lake sediment record indicates that 23 fires have occurred over the last 1800 years within a charcoal source area of 628 acres (254 hectares; distance to lake of ~1640 feet, or 500 meters).³⁶² The charcoal record also shows 23 fires, with a large shift in fire occurrence at AD 1100.³⁶³ The average interval between charcoal peaks increased from 45 to 272 years from AD 200–1100 to AD 1100 – present.³⁶⁴

Observed trends in the spatial distribution of fire over time are also available for the Clayoquot Valley:

- **Slopes and terraces:** The median time since last fire on terraces (4410 years) was 6 times greater than on hill slopes (740 years) ($P < 0.001$).³⁶⁵ On hill slopes, fires frequently spread up to 820 feet (250 m) but not beyond, as the proportion of site pairs with similar time since last fire declined sharply at scales greater than 820 feet (> 250 m).³⁶⁶ In contrast, there were no significant spatial relationships of time since last fire on terraces, suggesting fire extent was rarely larger than the smallest distances between sites (328-820 feet, 100–250 m).³⁶⁷
- **South- and north-facing slopes:** On hill slopes in the Clayoquot Valley, all south-facing and southwest-facing sites have burned within the last 1000 years compared to only 27% of north- and east-facing sites burning over the same period.³⁶⁸ Near Clayoquot Lake, areas on south-facing slopes burned in the last 200 years (since AD 1800), and probably burned several times during the last 1,800 years.³⁶⁹ In contrast, areas on north-facing slopes generally have not burned for over 6000 years (since at least AD 200).³⁷⁰ This spatial pattern may result only if fire is >25 times more likely to occur on susceptible sites (south-facing slopes) than on less susceptible sites.³⁷¹

In mountain hemlock forests in the vicinity of Frozen Lake and Mount Barr Cirque Lake in southwest British Columbia (i.e., the Fraser Valley), overall fire frequency varied continuously throughout the Holocene, suggesting that fire regimes are linked to climate via large-scale atmospheric circulation patterns.³⁷² In the Late Holocene, synchronous decreases in fire frequency (i.e., to 2-5 events per 1000

³⁵⁹ Verbatim from Gavin et al. (2003b, p. 194). Gavin et al. refer the reader to Figure 6 in the cited article for this information.

³⁶⁰ Verbatim from Gavin et al. (2003a, p. 573). *An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada.*

³⁶¹ Nearly verbatim from Gavin et al. (2003a, p. 578)

³⁶² Verbatim from Gavin et al. (2003a, p. 579)

³⁶³ Verbatim from Gavin et al. (2003a, p. 579). Gavin et al. refer the reader to Fig. 6a in the cited article for this information.

³⁶⁴ Verbatim from Gavin et al. (2003a, p. 579)

³⁶⁵ Nearly verbatim from Gavin et al. (2003b, p. 194)

³⁶⁶ Verbatim from Gavin et al. (2003b, p. 196)

³⁶⁷ Verbatim from Gavin et al. (2003b, p. 196)

³⁶⁸ Nearly verbatim from Gavin et al. (2003b, p. 186)

³⁶⁹ Nearly verbatim from Gavin et al. (2003a, p. 583)

³⁷⁰ Nearly verbatim from Gavin et al. (2003a, p. 583)

³⁷¹ Verbatim from Gavin et al. (2003a, p. 573)

³⁷² Nearly verbatim from Hallett et al. (2003, 292). *11,000 years of fire history and climate in the mountain hemlock rain forests of southwestern British Columbia based on sedimentary charcoal.*

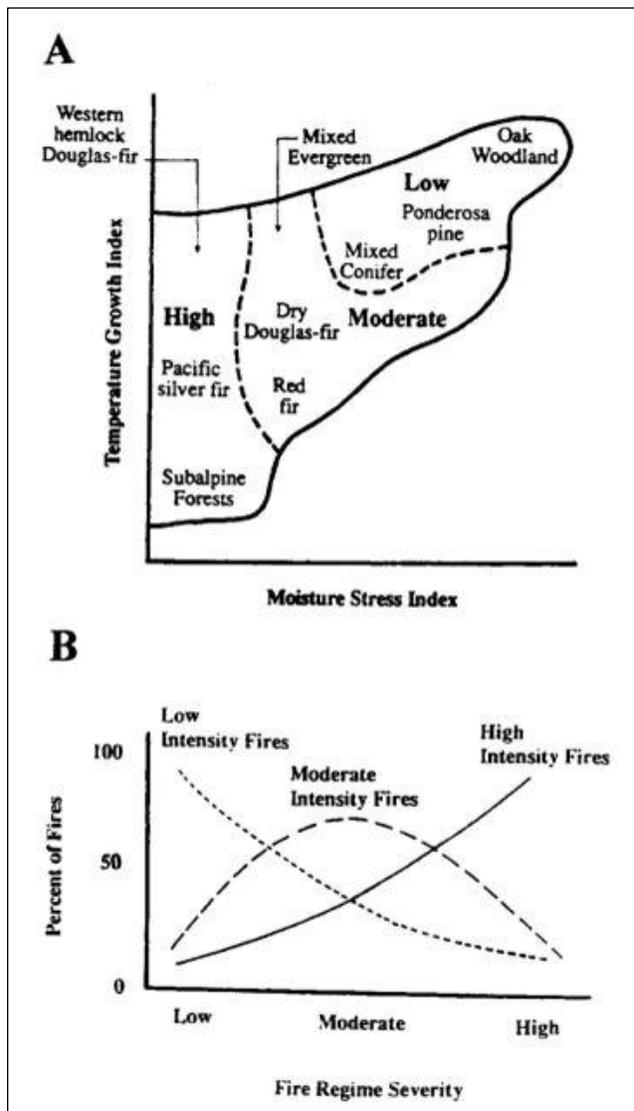


Figure 10. A. Historic fire regimes of the Pacific Northwest can be broadly defined into three categories: low-, moderate-, and high-severity. Each fire regime has a number of forest types within it that have similar landscape patterns created by fire. **B.** Historic fire intensity and associated effects varied by fire regime. *Source: Reproduced from Agee (1998, Figure 1) by authors of this report.*

³⁷³ Nearly verbatim from Hallett et al. (2003, 309). See Figure 8 in Hallett et al. for information on the number of fire events per 1000 years.

³⁷⁴ Verbatim from Hallett et al. (2003, 308)

³⁷⁵ Verbatim from Hallett et al. (2003, 308). Hallett et al. cite Watson and Luckman (2001) for information on the last fires recorded at the mountain hemlock sites. For information on large fires in the northwestern U.S., Hallett et al. cite Hemstrom & Franklilnk (1982), Dickman & Cook (1989), Agee (1991, 1993), Huff (1995), and Heyerdahl et al. (2001). For information on large fires in western Canada, Hallett et al. cite Johnson & Fryer (1987), Masters (1990), Gavin (2000), and Hallett (2001).

³⁷⁶ Nearly verbatim from Bachelet et al. (2007, p. 4). Bachelet et al. refer the reader to Table 1 in the cited article for this information.

³⁷⁷ Nearly verbatim from Gedalof et al. (2005, p. 172)

years) between 3500 and 2400 and between 600 and 0 cal. yrs. BP in mountain hemlock forests correspond to Neoglacial advances such as the Tiedemann and Little Ice Age, suggesting dominance of the Aleutian Low and frequent westerly storm tracks.³⁷³ Modern fire frequencies of 2–5 events per 1000 years were established after 1300 cal. yrs. BP.³⁷⁴ The last fires recorded at the mountain hemlock sites correspond to a dry period around 150 cal. yrs. BP (~AD 1800) when large fires occurred at many sites in the northwestern United States and western Canada.³⁷⁵

Pacific Northwest

Information on fire regimes for national forests in the Pacific Northwest is provided in Table 12. Historically, drought patterns in the West are related to large-scale climate patterns in the Pacific and Atlantic oceans (i.e., PDO, ENSO, Atlantic Multidecadal Oscillation; see Appendix 3. Major Climate Patterns in the NPLCC: ENSO and PDO).³⁷⁶ Gedalof et al. (2005) provide evidence for a climatic component in forcing extreme wildfire years in the American Northwest (Washington, Oregon, Idaho).³⁷⁷ The principal findings of the analysis were:

- **Role of antecedent drought, fire year drought, and the 500 hPa height:** Years with region-wide increases in area burned are characterized by enhanced drought in the seasons preceding the fire (i.e., antecedent

drought), followed by continued drought and increases in the 500 hPa height (i.e., an atmospheric surface layer of constant pressure, wherein areas of high height are associated with a relatively warm column of air and areas of low height are associated with a relatively cold column of air) over western North America and the eastern Pacific Ocean in the month prior to, throughout, and the month following the normal fire season.³⁷⁸

- **Role of ecological characteristics:** Distinct ecological characteristics modulate the response to atmospheric forcing, with wetter forests requiring more severe drought and prolonged blocking (i.e., an anomalous high-pressure system that remains quasi-stationary over the far eastern Pacific Ocean or western North America for prolonged intervals and diverts moisture away from areas below and downstream from it) to burn than drier forests, which may respond to blocking events without antecedent drought.³⁷⁹ For example, prolonged antecedent drought preconditions many of the forests of the region to burn, in particular mesic (i.e., well-balanced moisture) to wet highly productive forests dominated by Sitka spruce and western hemlock.³⁸⁰
- **Role of ENSO and PDO:** The Pacific Decadal Oscillation (PDO) appears to influence wildfire activity, although area burned responds to the annual to interannual fluctuations in the PDO more strongly than to interdecadal variability.³⁸¹ CIG (2004) also found that during the 20th century, the PDO has had a detectable influence on the area burned by fire in the Pacific Northwest (Figure 11).³⁸² It is unclear whether the PDO influences wildfire activity through its influence on drought severity (i.e., largely a wintertime connection) or by altering the statistics of summertime circulation.³⁸³ No significant association to the El Niño-Southern Oscillation (ENSO) was found for any of the records of area burned.³⁸⁴ However, other researchers found that in the Pacific Northwest El Niño years bring drier conditions and more fires.³⁸⁵



Figure 11. Relationship between the Pacific Decadal Oscillation and fire area burned for national forests in Oregon and Washington, 1922-1995. *Source: CIG (2004)*

Fire history reconstructions from tree rings and lake sediment indicate fire has been a prominent natural disturbance of Pacific Northwest forest ecosystems since at least the end of the last glaciation over 12,000 years ago.³⁸⁶ Several sites indicate that increased fire activity lagged the change to more thermophilous

³⁷⁸ Nearly verbatim from Gedalof et al. (2005, p. 173)

³⁷⁹ Nearly verbatim from Gedalof et al. (2005, p. 173)

³⁸⁰ Nearly verbatim from Gedalof et al. (2005, p. 172-173)

³⁸¹ Verbatim from Gedalof et al. (2005, p. 173)

³⁸² Nearly verbatim from CIG (2004, p. 1)

³⁸³ Verbatim from Gedalof et al. (2005, p. 173)

³⁸⁴ Verbatim from Gedalof et al. (2005, p. 173)

³⁸⁵ Nearly verbatim from Bachelet et al. (2007, p. 4). Bachelet et al. cite Swetnam & Baisan (2003) and Westerling & Swetnam (2003) for this information.

³⁸⁶ Verbatim from CIG (2004, p. 1)

(i.e., warmth-loving) vegetation by several centuries in the late-glacial period.³⁸⁷ This probably reflects a delayed response in the build up of fuel to support fires, but it may also be related to climate variations in the late-glacial period.³⁸⁸ The records (i.e., of lake sediment) suggest that fire frequency has changed continuously and no long-term stationarity is evident in the fire frequency record.³⁸⁹

There are also distinct features in the spacing of fire episodes within regions that suggest spatial coherency in the disturbance regimes:³⁹⁰

- **Washington Cascades and Pacific Northwest:** Like Battle Ground Lake (southwest Washington), all of the sites (i.e., several lakes in western WA, OR, and on Vancouver Island, BC) indicate decreased fire activity in the early and middle Holocene, but only at Little Lake (central Oregon Coast Range) and Hall Lake (east Puget Sound) did this trend continue toward present (Kirk Lake, east Puget Sound, lacks charcoal data after ~2500 cal. yrs. BP).³⁹¹
- **Oregon Coast Range:** At Little Lake, fire episodes in the middle to late Holocene were larger or of higher severity, but less frequent than during the early Holocene.³⁹²
- **Northern California:** Charcoal records from the summer-dry Klamath Mountains of northern California indicate that fires were frequent through the Holocene with little long-term trend in the data.³⁹³ Two sites from the Klamath region, Bluff and Crater Lakes, suggest periods of frequent fire, such as at approximately 4000 and 1000 cal. yrs. BP.³⁹⁴

Western Washington

Near Panther Potholes in the North Cascades, fire frequency varies throughout the Holocene record, with frequent fires in the Early Holocene and the highest fire frequency (9 fires per 1000 years) approximately 8,500 calendar years Before Present (cal. yrs. BP).³⁹⁵ Fire frequency markedly declines approximately 8,000 cal. yrs. BP and remains low throughout the Mid-Holocene.³⁹⁶ Fires again became more frequent in the Late Holocene with high fire frequency between 3000 and 2000 cal. yrs. BP and 1000 and 500 cal. yrs. BP.³⁹⁷ Additional information for the Late Holocene is provided in Table 13.

The vegetation and fire regimes on Mount Constitution (Orcas Island) 5300-7000 years ago were similar to those at present, suggesting that the climate was also similar.³⁹⁸ High charcoal accumulation rates

³⁸⁷ Verbatim from Walsh et al. (2008, p. 262)

³⁸⁸ Verbatim from Walsh et al. (2008, p. 262)

³⁸⁹ Nearly verbatim from Whitlock et al. (2003, p. 10). Whitlock et al refer the reader to Figure 2 in the cited article for this information.

³⁹⁰ Verbatim from Whitlock et al. (2003, p. 10)

³⁹¹ Nearly verbatim from Walsh et al. (2008, p. 261)

³⁹² Verbatim from Walsh et al. (2008, p. 261)

³⁹³ Verbatim from Whitlock et al. (2003, p. 10)

³⁹⁴ Verbatim from Whitlock et al. (2003, p. 10)

³⁹⁵ Nearly verbatim from Prichard et al. (2009, p. 64). *Holocene fire and vegetation dynamics in a montane forest, North Cascade Range, Washington, USA*

³⁹⁶ Verbatim from Prichard et al. (2009, p. 64)

³⁹⁷ Verbatim from Prichard et al. (2009, p. 64)

³⁹⁸ Nearly verbatim from Sugimura et al. (2008, p. 548-549). *Millennial-scale changes in local vegetation and fire regimes on Mount Constitution, Orcas Island, Washington, USA, using small hollow sediments*

Table 12. Biophysical characteristics of the 12 National Forests in the northwestern U.S. within the NPLCC region.

National Forest	Dominant forest types*	Mean annual precipitation inches (cm)	Typical fire regime(s) [†]					
			1	2	3	4	5	6
Deschutes	Lodgepole pine, ponderosa pine, Douglas-fir, grand fir	197 (501)	x	x				
Gifford Pinchot	Western hemlock, Douglas-fir, Pacific silver fir, mountain hemlock	61.8 (157)				x	x	
Mount Baker-Snoqualmie	Western hemlock, Douglas-fir, Pacific silver fir, mountain hemlock	65.4 (166)					x	x
Mt. Hood	Western hemlock, Douglas-fir, grand fir, mountain hemlock, subalpine fir	60.2 (153)				x	x	
Olympic	Sitka spruce, western hemlock, Pacific silver fir, Douglas-fir, mountain hemlock	68.5 (174)					x	x
Rogue River	Douglas-fir, white fir, red fir, ponderosa pine	28 (71)			x	x	x	
Siskiyou	Douglas-fir, western hemlock, coast redwood, white fir, red fir	51.2 (130)		x	x	x	x	
Siuslaw	Western hemlock, Sitka spruce, Douglas-fir, grand fir, Pacific silver fir	66.1 (168)				x	x	x
Umpqua	Douglas-fir, ponderosa pine, grand fir, incense cedar	39 (98)				x	x	
Wenatchee	Douglas-fir, grand fir, ponderosa pine, subalpine fir	39 (99)		x	x	x		
Willamette	Douglas-fir, incense cedar, ponderosa pine, Oregon white fir, red fir, mountain hemlock	40.6 (103)	x	x	x	x		
Winema	Ponderosa pine, lodgepole pine, Douglas-fir, grand fir	25 (64)	x	x	x			

Source: Modified from Gedalof et al. (2005, Table 1, p. 156) by authors of this report.

***Bolded species** are those most commonly occurring

[†]Fire regimes based on Agee (1993): 1) infrequent light surface fires (> 25-year return interval); 2) frequent light surface fires (1-25 year return interval); 3) infrequent severe surface fire (>25-year return interval); 4) short return interval crown/severe surface fire (25-100 years); 5) long return interval crown/severe surface fire (100-300 years); 6) very long return interval crown/severe surface fire (300+ years).

indicate that fire was common, and the occasional sharp peaks suggest that at least some of the fires were severe.³⁹⁹ From 2000 years BP to present, increased charcoal accumulation rates suggest that fire frequency, severity, and/or extent increased at all sites, leading to the modern fire regime of one fire every 100-200 years.⁴⁰⁰

The fire history at Battle Ground Lake (southwest WA) was apparently driven by climate, directly through the length and severity of the fire season, and indirectly through climate-driven vegetation shifts, which affected available fuel biomass.⁴⁰¹ For example, in the middle to late Holocene (~5200 cal yr BP to present), forest dominated by Douglas-fir, *Thuja*-type (e.g., western redcedar), and western hemlock supported less frequent, but mostly large or high-severity fire episodes.⁴⁰² Fire episodes were least frequent, but were largest or most severe, after approximately 2500 cal. yrs. BP.⁴⁰³

Table 13. Major vegetation type and mean fire return interval near Panther Potholes, North Cascades in the Late Holocene (~2,000 calendar years Before Present to present).		
Vegetation type	Sample tree species	Mean fire return interval (years ± SD)
Moist montane conifer forest with increase in subalpine species	Western redcedar declines as Alaska yellow-cedar appears and increases. Pollen from western hemlock and the cypress family increases.	197 ± 167
<i>Source: Modified from Prichard et al. (2009, Table 2, p. 60) by authors of this report.</i> SD = standard deviation; cal. yrs.		

Klamath Mountains

For thousands of years, fire has been a major evolutionary force in the Klamath Mountains of northwest California and southwest Oregon, influencing forest structure, species composition, soil properties, wildlife habitat, landscape patterns, watershed hydrology, nutrient cycling and numerous other ecosystem processes.⁴⁰⁴ The unique flora, combined with varied parent materials, topographic heterogeneity and steep climatic gradients, has created an extraordinary variety of forest types ranging from coastal temperate rainforest to semi-arid oak woodlands.⁴⁰⁵ As a result, a broad range of fire environments and resulting fire regimes are also present.⁴⁰⁶

Frost & Sweeney's (2000) initial analysis of 20th century fire history suggests that forests of the Klamath-Siskiyou region have experienced a reduction in both the total amount of area burned and the average fire size since the middle of the 1900s, the beginning of modern fire suppression.⁴⁰⁷ While large fire events

³⁹⁹ Verbatim from Sugimura et al. (2008, p. 546)

⁴⁰⁰ Nearly verbatim from Sugimura et al. (2008, p. 548)

⁴⁰¹ Nearly verbatim from Walsh et al. (2008, p. 251). *A 14,300-year-long record of fire-vegetation-climate linkages at Battle Ground Lake, southwestern Washington.*

⁴⁰² Nearly verbatim from Walsh et al. (2008, p. 251)

⁴⁰³ Nearly verbatim from Walsh et al. (2008, p. 251)

⁴⁰⁴ Verbatim from Frost & Sweeney (2000, p. 2). *Fire regimes, fire history and forest conditions in the Klamath-Siskiyou Region: An overview and synthesis of knowledge.* Frost & Sweeney cite Chang (1996) and Agee (1993) for this information.

⁴⁰⁵ Verbatim from Frost & Sweeney (2000, p. 3)

⁴⁰⁶ Verbatim from Frost & Sweeney (2000, p. 3)

⁴⁰⁷ Nearly verbatim from Frost & Sweeney (2000, p. 35)

comprise a larger proportion of area burned in the second half of the century, available data does not suggest that the probability or size of large fires has changed.⁴⁰⁸

In terms of total area, the predominant fire regime was of relatively frequent fires (e.g. mean fire return intervals of 10-50 years) of mostly low and moderate severity, with varying-sized patches of high severity.⁴⁰⁹ This fire regime was predominant in the foothill, lower- and mid-montane forests in both western and eastern subregions of the Klamath Mountains and the Jeffrey pine type on ultramafic soils (i.e., composed of igneous rocks, mostly those of the mafic type).⁴¹⁰ Greater variability and a higher proportion of moderate to high severity fire occurred in the cooler and more mesic (i.e., of moderate moisture) forests of the coastal, upper montane and subalpine zones and in riparian settings.⁴¹¹ Old-growth forest characteristics such as large snags and live trees were sustained on many sites for long periods and through many disturbances, thus providing habitat continuity over time.⁴¹²

More specific information on fire frequency, severity, seasonality, and size in subregions of the Klamath Mountains is available:

- **Fire frequency:** Available studies indicate that median fire return intervals in forests of the Klamath Mountains vary considerably with forest type, ranging from as high as 140 years in Douglas-fir/mixed conifer forests to 10 years or less in tanoak, Jeffrey pine and ponderosa pine/Douglas-fir.⁴¹³ Both subregional and forest type differences are evident, but overall, fires were moderately frequent, averaging between 15-40 years in 19 of the 32 fire return intervals that have been reported.⁴¹⁴ Generally, it appears that fire frequency increases from west to east and from higher to lower elevations.⁴¹⁵ For example, although no data are presented, Atzet & Wheeler (1982) estimate that the fire-free period varies between 100 – 200 years in the coastally influenced portion of southwest Oregon.⁴¹⁶ Variation within and between study areas has been reported for Douglas-fir/mixed conifer and white fir forests:
 - **Douglas-fir/mixed conifer forest:** Average intervals between fires vary from modal values of 15 years to 120 years.⁴¹⁷
 - **White fir:** A mean fire return interval of 39 years was reported for white fir forests in the western Klamath Mountains, with a range of fire-free periods from 12 to 161 years.⁴¹⁸

⁴⁰⁸ Verbatim from Frost & Sweeney (2000, p. 37)

⁴⁰⁹ Verbatim from Frost & Sweeney (2000, p. 36)

⁴¹⁰ Verbatim from Frost & Sweeney (2000, p. 36-37)

⁴¹¹ Verbatim from Frost & Sweeney (2000, p. 37)

⁴¹² Verbatim from Frost & Sweeney (2000, p. 37)

⁴¹³ Nearly verbatim from Frost & Sweeney (2000, p. 6-7). Frost & Sweeney cite van Norman (1998) for information on Douglas-fir/mixed conifer forests, White et al. (*in press*) for information on tanoak and Jeffrey pine, and Taylor & Skinner (1994) for information on ponderosa pine/Douglas-fir. Frost & Sweeney also refer the reader to Table 1 in the cited report.

⁴¹⁴ Verbatim from Frost & Sweeney (2000, p. 7)

⁴¹⁵ Verbatim from Frost & Sweeney (2000, p. 7). Frost & Sweeney cite Atzet & Wheeler (1982) for this information.

⁴¹⁶ Verbatim from Frost & Sweeney (2000, p. 7)

⁴¹⁷ Nearly verbatim from Frost & Sweeney (2000, p. 7). Frost & Sweeney cite Taylor & Skinner (1998) for the fire return interval of 15 years and van Norman (1998) for the fire return interval of 120 years.

⁴¹⁸ Nearly verbatim from Frost & Sweeney (2000, p. 7). Frost & Sweeney cite Stuart & Salazar (*in press*) for this information.

- **Fire severity:** Since most of the forests in the Klamath-Siskiyou region burned at moderate to high frequencies, it follows that most fires produced moderate to low-severity effects on the vegetation.⁴¹⁹ Examination of early historical accounts of fires in the Klamath Mountains generally supports this conclusion.⁴²⁰ Evidence collected from dendrochronology studies indicates the dominance of moderate or “mixed” severity fires, where a complex, irregular pattern of tree mortality and openings are created.⁴²¹ These historic patterns of fire severity are consistent with observation of recent fires in wildlands of the Klamath Mountains, many of which continue to burn in a mosaic pattern and result in varying levels of tree mortality.⁴²²
- **Seasonality:** In general, seasonal fire scar positions have been found in the latter portions of annual rings, indicating that most fires occurred late in the growing season, from mid-summer to early fall.⁴²³ This is consistent with typical lightning patterns observed in the region, with most of it striking in the late summer.⁴²⁴ After being ignited in July and August, many fires appear to have the ability to spread over weeks or months, with periods of smoldering or slow progression alternating with aggressive runs when weather becomes hot or windy.⁴²⁵ The more xeric (i.e., dry), low-elevation forest types, including interior oak woodland, ponderosa pine, and Jeffrey pine are the forests that are most likely to burn early in the fire season, especially those on southerly aspects.⁴²⁶
- **Fire size:** Relatively few of the fire history studies conducted in the Klamath Mountains have presented data on the spatial extent of fires.⁴²⁷ Information is available for subregions of the Klamath Mountains:
 - **Northern boundary:** Most of the fires that burned in the ~111,200 acre (45,000 hectare, ha) Little River watershed (near the northern boundary of the Klamath-Siskiyou region) were between 25 and 988 acres (10 and 400 ha), with a few up to 7413 acres (3000 ha) in size.⁴²⁸
 - **Coastal and western subregions:** Large fire years are often associated with regional events and extreme climatic conditions.⁴²⁹ Very large, often stand-replacement fires occur, on average, every 200 years in coastal and western subregions.⁴³⁰ The 1987 wildfires and ~121,080 acre (49,000 ha) Big Bar fire complex that burned in 1999 are the most recent examples of this pattern.⁴³¹

⁴¹⁹ Verbatim from Frost & Sweeney (2000, p. 8)

⁴²⁰ Verbatim from Frost & Sweeney (2000, p. 8). Frost & Sweeney cite LaLande (1995), McKinley & Frank (1995), and Morris (1934) for this information.

⁴²¹ Verbatim from Frost & Sweeney (2000, p. 8). Frost & Sweeney refer the reader to Tables 1 and 2 in the cited report for this information.

⁴²² Verbatim from Frost & Sweeney (2000, p. 9)

⁴²³ Verbatim from Frost & Sweeney (2000, p. 9)

⁴²⁴ Verbatim from Frost & Sweeney (2000, p. 9). Frost & Sweeney cite Automated Lightning Detection System (1999) for this information.

⁴²⁵ Verbatim from Frost & Sweeney (2000, p. 9)

⁴²⁶ Verbatim from Frost & Sweeney (2000, p. 10)

⁴²⁷ Verbatim from Frost & Sweeney (2000, p. 10)

⁴²⁸ Verbatim from Frost & Sweeney (2000, p. 10). Frost & Sweeney cite van Norman (1998) for this information.

⁴²⁹ Verbatim from Frost & Sweeney (2000, p. 10). Frost & Sweeney cite McKelvey & Busse (1996), LaLande (1995), and Morford (1970) for this information.

⁴³⁰ Nearly verbatim from Frost & Sweeney (2000, p. 10). Frost & Sweeney cite Atzet & Wheeler (1982) for this information.

⁴³¹ Verbatim from Frost & Sweeney (2000, p. 10). Frost & Sweeney cite Agee (1991a) for this information.

- **Siskiyou Mountains:** Mixed severity fires in Douglas-fir and white fir forests of Oregon’s Siskiyou Mountains were historically small to intermediate sizes, ranging from ~210 to 1420 acres (86 to 576 ha).⁴³²
- **Northwest California:** In similar forest types to the Siskiyou Mountains, a mean size of 865 acre (350 ha) for historical fires was reported, with a range of 69 to 3310 acres (28 to 1340 ha), and suggests that large spreading fires are characteristic of Douglas-fir dominated forests in this region.⁴³³

Western Oregon

Pollen and high-resolution charcoal records from three lakes were examined to reconstruct the vegetation and fire history of the Oregon Coast Range for the last 9000 years.⁴³⁴ High fire-episode frequency occurs in conjunction with forests comprised primarily of fire-adapted taxa and lower fire-episode frequency is associated with forests dominated by fire-sensitive taxa.⁴³⁵ Results also indicate shared high fire activity at all three sites at a time scale of 100 years over the last 4600 years.⁴³⁶ Observed trends in mean fire interval at the three lakes during the Late Holocene are provided in Table 14.

Table 14. Observed trends in mean fire interval at three western Oregon lakes during the Late Holocene.

Lake	Mean fire interval	Notes	Sources
Taylor Lake (northern Oregon)	220 ± 30 years (range 80–430, n = 13) over the last approximately 2,700 years.	Similar to the present-day estimates of 300 years or greater in Sitka spruce forests. Fires are rare currently because the ignition season does not coincide with months of dry fuels.	Long & Whitlock (2002); Long et al. (2007)
Lost Lake (central Oregon)	220 years	Similar to present-day estimates of 150-300 years for western hemlock forests of the Coast Range	Long et al. (2007)
Little Lake (southern Oregon)	210 ± 30 years (range 60–400, n = 12) over the last approximately 2,700 years.	Similar to present-day estimates of 150-300 years for western hemlock forests of the Coast Range. Two fires were recorded in 1982 and 1929.	Long et al. (1998); Long et al. (2007)

Table created by authors of this report.

The Neskowin Crest Research Area along the central coast of Oregon in a Sitka spruce-western hemlock zone is in the area affected by the catastrophic Nestucca Burn of 1845, a fire that spread west from the Willamette Valley to the coast, covering more than ~296,530 acres (120,000 ha).⁴³⁷ However, the fire appears to have died down or gone out in the steep north-trending canyons on the northwest corner of one study site.⁴³⁸ The results contrast with evidence from a similar coastal spruce–hemlock stand less than ~62 miles (100 km) farther south.⁴³⁹ There, topographic constraints were not evident, possibly because they

⁴³² Nearly verbatim from Frost & Sweeney (2000, p. 10). Frost & Sweeney cite Agee (1991a) for this information.

⁴³³ Nearly verbatim from Frost & Sweeney (2000, p. 10). Frost & Sweeney cite Taylor & Skinner (1998) for this information.

⁴³⁴ Verbatim from Long et al. (2007, p. 917). *Holocene vegetatin and fire history of the Coast Range, western Oregon, USA.*

⁴³⁵ Verbatim from Long et al. (2007, p. 923)

⁴³⁶ Nearly verbatim from Long et al. (2007, p. 923). Long et al. refer the reader to Figure 5 in the cited article for this information.

⁴³⁷ Nearly verbatim from Harcombe et al. (2004, p. 72)

⁴³⁸ Nearly verbatim from Harcombe et al. (2004, p. 78)

⁴³⁹ Verbatim from Harcombe et al. (2004, p. 78)

were overridden by high fire intensity.⁴⁴⁰ Taken together, the studies of coastal spruce–hemlock forest illustrate that high spatiotemporal variability in fire effects may occur through much of the range of coastal spruce–hemlock forests.⁴⁴¹

On shorter time frames, analyses of fire history reveal a significant correlation of fire activity with decadal-scale (Pacific Decadal Oscillation), episodic (El Niño/Southern Oscillation), and interannual natural climate variation, with larger areas burned during warm and dry phases/years.⁴⁴² An average of 317,300 acres (128,407 ha) burned per year over the last five years and 648,000 acres (262,236 ha) burned in 2007.⁴⁴³

Northwest California

West of Mt. Shasta near Mt. Eddy, fires were frequent in four glacial basins (i.e., the Crater Creek, Bluff Lake, Mumbo, and Cedar Basins) during the 400-500 years before the second half of the 20th century.⁴⁴⁴ Specific information on fire frequency, size, intensity, and the pattern of fire activity is available:

- **Fire frequency:** Basin-wide composite median fire return intervals were 7.5 years (range: 2-47 years) for Crater Creek Basin, 6 years (range: 1-37 years) for Bluff Lake Basin, 4 years (range: 1-43 years) for Mumbo Basin, and 9.5 years (range: 2-76 years) for Cedar Basin.⁴⁴⁵ No fires during the last half of the 20th century were detected in fire scars.⁴⁴⁶
- **Fire size and intensity:** The data from this study suggest that many fires in these higher-elevation environments (i.e., upper montane and subalpine glacier basins) of the Klamath Mountains, though frequent, were small, often scarring only a single tree, and probably of low or mixed intensity.⁴⁴⁷ No fire dates met the criteria for an extensive fire year and only Cedar Basin met the criteria for large fires.⁴⁴⁸ More specifically, most fires were found to have scarred only one tree: 44 of 51 fires (86%) in Crater Creek Basin, 41 of 57 fires (72%) in Bluff Lake Basin, 32 of 44 fires (73%) in Mumbo Basin, and 23 of 39 fires (59%) in Cedar Basin were detected on only single trees.⁴⁴⁹ This contrasts with fire history studies in lower and mid-montane conifer forests of the Klamath Mountains where most fires were found to have scarred multiple trees.⁴⁵⁰

⁴⁴⁰ Nearly verbatim from Harcombe et al. (2004, p. 78). Harcombe et al. cited Wimberly and Spies (2001) for this information. They also cite several other studies as corroboration: Turner and Romme (1994), Lertzman and Fall (1998), Heyerdahl et al. (2001), Wimberly and Spies (2001), Gavin et al. (2003a).

⁴⁴¹ Nearly verbatim from Harcombe et al. (2004, p. 78)

⁴⁴² Nearly verbatim from Shafer et al. (2010, p. 183). Shafer et al. cite Hessler et al. (2004), Pierce et al. (2004), Gedalof et al. (2005), Trouet et al. (2006), Kitzberger et al. (2007), and Heyerdahl et al. (2008) for this information.

⁴⁴³ Verbatim from Shafer et al. (2010, p. 183). Shafer et al. cite NIFC (2010) for this information.

⁴⁴⁴ Nearly verbatim from Skinner (2003, p. 149). *Fire history of upper montane and subalpine glacial basins in the Klamath Mountains of Northern California.*

⁴⁴⁵ Verbatim from Skinner (2003, p. 145)

⁴⁴⁶ Verbatim from Skinner (2003, p. 149)

⁴⁴⁷ Nearly verbatim from Skinner (2003, p. 148)

⁴⁴⁸ Verbatim from Skinner (2003, p. 147). Skinner refers the reader to Table 4: Scale C5 in the cited article for this information.

⁴⁴⁹ Verbatim from Skinner (2003, p. 145)

⁴⁵⁰ Verbatim from Skinner (2003, p. 145)

- **Patterns of fire activity:** Two periods of heightened fire activity are evident, 1700-1749 and 1850-1899.⁴⁵¹ In addition, though there was great variation in fire return intervals in the fire scar record, the current length of the fire-free period has approached the maximum in all four basins simultaneously.⁴⁵² A fire-free period of this length appearing synchronously in all four basins has not occurred previously in the fire scar record.⁴⁵³

In the Bald Hills of Redwood National Park since 1993, park managers have instituted a robust prescribed fire program, burning 499 to ~2000 acres (202-809 ha) annually, with an approximate three to five year return interval for individual sites.⁴⁵⁴ The Bald Hills area encompasses approximately 4200 acres (1700 ha) of Oregon white oak woodlands and grasslands that divide the Redwood Creek and Klamath River drainages.⁴⁵⁵

To clarify the influence of overstory structure on fuels and fire intensity in oak woodlands and savannas, Engber et al. (2011) examined fuelbeds across a gradient from open grassland to Douglas-fir-invaded Oregon white oak woodland.⁴⁵⁶ Mean fire temperatures at approximately 12 inches (30 cm) height ranged from ~166 °F (74.7 °C) in invaded woodland up to 406.2 °F (207.9 °C) in grassland.⁴⁵⁷ Highly flammable grassland and savanna communities maintain heavy herbaceous mass, but low woody mass, favoring quick-spreading, relatively high-intensity fires.⁴⁵⁸

Future Projections

Global

Lightning is projected to change under the changing climate, which is expected to affect fire ignition and therefore burned area.⁴⁵⁹

Future projections indicate an impending shift to a temperature-driven global fire regime in the 21st century, creating an unprecedentedly fire-prone environment.⁴⁶⁰ Vast portions of the continental land area, particularly across North America and Eurasia, are projected to experience relatively large changes in fire probabilities (GFDL CM2.1 run with A2 and B1 emissions scenarios for three future periods – 2010-2039, 2040-2069, 2070-2099 – vs. 1961-1990).⁴⁶¹ The net outcome implies that while parts of the world

⁴⁵¹ Verbatim from Skinner (2003, p. 148). Skinner refers the reader to Figure 3 in the cited article for this information.

⁴⁵² Verbatim from Skinner (2003, p. 149)

⁴⁵³ Verbatim from Skinner (2003, p. 149)

⁴⁵⁴ Nearly verbatim from Engber et al (2011, p. 35)

⁴⁵⁵ Nearly verbatim from Engber et al (2011, p. 35)

⁴⁵⁶ Nearly verbatim from Engber et al (2011, p. 32)

⁴⁵⁷ Verbatim from Engber et al (2011, p. 32)

⁴⁵⁸ Verbatim from Engber et al (2011, p. 32)

⁴⁵⁹ Verbatim from Liu et al (2013, p. 12). *Wildland fire emissions, carbon, and climate: Wildfire-climate interactions.*

⁴⁶⁰ Verbatim from Pechony & Shindell (2010, p. 19167)

⁴⁶¹ Nearly verbatim from Krawchuk et al. (2009, p. 8). *Global pyrogeography: the current and future distribution of wildfire.* Krawchuk et al. refer the reader to Figures 2 and S5 in the cited article for this information. *Note: Krawchuk et al. compared projections for the three most significant climate predictors identified in the statistical analysis (mean temperature of the warmest month, annual precipitation, mean temperature of the wettest month) with the average of those projected by simulations of 15 other AOGCMs. Krawchuk et al.'s projections appear*

may experience regional increases in fire activity, others experience roughly equivalent decreases.⁴⁶² For example, in a study using the Keetch-Byram Drought Index (an indicator of soil moisture deficit) to assess wildfire potential, future wildfire potential increases significantly in the United States, South America, central Asia, southern Europe, southern Africa, and Australia (2070-2100 vs. 1961-1990 under the HadCM3, CGCM2, CSIRO, and NIES GCMs and A1F1, A2a, B1a, and B2a emissions scenarios).⁴⁶³

Western United States

Total area burned across the western United States is projected to increase by 54% for 2046-2055 relative to 1996-2005 (GISS GCM 3 run with A1B).⁴⁶⁴ Statistically significant increases in area burned are projected for the Rocky Mountains Forest (175%), Pacific Northwest Forest (78%), and Desert Southwest (43%) ecoregions.⁴⁶⁵ Simulated increases in temperature are responsible for more than 80% of the predicted increase in area burned in these ecoregions.⁴⁶⁶ In the Pacific Northwest and Rocky Mountains Forest ecoregions, interannual variability in predicted area burned is similar to that in observed area burned.⁴⁶⁷

In a modeling study by McKenzie et al. (2004), they conclude even for a very low-end climatic change scenario (the PCM GCM run using B2 scenario and comparing 2070-2100 to 1970-2000), it seems likely that area burned will at least roughly double by the end of this century in most western states, and there seems to be no reason to believe it will decrease.⁴⁶⁸ Their analysis also revealed state-by-state variations in the sensitivity of fire to climate.⁴⁶⁹ For example at the low end, fire in California and Nevada appears to be relatively insensitive to changes in summer climate, and area burned in these states might not respond strongly to changed climate.⁴⁷⁰ For more information on projections specific to Northwest California, please refer to p. 72 in this section.

In either wetter or drier conditions, models indicate that fire could reduce forest and woody vegetation cover in the West in a future warmer world (Figure 12).⁴⁷¹ When coupled with higher atmospheric CO₂ concentrations and longer growing seasons, wetter conditions promote the expansion of woody vegetation.⁴⁷² The build-up of fuels combined with natural climate variability, and the likely occurrence of longer and more intense periodic droughts in the future, increases the likelihood of wildfires.⁴⁷³ While

relatively conservative, close to, or below the AOGCM ensemble average for the two temperature-related variables. For precipitation, the GFDL CM2.1 projections tended to lie in the lower half of the distribution, suggesting a slight tendency toward drier conditions. Krawchuk et al. conclude their results may be indicative of the general magnitude and direction of projected changes expected from a larger number of AOGCMs (see p. e5103).

⁴⁶² Verbatim from Krawchuk et al. (2009, p. 9)

⁴⁶³ Nearly verbatim from Liu et al. (2010, p. 685). *Trends in global wildfire potential in a changing climate.*

⁴⁶⁴ Nearly verbatim from Spracklen et al. (2009, p. 7)

⁴⁶⁵ Nearly verbatim from Spracklen et al. (2009, p. 7). Spracklen et al. report statistical significance as $p < 0.05$.

Spracklen et al. refer the reader to Table 2 in the cited article for this information.

⁴⁶⁶ Verbatim from Spracklen et al. (2009, p. 8)

⁴⁶⁷ Nearly verbatim from Spracklen et al. (2009, p. 8)

⁴⁶⁸ Nearly verbatim from McKenzie et al. (2004, p. 897)

⁴⁶⁹ Nearly verbatim from McKenzie et al. (2004, p. 897)

⁴⁷⁰ Nearly verbatim from McKenzie et al. (2004, p. 897)

⁴⁷¹ Verbatim from Bachelet et al. (2007, p. 13)

⁴⁷² Verbatim from Bachelet et al. (2007, p. 12). Bachelet et al. refer the reader to Figure 3 in the cited report for this information.

⁴⁷³ Verbatim from Bachelet et al. (2007, p. 12). Bachelet et al. cite Bachelet et al. (2001) for this information.

fuel loads are building, lightning and fire season length are expected to increase.⁴⁷⁴ Ironically, more frequent human-induced fires could reduce the fuel build-up that has resulted from fire suppression in dry forests, and it could therefore reduce fire danger in the long run.⁴⁷⁵

Changes in relative humidity, especially drying over much of the West, are projected to increase the number of days of high fire danger (based on the Energy Release Component, ERC index) at least through the year 2089 in comparison to the base period (i.e., 2010-2029, 2030-2049, 2050-2069, and 2070-2089 vs. 1975-1996; PCM run with business-as-usual scenario, CO₂ doubles in 2070-2089).⁴⁷⁶ The Energy Release Component (i.e., an indicator of fire danger calculated as the available heat per unit area in kilojoules per square meter, kJ/m²) threshold index of 60 and greater (range: 0-100), which corresponds to many of the largest and most expensive fires, shows substantial consistency throughout the 21st century.⁴⁷⁷ Nearly all of the western U.S. is projected to experience increases in the number of days that this large threshold value is exceeded by as much as two weeks depending on the region (Table 15).⁴⁷⁸

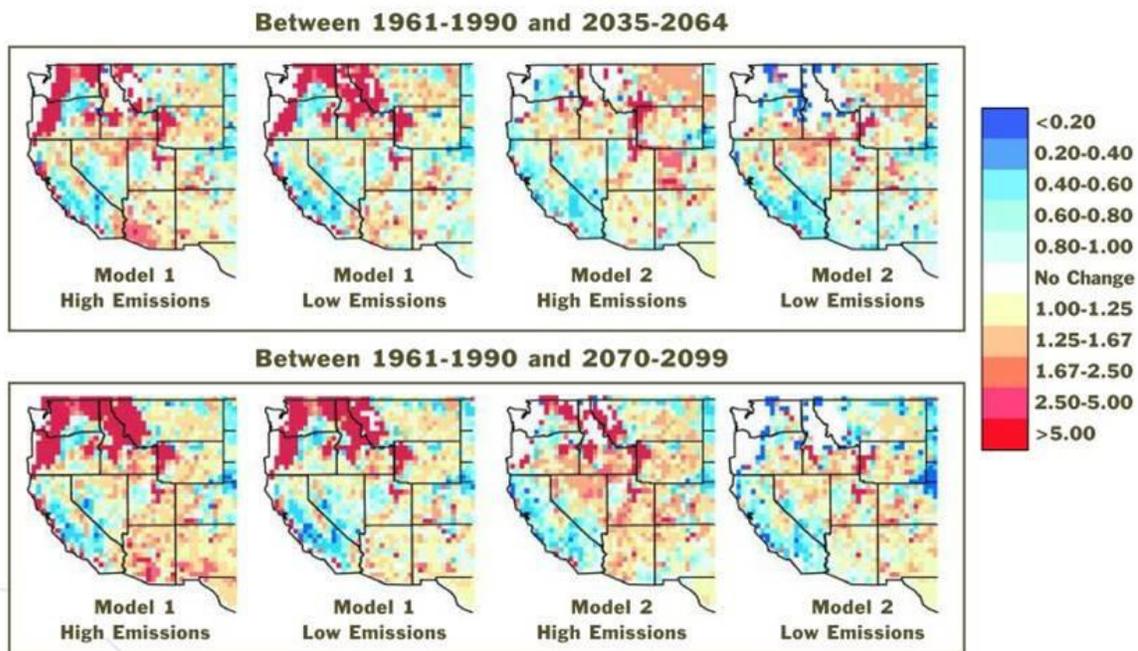


Figure 12. Projected change in plant biomass burned by wildfires from historical conditions based on two different climate models (Model 1 = HADCM3; Model 2 = CGCM2) and using high (SRES A2) and low (SRES B2) greenhouse gas emission scenarios. Values are fractions compared to the present. Values greater than 1.00 are increases; values less than 1.00 are decreases.

Source: Reproduced from Bachelet et al. (2007, Figure 4, p. 14) by authors of this report.

⁴⁷⁴ Verbatim from Bachelet et al. (2007, p. 12). Bachelet et al. cite Price & Rind (2004) for this information.

⁴⁷⁵ Verbatim from Bachelet et al. (2007, p. 12)

⁴⁷⁶ Nearly verbatim from Brown et al. (2004, p. 365). *The impact of Twenty-First Century climate change on wildland fire danger in the western United States: an applications perspective.*

⁴⁷⁷ Nearly verbatim from Brown et al. (2004, p. 384)

⁴⁷⁸ Verbatim from Brown et al. (2004, p. 384)

Table 15. Change in fire danger for medium and large fires, measured with the Energy Release Component (ERC) index, in the western U.S. for four future time periods compared to 1975-1996.

Year	Risk of medium sized fires: ERC 40-59 (99-988 acres, 40-400 ha)	Risk of large fires: ERC ≥ 60 (>988 acres, >400 ha)
2010-2029	~ +1 week in MT and central CA Little change elsewhere	+1 to 2 weeks across most of the West Exceptions: Pacific Coast, MT, WY, & CO
2030-2049	+1 to 2 weeks in MT ~ +1 week in WA, northern ID, southeast NM ~ -1 week in southern ID Little change elsewhere	~ +1 week over much of the West Nearly +2 weeks in ID, eastern OR & WA
2050-2069	Nearly +1 week in western MT & WY ~ -1 week in eastern OR & WA	Similar to the 2030-2049 time period Largest increases in ID, eastern OR & WA
2070-2089	+1 to 2 weeks in CA, AZ, & NM Nearly -1 week in ID, eastern OR & WA	Nearly +2 weeks over much of the West +40 to 55 average annual days in southern ID +110 to 120 average annual days in AZ Little or no change in MT, WY, & CO

Source: Brown et al. (2004, p. 368, 371, 374-375, 377-379)
*Table created by authors of this report. In this study, the United States Department of Agriculture Forest Service National Fire Danger Rating System is used with output from a general circulation model (i.e., the Parallel Climate Model) to assess the impact of a business-as-usual climate scenario for the period 2010–2089 over the western U.S.*⁴⁷⁹

Southcentral and Southeast Alaska

In a study using the dynamic global vegetation model MC1, the model projects a northern expansion of temperate forests across the southern half of the state, primarily into tundra, which promotes more fires in the region because forests have a shorter fire return interval than tundra (2050-2099 vs. 1950-1999 under two climate change scenarios, CGCM1 and HADCM2SUL).⁴⁸⁰ The simulated area burned state wide is 17%–39% greater between 2050 and 2100 than what was simulated between 1950 and 2000, with large interannual and interdecadal variability.⁴⁸¹

Perhaps the greatest change to forests surrounding Juneau will result from the introduction of fire.⁴⁸² The hemlock and spruce dominated forests of coastal southeastern Alaska and British Columbia are not adapted to fire, and warmer weather, along with lightening as a source of ignition, will result in fire becoming a major disturbance force disrupting the rainforest environment.⁴⁸³

⁴⁷⁹ Nearly verbatim from Brown et al. (2004, p. 368)

⁴⁸⁰ Verbatim from Bachelet et al. (2005, p. 2251). Bachelet et al. refer the reader to Table 2 in the cited article for this information. *Note: Scenarios were based on greenhouse gas experiments with sulfate aerosols from the Canadian Climate Center (CGCM1) and the Hadley Centre (HADCM2SUL).*

⁴⁸¹ Verbatim from Bachelet et al. (2005, p. 2251). Bachelet et al. refer the reader to Figure 8 in the cited article for this information.

⁴⁸² Verbatim from Kelly et al. (2007, p. 52)

⁴⁸³ Verbatim from Kelly et al. (2007, p. 52)

Western British Columbia

Fire will probably continue to be a rare event on the wet coast.⁴⁸⁴

Pacific Northwest

The diverse vegetation types and carbon pools of the U.S. Pacific Northwest are tightly coupled to fire regimes that depend on climate and fire suppression.⁴⁸⁵ Changes in 21st century climate are projected to cause an increase in wildfires in many ecosystems, which may adversely affect the terrestrial carbon sink.⁴⁸⁶ Growing evidence points towards increasing lightning activity (a common source of ignition) over the western U.S. under climate change.⁴⁸⁷ Projected temperature increases during the 21st century could lead to larger and/or more frequent fires in drier climates if trends forecast from climate models occur, especially if precipitation does not increase.⁴⁸⁸ Specific projections for forest area burned include:

- A 78% increase in forest area burned by the middle of the 21st century is estimated for the Pacific Northwest (2050 vs. 2000).⁴⁸⁹
- Increases of up to 6-fold in area burned are estimated for regions in the Pacific Northwest by the end of the century.⁴⁹⁰
- In a modeling study of the western three-quarters of Washington and Oregon by Rogers et al. (2011), simulations displayed large increases in area burned (76%-310%) and burn severities (29%-41%) by the end of the 21st century (2070-2099 vs. 1971-2000; CSIRO Mk3, MIROC 3.2 medres, and Hadley CM3 GCMs under A2 emissions scenario) (Figure 29).⁴⁹¹

Using the U.S. Forest Service National Fire Danger Rating System Energy Release Component (NFDRS ERC, an indicator of fire severity and associated decision making), decadal scale trends of ERC fire danger in the context of a historical base or “observed” period (1975-1996) have been assessed.⁴⁹² The Parallel Climate Model and a business-as-usual climate scenario for the period 2006-2099 over the western U.S. were used for the assessment.⁴⁹³ The ERC 60 and greater threshold represents the more extreme fire danger events (compared to ERC 40-59 events).⁴⁹⁴ For western Oregon, western Washington,

⁴⁸⁴ Verbatim from Pojar (2010, p. 21)

⁴⁸⁵ Verbatim from Rogers et al. (2011, p. 1). *Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest.*

⁴⁸⁶ Verbatim from Rogers et al. (2011, p. 1). Rogers et al. cite Flannigan et al. (2009) for information on wildfire projections. For information on the terrestrial carbon sink, Rogers et al. cite Kasischke et al. (1995), Williams et al. (2004), and Mouillot & Field (2005).

⁴⁸⁷ Verbatim from Shafer et al. (2010, p. 184). Shafer et al. cite Price & Rind (1994) and Del Genio et al. (2007) for this information.

⁴⁸⁸ Verbatim from CIG (2004, p. 1)

⁴⁸⁹ Nearly verbatim from Shafer et al. (2010, p. 186). Shafer et al. cite Spracklen et al. (2009b) for this information.

⁴⁹⁰ Verbatim from Shafer et al. (2010, p. 186). Shafer et al. cite McKenzie et al. (2004) and Littell et al. (2009b) for this information.

⁴⁹¹ Nearly verbatim from Rogers et al. (2011, p. 1)

⁴⁹² Nearly verbatim from Brown et al. (2004, p. 368)

⁴⁹³ Brown et al. (2004, see p. 371)

⁴⁹⁴ Nearly verbatim from Brown et al. (2004, p. 378)

and northwestern California, the difference in the mean annual number of days with ERC threshold of ≥ 60 for four future time periods compared to the 1975-1996 baseline are:⁴⁹⁵

- **2010-2029:** An increase of 0-3 days western Washington and northwestern Oregon, an increase of 3-6 days in eastern Puget Sound, Washington's Cascade Mountain spine, the Portland metro area and areas east to the Cascade Mountain spine and the central Oregon coast, and 6-9 days in southern Oregon and northwestern California is projected.⁴⁹⁶
- **2030-2049:** An increase of 0-3 days in western Washington and a small portion of northwestern Oregon, an increase of 3-6 days for the eastern Puget Sound and I-5 corridor through central Oregon, and an increase of 6-9 days along the Cascade Mountain spine, I-5 corridor in southern Oregon, and northwestern California is projected.⁴⁹⁷
- **2050-2069:** An increase of 0-3 days in western Washington and a small portion of northwestern Oregon, an increase of 3-6 days in the Puget Sound region, the remainder of western Oregon, and portions of northwest California, and an increase of 6-9 days along the Cascade Mountain spine of Washington and northern Oregon is projected.⁴⁹⁸
- **2070-2089:** An increase of 0-3 days in western Washington and a small portion of northwestern Oregon, an increase of 3-6 days in the eastern and southeastern Puget Sound to the Cascade Mountain spine of Washington and the remainder of the Oregon Coast, an increase of 6-9 days along the Cascade Mountain spine in Oregon and portions of northwestern California, and an increase of at least 9 days but less than 12 days in the central portion of northwestern California is projected.⁴⁹⁹

Western Washington

In Washington's forested ecosystems (Western and Eastern Cascades, Okanogan Highlands, Blue Mountains) the mean area burned is expected to increase by a factor of 3.8 by the 2040s compared to 1980-2006 (Figure 13; A1B and B1 scenarios, model projections based on Mote & Salathé's [2010] delta-method composite future climate).⁵⁰⁰ The largest proportional increases are in the Western Cascades and Blue Mountains, although the Western Cascades model was the weakest statistically acceptable model, and the area burned is still small despite the large proportional increase.⁵⁰¹

Across Washington State, future area burned projected from the best statistical model used by Littell et al. (2010) suggests a doubling or tripling by the 2080s:⁵⁰²

- **2020s:** The future median regional area burned, averaged over both GCMs, is projected to increase from about 0.5 million acres (0.2 million hectares, ha) to 0.8 million acres (0.3 million ha).⁵⁰³

⁴⁹⁵ Nearly verbatim from Figure 7 in Brown et al. (2004, p. 382)

⁴⁹⁶ This information was summarized from Figure 7 in Brown et al. (2004, p. 382) by the authors of this report.

⁴⁹⁷ This information was summarized from Figure 7 in Brown et al. (2004, p. 382) by the authors of this report.

⁴⁹⁸ This information was summarized from Figure 7 in Brown et al. (2004, p. 382) by the authors of this report.

⁴⁹⁹ This information was summarized from Figure 7 in Brown et al. (2004, p. 382) by the authors of this report.

⁵⁰⁰ Nearly verbatim from Littell et al. (2010, p. 142)

⁵⁰¹ Verbatim from Littell et al. (2010, p. 142-143)

⁵⁰² Nearly verbatim from Littell et al. (2010, p. 140). Littell et al. refer the reader to Figure 6 in the cited article for this information.

⁵⁰³ Nearly verbatim from Littell et al. (2010, p. 140, 142)

- **2040s:** The future median regional area burned, averaged over both GCMs, is projected to increase to 1.1 million acres (0.5 million ha).⁵⁰⁴
- **2080s:** The future median regional area burned, averaged over both GCMs, is projected to increase to 2.0 million acres (0.8 million ha).⁵⁰⁵ The probability of exceeding the 95% quantile area burned for the period 1916-2006 increases from 0.05 to 0.48.⁵⁰⁶

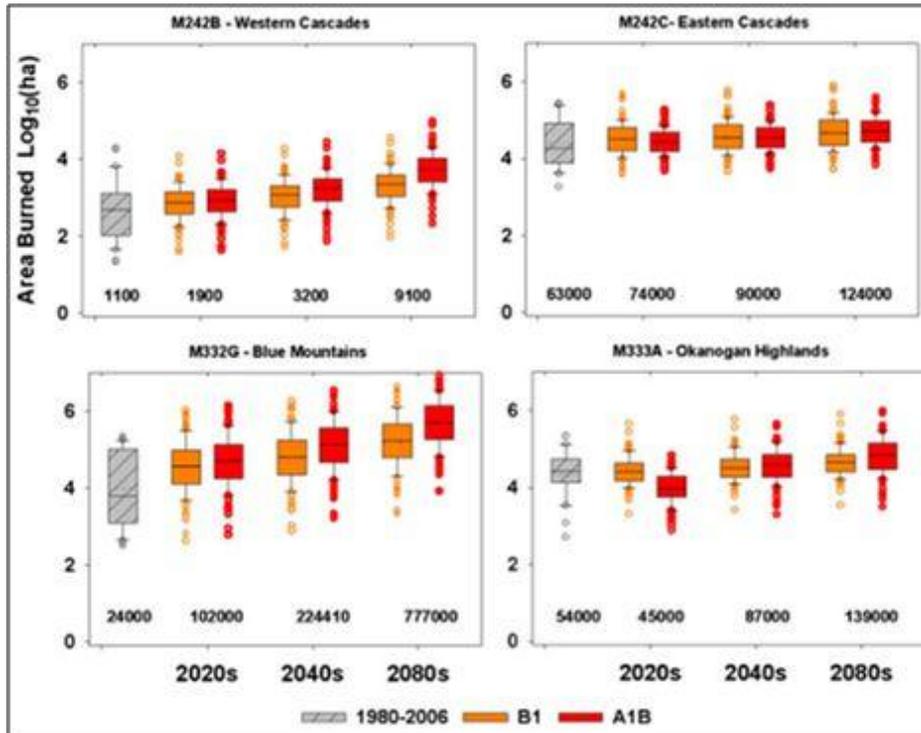


Figure 13. Projections of future area burned in WA's forested ecoregions for which adequate statistical fire models could be constructed. All model projections were based on delta-method composite future climate (Mote & Salathé 2010). The values below each set box-and-whiskers plots indicate the average of A1B (red) and B1 (orange) future area burned estimates for the ecoregions in hectares.

Source: Modified from Littell et al. (2010, Figure 7, p. 143) by authors of this report.

Western Oregon

Despite the different seasonal climate conditions influencing fire occurrence for different forest types, an increase in fire activity is expected for all major forest types in Oregon and the western U.S. under projected climate changes.⁵⁰⁷ Please see the previous section on the Pacific Northwest for additional information on western Oregon.

Northwest California

Earlier snowmelt, higher temperatures and longer dry periods over a longer fire season will directly increase wildfire risk.⁵⁰⁸ Indirectly, wildfire risk will also be influenced by potential climate-related

⁵⁰⁴ Nearly verbatim from Littell et al. (2010, p. 142)

⁵⁰⁵ Nearly verbatim from Littell et al. (2010, p. 142)

⁵⁰⁶ Verbatim from Littell et al. (2010, p. 142). Littell et al. refer the reader to Table 1 in the cited article for this information.

⁵⁰⁷ Verbatim from Shafer et al. (2010, p. 184). Shafer et al. refer the reader to Figures 5.3f and 5.3g in the cited report for this information. Shafer et al. also cite Bachelet et al. (2001), Whitlock et al. (2003), and Keeton et al. (2007) for this information.

⁵⁰⁸ Verbatim from Moser et al. (2012, p. 3)

changes in vegetation and ignition potential from lightning.⁵⁰⁹ Human activities will continue to be the biggest factor in ignition risk.⁵¹⁰ New studies in the California Climate Change Center’s third assessment demonstrate that the distribution of where and to what degree wildfire risk increases in California will also be driven to a large extent by changes in land use and development.⁵¹¹

In either wetter or drier conditions, models indicate that fire could reduce forest and woody vegetation cover in the West in a future warmer world (Table 16).⁵¹² For instance, some climate models project an increase in annual average precipitation in California.⁵¹³ Under these circumstances, the vegetation model simulates increased fire intensity and area burned because increased precipitation reduces fire and promotes fuel buildup during relatively wet years, setting the stage for larger, more intense fires during inevitable dry years.⁵¹⁴

Table 16. Impacts of future climate change on fire in Oregon and California.

	Years	Oregon	California
Area burned by wildfires	1901-2000	3,299 km ²	7,352 km ²
	2001-2100	0.21	0.19
	2031-2060	+0.19	+0.14
	2071-2090	+0.57	+0.19
Biomass burned by wildfires	1901-2000	13.39 Tg C	22.39 Tg C
	2001-2100	+0.08	-0.23
	2031-2060	+0.01	-0.26
	2071-2090	+0.52	-0.25

Source: Modified from Bachelet et al. (2007, Table 3, p. 15) by authors of this report.
Note: Impacts of future climate change on fire simulated by vegetation model MCI (Lenihan et al., 2003; Bachelet et al., 2001). Reported are area burned (km²) and biomass burned in Tg (million tons) C, averaged over the historical period, and future fractional changes for the entire 21st century (2001–2100) and the middle (2031–2060) and late (2071–2090) 21st century in the CGCM2 climate model and the SRES A2 greenhouse gas emission scenario.

Previous research estimated that the long-term increase in fire occurrence associated with a higher emissions scenario is substantial.⁵¹⁵

- Projected increases in the number of large fires statewide range from 58 percent to 128 percent above historical levels by 2085.⁵¹⁶
- Under the same emissions scenario, estimated burned area will increase by 57 percent to 169 percent, depending on location.⁵¹⁷

⁵⁰⁹ Verbatim from Moser et al. (2012, p. 3)

⁵¹⁰ Verbatim from Moser et al. (2012, p. 3)

⁵¹¹ Nearly verbatim from Moser et al. (2012, p. 3)

⁵¹² Verbatim from Bachelet et al. (2007, p. 13)

⁵¹³ Verbatim from Bachelet et al. (2007, p. 14). Bachelet et al. refer the reader to Figure 3 in the cited report for this information. Bachelet et al. also cite Price et al. (2004) for this information.

⁵¹⁴ Verbatim from Bachelet et al. (2007, p. 14). Bachelet et al. cite Lenihan et al. (2003) for this information.

⁵¹⁵ Nearly verbatim from Moser et al. (2012, p. 3)

⁵¹⁶ Nearly verbatim from Moser et al. (2012, p. 3)

⁵¹⁷ Verbatim from Moser et al. (2012, p. 3)

Statistical fire model predictions of the probability of burning for a ~3540 foot (1080 meter) landscape by Krawchuk & Moritz (2012) show (2010-2039, 2040-2069, and 2070-2099 vs. 1971-2000 run with warmer-drier GFDL CM2.1 and warmer-wetter PCM, and each run under A1 and B1):

- A greater change in the probability of burning in the distant future (2070-2099) than near future (2010-2039), as would be expected from the greater changes in climate by the end of the century.⁵¹⁸
- The magnitude of changes in the probability of burning were much greater for those landscapes likely to incur increases (i.e., more fire) than decreases, with most extreme increases roughly three to four times greater than extreme decreases.⁵¹⁹
- In general, the direction of projected change was the same for the probability of at least one fire, and for two or more fires, but there were exceptions, largely in drier landscapes in eastern California.⁵²⁰
- Changes in the mean fire frequency varied across the State (Figure 14).⁵²¹
- The largest changes in mean fire return interval (mFRI) were found within the current geographic range of the Douglas-fir Wildlife Habitat Relationship (WHR) type, with a median fire return interval dropping by almost 100 years by 2070-2099 (Figure 15).⁵²² Results for the Redwood WHR, found in northwest California, are also available (Figure 15).

In a similar study by Westerling & Bryant (2008), the probability of fires exceeding a threshold of ~500 acres (200 hectares) in 2005-2034, 2035-2064, and 2070-2099 (vs. a modeled 1961-1990 baseline; GFDL and PCM GCMs under A2 and B1) was estimated using a logistic probability model for California and neighboring states.⁵²³ Projected increases in Northern California ranged from +15% (B1 PCM) to +90% (A2 GFDL), increasing with temperature.⁵²⁴ Table 1 in Westerling & Bryant indicates the projected increase under B1 GFDL is 38%; the projected increase under A2 PCM is 37%.⁵²⁵ Westerling & Bryant (2008) note the reader should not place too much emphasis on the numerical levels of any one aspect of the model's results in isolation, but instead assess the direction and degree of change in each scenario relative to the others.⁵²⁶

In a later study projecting the current managed fire regimes of California onto future scenarios for climate, population and development footprint, the increase in wildfire burned area associated with the higher emissions pathway (A2) is substantial, with increases statewide ranging from 36% to 74% by 2085, and increases exceeding 100% in much of the forested areas of Northern California in every SRES A2 scenario by 2085 (Figure 16) (2005-2034, 2035-2064, and 2070-2099 vs. 1961-1990; CNRM CM3,

⁵¹⁸ Nearly verbatim from Krawchuk & Moritz (2012, p. 23)

⁵¹⁹ Nearly verbatim from Krawchuk & Moritz (2012, p. 23)

⁵²⁰ Nearly verbatim from Krawchuk & Moritz (2012, p. 23-24)

⁵²¹ Nearly verbatim from Krawchuk & Moritz (2012, p. 37)

⁵²² Nearly verbatim from Krawchuk & Moritz (2012, p. 37)

⁵²³ Westerling & Bryant (2008, p. S232)

⁵²⁴ Nearly verbatim from Westerling & Bryant (2008, p. S244). Westerling & Bryant refer the reader to Table 1 and Figure 6 in the cited article for this information.

⁵²⁵ Westerling & Bryant (2008, Table 1, p. S245)

⁵²⁶ Nearly verbatim from Westerling & Bryant (2008, p. S248)

GFDL CM2.1, and NCAR PCM1, each run under A2 and B1).⁵²⁷ Earlier in the 21st century, initial increases for burned area are relatively modest, with little difference between emissions scenarios:

- **By 2020**, the increases range from 6% to 23%, with median increases between 15% and 19%.⁵²⁸
- **By 2050** the spread in modeled outcomes widens, with predicted increases in burned area ranging from 7% to 41%, and median increases between 21% and 23%, but again differences due to emissions scenarios are relatively small compared to other factors.⁵²⁹
- **By 2085**, the range of modeled outcomes is very large, with total burned area increasing anywhere from 12% to 74%.⁵³⁰ On average, the largest increases occur in 2085 for SRES A2 scenarios, with a median statewide increase in burned area of 44%, and the biggest increases occurring for the warmer, drier GFDL CM2.1 and CNRM CM3 model runs (range: 38% – 74%, median 56%).⁵³¹

In a modeling study using the MC1 dynamic general vegetation model (comparing 2070-2099 vs. 1961-1990 run using the GFDL-A2, GFDL-B1, and PCM-A2 scenarios), the future trends in simulated total area burned in California were characterized by considerable interannual variability, but for nearly every year during the future period, total area burned was greater than the simulated mean total annual area burned over the 1895 – 2003 historical period.⁵³² By the end of the century, predicted total annual area burned ranged from 9% to 15% greater than historical.⁵³³ Figure 17 shows the percent change in mean annual area burned for the 2050 – 2099 future period relative to the mean annual area burned for the historical period (1895 – 2003) for the entire state.

Climatic change results in more frequent and more intense fires in northern California, where escape frequencies increased by more than 100%, based on relatively conservative GCM output and despite more extensive utilization of available fire-fighting resources (2 x CO₂ vs. present CO₂; Changed Climate Fire Modeling System with climate change scenarios based on GISS).⁵³⁴ By using “conservative” climate model projections and disregarding various feedbacks (e.g., indirect effects of climate change on rates of plant growth or vegetation distribution, effects of increased lightning on ignitions), the estimates reported represent a *minimum* expected change, or best-case forecast (emphases in original).⁵³⁵ The greatest increases in fire spread rates and area burned occur in landscapes dominated by grass and brush.⁵³⁶ However, climate change had little impact in the Humboldt ranger unit due to comparatively slow fires, effective fire suppression, and GCM predictions of a wetter, less windy climate.⁵³⁷ Like the redwood

⁵²⁷ Nearly verbatim from Westerling et al. (2011, p. S445). *Climate change and growth scenarios for California wildfire*.

⁵²⁸ Nearly verbatim from Westerling et al. (2011, p. S457)

⁵²⁹ Verbatim from Westerling et al. (2011, p. S457)

⁵³⁰ Verbatim from Westerling et al. (2011, p. S457)

⁵³¹ Verbatim from Westerling et al. (2011, p. S457)

⁵³² Nearly verbatim from Lenihan et al. (2008a, p. S224-S225). *Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California*. Lenihan et al. refer the reader to Figure 7a in the cited article for information on the interannual variability of simulated total area burned.

⁵³³ Nearly verbatim from Lenihan et al. (2008a, p. S225)

⁵³⁴ Verbatim from Fried et al. (2004, p. 188). *The impact of climate change on wildfire severity: A regional forecast for northern California*.

⁵³⁵ Nearly verbatim from Fried et al. (2004, p. 184)

⁵³⁶ Verbatim from Fried et al. (2004, p. 188)

⁵³⁷ Nearly verbatim from Fried et al. (2004, p. 179)

forests of Santa Clara, those in Humboldt showed almost no change in escapes or area burned.⁵³⁸ The small area of grassland in Humboldt experienced a decrease in burned area and suppression efforts (Table 17).⁵³⁹

Table 17. Simulated annual escape frequency and area burned by contained fires under present and double-CO2 climate scenarios, organized by vegetation fuel type for California Department of Forestry and Fire Protection, Humboldt Ranger Unit.

Fuel Type	Number of fires	Number of escapes			Hectares in contained fires		
		Present climate	2 x CO ₂	% Change	Present climate	2 x CO ₂	% Change
Grass	15.1	0.0	0.0	0	15.5	11.4	-27
Redwood	158.9	0.6	0.6	0	83.7	80.1	-4
Overall	174.0	0.6	0.6	0	99.3	91.5	-8

Source: Modified from Fried et al. (2004, Table II, p. 179) by authors of this report.

Information Gaps

The role of future fire in forested landscapes depends as much or more on fire effects and fire severity as on the area burned.⁵⁴⁰ Physically based models at finer spatial scales are needed to address impacts of changing fire regimes on vegetation and watershed hydrology.⁵⁴¹ The impacts and benefits of silvicultural treatments on forest ecosystem processes such as fire severity are generally poorly quantified.⁵⁴²

Because land-cover patterns can affect atmospheric circulation and cloud formation, changes in forest structure in the aftermath of fire, wind or ice storms, hurricanes, landslides, drought, and pest outbreaks may alter weather or climate conditions.⁵⁴³ This interaction needs to be studied and better understood.⁵⁴⁴

In a study of the effects of bark beetle-caused tree mortality on wildfire, Hicke et al. (2012) state several fuels and fire characteristics have either no or few studies associated with them or a significant amount of disagreement, suggesting gaps in understanding.⁵⁴⁵ Changes in fuels and fire behavior in the red phase (i.e., the condition of a dead tree approximately 1 to 4 years after bark beetle attack, referring to the often reddish color of the dried needles) the condition of a tree, are not well understood.⁵⁴⁶ Additional studies are needed on the effects of altered foliar moisture and volatile organic compounds on fire behavior in forest types other than lodgepole pine.⁵⁴⁷ In addition, more information is required on the influence of red phase stands on fire characteristics in less extreme weather conditions (e.g., early season, lower wind speeds).⁵⁴⁸ The influence of a range of mortality rates and times since initial attack within a stand on fire behavior has not been documented, yet most studies reported a mixture of green, red, and/or gray trees

⁵³⁸ Verbatim from Fried et al. (2004, p. 179)

⁵³⁹ Verbatim from Fried et al. (2004, p. 179)

⁵⁴⁰ Verbatim from Littell et al. (2010, p. 153)

⁵⁴¹ Verbatim from Littell et al. (2010, p. 153)

⁵⁴² Verbatim from Littell et al. (2010, p. 153)

⁵⁴³ Verbatim from Dale et al. (2008, p. 732). Dale et al. cite Segal et al. (1988) for information on the effects of atmospheric circulation and cloud formation on land-cover patterns.

⁵⁴⁴ Verbatim from Dale et al. (2008, p. 732)

⁵⁴⁵ Nearly verbatim from Hicke et al. (2012, p. 88)

⁵⁴⁶ Nearly verbatim from Hicke et al. (2012, p. 88)

⁵⁴⁷ Verbatim from Hicke et al. (2012, p. 88)

⁵⁴⁸ Verbatim from Hicke et al. (2012, p. 88)

within an attacked stand (i.e., gray trees refer to the condition of a dead tree approximately 3 to 5 years after bark beetle attack, when needles drop from the tree, leaving the grayish bark highly visible).⁵⁴⁹ Documenting responses of fuels and fire characteristics across a gradient of mortality is critical for understanding if thresholds representing major shifts exist.⁵⁵⁰ Studies of ember and firebrand production and spotting in beetle-attacked locations are needed to improve understanding of fire behavior or large fire events.⁵⁵¹

Furthermore, multiple key processes in beetle-attacked stands need study.⁵⁵² Wide ranges of snagfall rates have been published; additional research is needed to understand this range and develop models.⁵⁵³ Studies have documented increases in herbaceous and/or shrubby vegetation following beetle outbreaks, yet the net impacts on increased fuel loads, ladder fuels, and fuel moisture have yet to be determined.⁵⁵⁴ Few studies have addressed microclimate changes, yet simulations have highlighted the importance of altered wind speeds.⁵⁵⁵ Other microclimate effects, such as on snowpack accumulation and duration and subsequent influences on fuel moisture during spring and summer, have yet to be quantified.⁵⁵⁶ Few studies have addressed drier forest types such as ponderosa pine or piñon pine (*Pinus edulis* and *Pinus monophylla*).⁵⁵⁷

Regarding the effects of invasive plants on fire regimes, research should focus both on the mechanisms by which invasive plant-fire regime cycles become established and on the management tools that can be used to reverse these changes or otherwise mitigate their negative effects.⁵⁵⁸

⁵⁴⁹ Nearly verbatim from Hicke et al. (2012, p. 88)

⁵⁵⁰ Verbatim from Hicke et al. (2012, p. 88)

⁵⁵¹ Verbatim from Hicke et al. (2012, p. 88)

⁵⁵² Nearly verbatim from Hicke et al. (2012, p. 88)

⁵⁵³ Verbatim from Hicke et al. (2012, p. 88). Hicke et al. cite Mielke (1950), Keen (1955), Schmid et al. (1985), and Mitchell & Preisler (1998) as examples of studies on snagfall rates.

⁵⁵⁴ Verbatim from Hicke et al. (2012, p. 88). Hicke et al. cite McCambridge et al. (1982), Reid (1989), Schulz (1995), Stone & Wolfe (1996), McMillin et al. (2003), Page & Jenkins (2003b), and Klutsch et al. (2009) as examples of studies on increases in herbaceous and/or shrubby vegetation following beetle outbreaks. Hicke et al. cite Kaufmann et al. (2008) for information on net impacts on increased fuel loads, ladder fuels, and fuel moisture.

⁵⁵⁵ Verbatim from Hicke et al. (2012, p. 88). Hicke et al. cite Simard et al. (2011) for information on microclimate changes, and Page & Jenkins (2007a) for information on simulations highlighting the importance of wind speeds.

⁵⁵⁶ Verbatim from Hicke et al. (2012, p. 88)

⁵⁵⁷ Nearly verbatim from Hicke et al. (2012, p. 88)

⁵⁵⁸ Nearly verbatim from Brooks et al. (2004, p. 687). *Effects of invasive alien plants on fire regimes.*

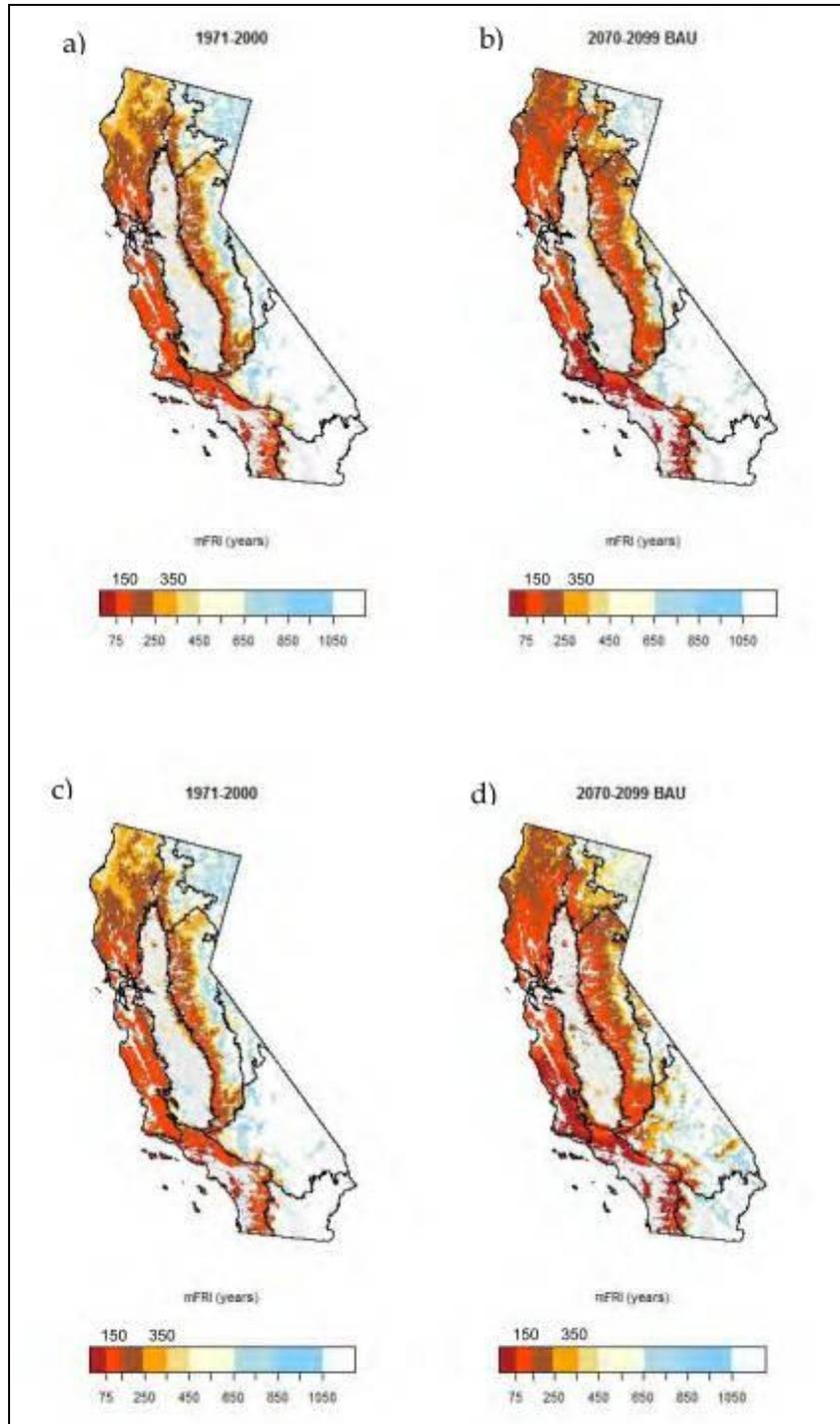


Figure 14. Mean Fire Return Interval (mFRI, $30 \div$ Expected Number of Fires) for 1971-2000 and 2070-2099 for (a-b) GFDL and (c-d) PCM GCMs. Urban, agricultural, and water are masked in grey. *Source: Reproduced from Krawchuk & Moritz (2012, Figure 17, p. 33) by authors of this report.*

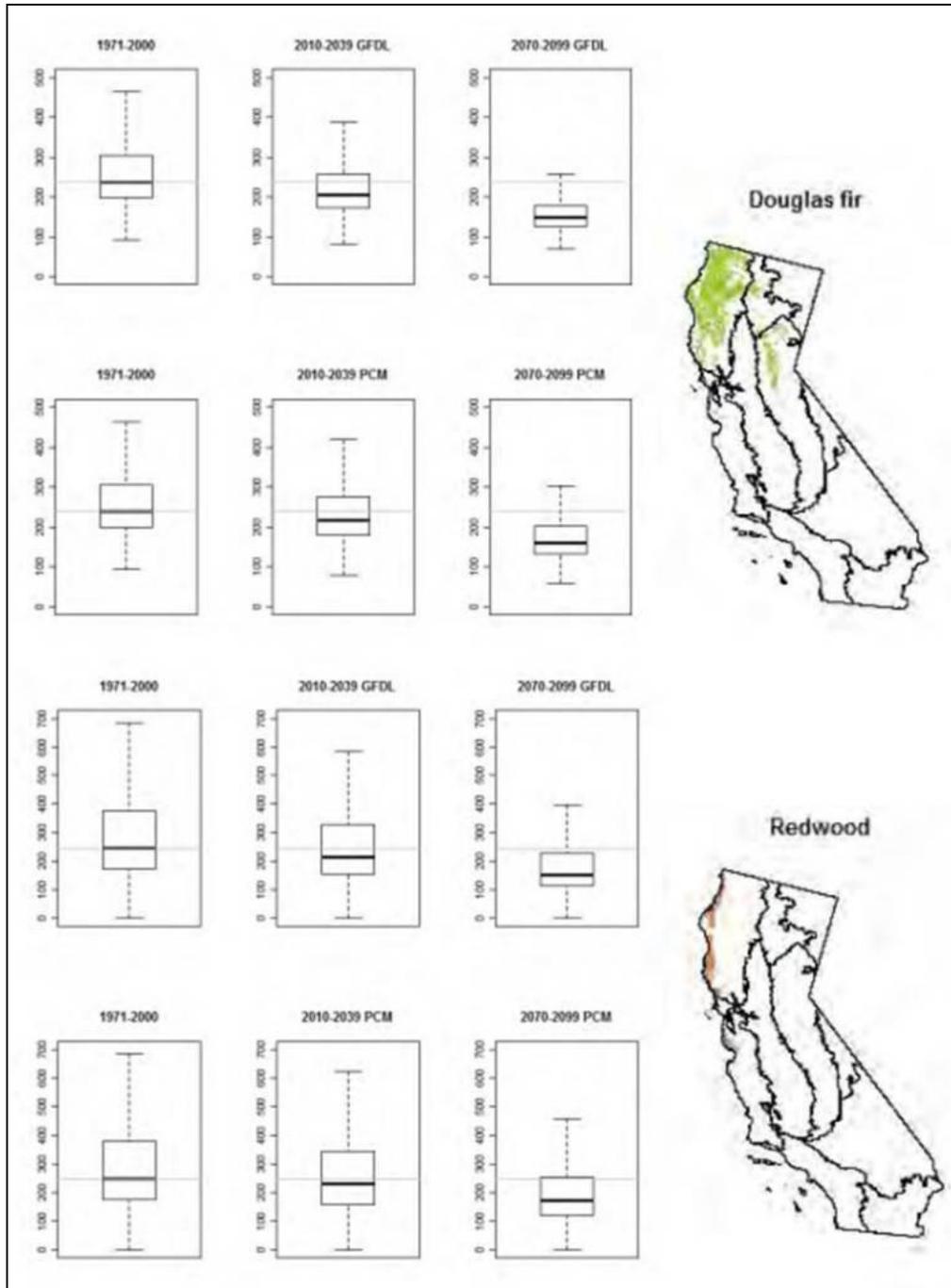


Figure 15. Box and Whisker Plots of mean fire return interval for 1971-2000, 2010-2039, and 2070-2099 based on GFDL and PCM GCMs for the Douglas-fir and Redwood Wildlife Habitat Relationship (WHR) Types. Note: outliers are not shown. The spatial distribution of each WHR is shown alongside the distributions of return interval. *Source: Modified from Krawchuck & Moritz (2012, Figure 18, p. 36) by authors of this report.*

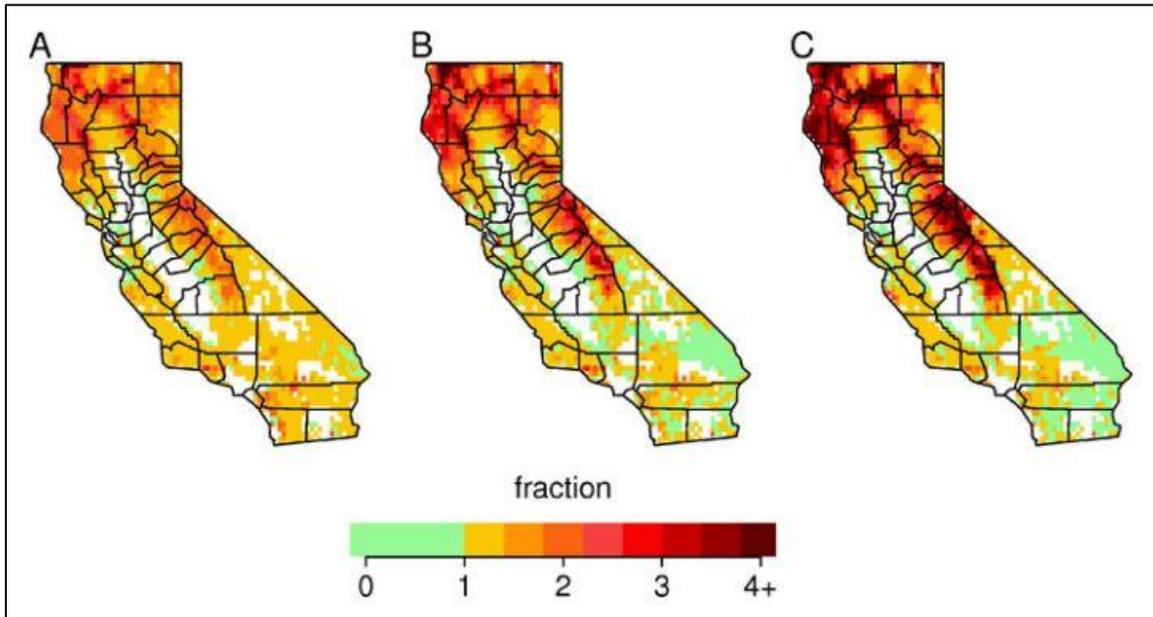


Figure 16. 2085 Predicted burned area as a multiple of reference period predicted burned area for three SRES A2 climate scenarios: a NCAR PCM1, b CNRM CM3, and c GFDL CM2.1, with high population growth, high sprawl, and a high threshold housing density for defining the limit to the wildland urban interface. The location of fire regimes is assumed to be fixed. A value of “ 1 ” indicates burned area is unchanged, while 4+ indicates that burned area is 400% or more of the reference period (i.e., a 300% increase).
 Source: *Reproduced from Westerling et al. (2011, Figure 5, p. S458) by authors of this report.*

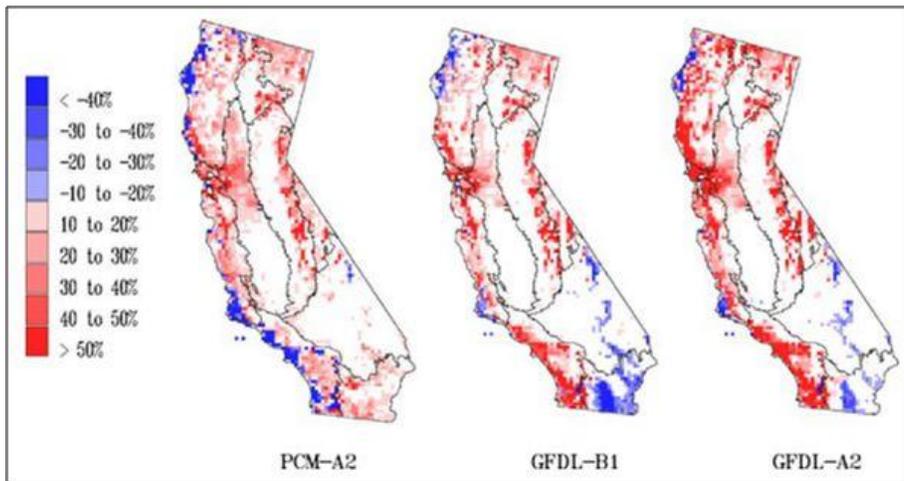


Figure 17. Percent change in mean annual area burned for the 2050 – 2099 future period relative to the mean annual area burned for the historical period (1895 – 2003).
 Source: *Reproduced from Lenihan et al. (2008a, Fig. 8, p. S226) by authors of this report.*

4. Altered insect, pathogen, and disease regimes

Infectious disease organisms are a focal group of species that will be greatly affected by climate change and that strongly interact with, and influence the size of, plant and animal populations.⁵⁵⁹ New species interactions, caused by wildlife range shifts in response to warming, will lead to new disease exposures, and latitudinal and altitudinal shifts in insect vectors will bring a suite of new diseases.⁵⁶⁰

In general, warming is likely to encourage northward expansion of more southern insects and diseases, while longer growing seasons may allow more insect generations per year.⁵⁶¹ Increased warming would most likely increase the diversity of insects at higher latitudes.⁵⁶² Because climate change can both directly and indirectly affect herbivores (i.e., herbivorous insects) and pathogens through various processes, the ultimate effects on patterns of disturbance include increased disturbance in some areas and decreased disturbance in others.⁵⁶³

Population irruptions (i.e., a sudden increase in population, occurring particularly when the natural ecological balance is disturbed) of phytophagous (i.e., feeding on plants) insects – disturbance events important to forest ecosystem functioning – are also directly sensitive to climate change components.⁵⁶⁴ Although there are many possible avenues for atmospheric changes to influence phytophagous insect outbreaks, because of the direct link between insect population success and seasonal temperature, outbreaks are predicted to be affected dramatically by global warming.⁵⁶⁵

Key Terms in this Section

Epidemic: *a change in disease intensity in populations over time and space, most often used to describe a widespread and severe outbreak*

Pathogen: *a bacterium, virus, or other microorganism that can cause disease; in forests, these include fungi, oomycetes (i.e., nonphotosynthetic fungi, commonly called water molds), bacteria, phytoplasmas (i.e., specialized bacteria that serve as obligate parasites of plant phloem tissue and transmitting insects), parasitic higher plants, viruses and nematodes (a type of worm).*

Plant disease: *“any malfunctioning of host cells and tissues that results from continuous irritation by a pathogenic agent or environmental factor and leads to the development of symptoms” (Agrios 2005, as cited in Sturrock et al. 2011, p. 134); requires a susceptible host plant, a virulent pathogen, and a favorable climate or environment*

Sources: Sturrock et al. (2011)

⁵⁵⁹ Verbatim from Running & Mills (2009, p. 23). Running & Mills cite Harvell et al. (2002) for this information.

⁵⁶⁰ Verbatim from Running & Mills (2009, p. 23). Running & Mills cite Parmesan & Yohe (2003) for information on new species interactions caused by range shifts in response to warming. Running & Mills cite Kovats et al. (1999) for information on new diseases brought on by latitudinal and altitudinal shifts in insect vectors.

⁵⁶¹ Verbatim from Shafer et al. (2010, p. 185)

⁵⁶² Verbatim from Dale et al. (2008, p. 727)

⁵⁶³ Verbatim from Dale et al. (2008, p. 727)

⁵⁶⁴ Nearly verbatim from Bentz et al. (2010, p. 602). *Climate change and bark beetles of the western United States and Canada: direct and indirect effects.* Bentz et al. cite Dale et al. (2001) for this information.

⁵⁶⁵ Verbatim from Bentz et al. (2010, p. 602). Bentz et al. cite Danks (1987) for information on the link between insect population success and seasonal temperature, and Bale et al. (2002) for information on outbreaks being affected by global warming.

Causes and types of disturbance from insects, pathogens, & disease in the NPLCC region

Native bark beetles (i.e., of the Order Coleoptera, Family Curculionidae, and Sub-family Scolytinae), which evolved within the coniferous forest ecosystems of western North America, are key agents of change in these systems (Table 18).⁵⁶⁶ Extensive host abundance and susceptibility, concentrated beetle density, favorable weather, optimal symbiotic associations, and escape from natural predators must occur jointly for beetles to surpass a series of thresholds and exert widespread disturbance.⁵⁶⁷ Beetle outbreaks raise tree mortality rates and can result in subsequent replacement by other tree species and plant associations.⁵⁶⁸ However, bark beetle attacks impact energy, water, carbon, and nitrogen cycling without immediately altering the physical structure of forests, thus differing from fire or logging disturbances.⁵⁶⁹

Increasing temperatures and forest homogeneity increase the likelihood of beetles exceeding thresholds, beyond which they generate amplifying feedback at scales from trees to landscapes.⁵⁷⁰ Climate change may affect the dynamics of herbivorous insect populations in two ways: directly, through the physiological processes of individual insects, and indirectly, through their host plants and natural enemies (Figure 18):⁵⁷¹

- **Direct effects of climate change:** Because of differences in temperature-dependent life-history strategies, including cold-induced mortality and developmental timing, responses to warming will differ among and within bark beetle species.⁵⁷² Increasing winter temperatures enhance winter survival probability of the bark beetle, particularly in high elevation areas.⁵⁷³
- **Indirect effects of climate change:** The success of bark beetle populations will also be influenced indirectly by the effects of climate on community associates and host-tree vigor, although little information is available to quantify these relationships.⁵⁷⁴ Well-documented positive relationships exist between bark beetle outbreaks and fire: trees weakened by fire have a higher vulnerability to insect attacks.⁵⁷⁵ Similarly, insect outbreaks increase fuel loads and thus fire hazard and severity.⁵⁷⁶ In addition, host susceptibility may increase under climate change as a result of increased drought stress.⁵⁷⁷ The highest vulnerability occurs during extremely high

⁵⁶⁶ Nearly verbatim from Bentz et al. (2010, p. 602)

⁵⁶⁷ Verbatim from Raffa et al. (2008, p. 501). *Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions.*

⁵⁶⁸ Verbatim from Bentz et al. (2010, p. 602). Bentz et al. cite Veblen et al. (1991) for this information.

⁵⁶⁹ Verbatim from Edburg et al. (2012, p. 416). Edburg et al. cite Brown et al. (2010) and Pugh & Small (2012) for this information.

⁵⁷⁰ Verbatim from Raffa et al. (2008, p. 512)

⁵⁷¹ Verbatim from Williams & Liebhold. (2002, p. 88). *Climate change and the outbreak ranges of two North American bark beetles.* Williams & Liebhold cite Mattson & Haack (1987), Heliövaara et al. (1991), Porter et al. (1991), Cammell & Knight (1992), and Landsberg & Stafford Smith (1992) for this information.

⁵⁷² Verbatim from Bentz et al. (2010, p. 602)

⁵⁷³ Verbatim from Shafer et al. (2010, p. 184). Shafer et al. cite Regniere & Bentz (2007) and Bentz (2008) for this information.

⁵⁷⁴ Verbatim from Bentz et al. (2010, p. 602)

⁵⁷⁵ Verbatim from Shafer et al. (2010, Case Study 2, p. 186). Shafer et al. cite Hood & Bentz (2007), Breece et al. (2008), and Youngblood et al. (2009) for this information.

⁵⁷⁶ Verbatim from Shafer et al. (2010, Case Study 2, p. 186). Shafer et al. cite Lundquist (2007), Page & Jenkins (2007), and Jenkins et al. (2008) for this information.

⁵⁷⁷ Verbatim from Shafer et al. (2010, p. 184)

temperature and extended drought, weakening the ability of trees to repel beetle parasitism.⁵⁷⁸ However, in order to overwhelm a tree's defense system, the mountain pine beetle depends on a synchronous emergence of a large number of adult beetles at an appropriate time of the year (a phenomenon referred to as "adaptive seasonality").⁵⁷⁹

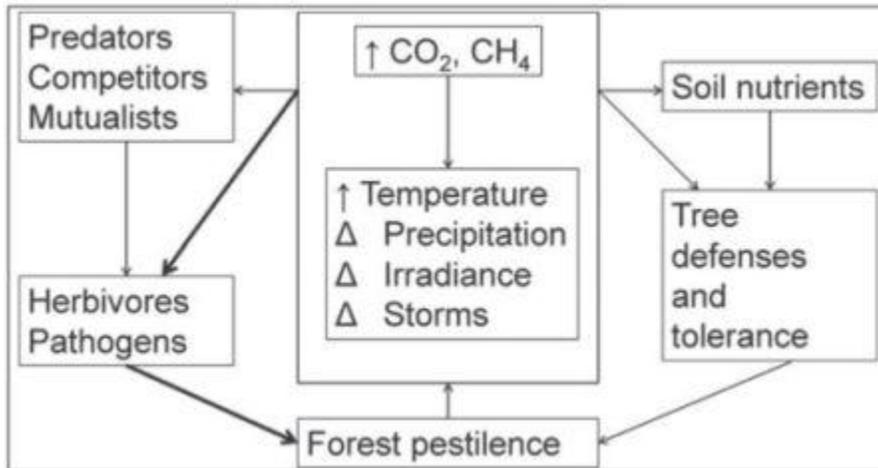


Figure 18. General pathways by which atmospheric changes associated with increasing greenhouse gases can influence forest disturbance from insects and pathogens. CO₂ = carbon dioxide, CH₄ = methane. Source: Reproduced from Ryan et al. (2012, Figure 2.9, p. 25) by authors of this report.

Outbreaks of forest diseases caused by native and introduced forest pathogens are predicted to become more frequent and intense as drought and other abiotic stressors are amplified under climate change.⁵⁸⁰ However, uncertainty pervades predictions about the future impacts of these diseases, in part because the effects of climate change on host-pathogen interactions are complex.⁵⁸¹ Climate influences the survival and spread of pathogens as well as the susceptibility of their hosts.⁵⁸² Climate change could alter the stages and rates of development of the pathogen, modify host resistance, and lead to changes in the physiology of host-pathogen interactions.⁵⁸³ The most likely effects are changes in the geographical distribution of hosts and pathogens and changes in mortality of hosts, caused in part by changes in the efficacy of control strategies.⁵⁸⁴ Fungi that cause foliar disease may be more responsive to climate change than most other organisms that cause forest disease because their ability to sporulate (i.e., to produce or form a spore) and infect is strongly associated with changes in temperature and precipitation.⁵⁸⁵

⁵⁷⁸ Verbatim from Shafer et al. (2010, p. 184). Shafer et al. cite Littell (2009b) for information on highest vulnerability and Raffa et al. (2008) for information on the weakened ability of trees to repel beetle parasitism.

⁵⁷⁹ Verbatim from Shafer et al. (2010, p. 184)

⁵⁸⁰ Verbatim from Sturrock et al. (2011, p. 144)

⁵⁸¹ Verbatim from Sturrock et al. (2011, p. 144)

⁵⁸² Verbatim from Kliejunas (2011, p. 7). *A Risk Assessment of Climate Change and the Impact of Forest Diseases on Forest Ecosystems in the Western United States and Canada.*

⁵⁸³ Verbatim from Kliejunas (2011, p. 7)

⁵⁸⁴ Verbatim from Kliejunas (2011, p. 7)

⁵⁸⁵ Verbatim from Kliejunas (2011, p. 13). Kliejunas cites Gadgil (1977), Hoff (1985), and Peterson (1973) for this information.

Although it is uncertain how specific forest pathogens will respond to climate change, some general inferences (i.e., based on ecological principles) can be drawn.⁵⁸⁶

- The effects of climate change on individual plant diseases will depend on the ecosystem and climate conditions.⁵⁸⁷ The distribution of pathogens and diseases, and their influence on the status and trend of forests, will change.⁵⁸⁸ The ranges of some diseases will expand, whereas the ranges of other diseases will shift.⁵⁸⁹ The influence of pathogens on the status and function of forests may change coincident with changes in species composition and climate.⁵⁹⁰
- Climate change affects forest diseases, increasing the ability of pathogens to survive through the winter and shortening regeneration times of bacteria and fungi.⁵⁹¹ Many pathogens currently are limited by winter temperature, and seasonal increases in temperature are expected to be greatest during winter.⁵⁹² Therefore, both overwintering survival of pathogens and disease severity are likely to increase.⁵⁹³
- Climate change will alter the epidemiology of plant diseases.⁵⁹⁴ Rapid climate change and unstable weather will make prediction of disease outbreaks more difficult.⁵⁹⁵
- The rate at which pathogens evolve and overcome host resistance may increase.⁵⁹⁶
- Because climate affects both host susceptibility to pathogens and pathogen reproduction and infection, the most substantial effect of climate change on plant diseases may be changes in interactions between biotic diseases and abiotic stressors.⁵⁹⁷
- Climate change may facilitate invasion by new nonnative pathogens and thus new epidemics.⁵⁹⁸
- Other indirect effects include the impacts of climate on competitors and natural enemies that regulate the abundance of potential pests and pathogens.⁵⁹⁹

Sturrock et al. (2011) divided diseases and their causal pathogens or agents into three groups:

- **Diseases caused by pathogens directly affected by climate** (e.g., sudden oak death, *Dothistroma* needle blight, Swiss needle cast, white pine blister rust): This group of pathogens can cause disease in a healthy, vigorous host, if the pathogen's environmental requirements are met.⁶⁰⁰ Their life cycles are directly affected by temperature and moisture.⁶⁰¹ In these cases, changes in temperature and moisture more directly affect the pathogen regardless of their effects on the host.⁶⁰²

⁵⁸⁶ Nearly verbatim from Kliejunas (2011, p. 7)

⁵⁸⁷ Verbatim from Kliejunas (2011, p. 7)

⁵⁸⁸ Verbatim from Kliejunas (2011, p. 7)

⁵⁸⁹ Verbatim from Kliejunas (2011, p. 7)

⁵⁹⁰ Verbatim from Kliejunas (2011, p. 7)

⁵⁹¹ Verbatim from Shafer et al. (2010, p. 185)

⁵⁹² Verbatim from Kliejunas (2011, p. 7)

⁵⁹³ Verbatim from Kliejunas (2011, p. 7)

⁵⁹⁴ Verbatim from Kliejunas (2011, p. 8)

⁵⁹⁵ Verbatim from Kliejunas (2011, p. 8)

⁵⁹⁶ Verbatim from Kliejunas (2011, p. 8)

⁵⁹⁷ Verbatim from Kliejunas (2011, p. 8)

⁵⁹⁸ Verbatim from Kliejunas (2011, p. 8)

⁵⁹⁹ Verbatim from Dale et al. (2008, p. 727)

⁶⁰⁰ Verbatim from Sturrock et al. (2011, p. 135)

⁶⁰¹ Verbatim from Sturrock et al. (2011, p. 135)

⁶⁰² Verbatim from Sturrock et al. (2011, p. 135)

- **Diseases caused by pathogens indirectly affected by climate** (e.g., *Armillaria* root disease, canker pathogens such as cytospora canker of alder): Whilst the ability of these pathogens to sporulate (i.e., produce or release spores), spread and infect new hosts is affected by temperature and moisture, factors that stress their hosts are often critical to their successful invasion of host tissues.⁶⁰³ Pathogens indirectly affected by climate tend to infect hosts that are stressed by (i) environmental factors, (ii) pathogens directly affected by climate, or (iii) insects.⁶⁰⁴
- **Decline diseases** (e.g., oak decline, yellow-cedar decline): Forest declines are diseases caused by a complex of predisposing, inciting and contributing factors (i.e., respectively, these factors are long-term, static, or slowly changing; short-term; and, usually secondary pathogens or insects that kill trees already affected by the other factors).⁶⁰⁵ As these difficulties accumulate the tree gradually becomes less able to produce, store and mobilize carbohydrates.⁶⁰⁶ It typically develops symptoms of “dieback,” and unless the situation improves significantly the tree eventually dies.⁶⁰⁷ *For additional information on yellow-cedar decline, please see Chapter VI.2.*

Diseases and pathogens currently found or projected to be found in the NPLCC region include:

- **Swiss needle cast:** Swiss needle cast (i.e., a fungal foliage disease) of Douglas-fir is caused by *Phaeocryptopus gaeumannii* and symptoms include chlorosis (i.e., abnormal reduction or loss in the green color of leaves), reduced needle retention, and reduce tree growth.⁶⁰⁸ *P.gaeumannii* is native to the Pacific Northwest.⁶⁰⁹ Accumulating evidence supports Boyce’s (1940) hypothesis that warm, humid summers with episodic rain are highly conducive to fungal growth and may allow the disease to reach epidemic levels, even in areas where it is native.⁶¹⁰ The primary mechanism of damage appears to be the fruiting bodies produced in the stomatal apertures.⁶¹¹ The fruiting bodies occlude the stomates and reduce rates of carbon dioxide assimilation.⁶¹²
- **Sudden oak death:** a disease of oak trees caused by the non-native pathogen *Phytophthora ramorum*. Temperatures for optimal growth of *P. ramorum* are between approximately 64 °F and 72 °F (18-22 °C).⁶¹³ In addition to mild and wet conditions, heavy precipitation events facilitate infection of new trees.⁶¹⁴ Infected trees are more susceptible to mortality during droughts, which can lead to large diebacks of infected trees during extended drought periods.⁶¹⁵
- **Dothistroma needle blight:** Dothistroma needle blight is primarily caused by *Dothistroma septosporum* (i.e., a fungal foliar disease).⁶¹⁶ Infection depends on several factors including the

⁶⁰³ Verbatim from Sturrock et al. (2011, p. 139)

⁶⁰⁴ Verbatim from Sturrock et al. (2011, p. 139)

⁶⁰⁵ Verbatim from Sturrock et al. (2011, p. 140)

⁶⁰⁶ Verbatim from Sturrock et al. (2011, p. 140)

⁶⁰⁷ Verbatim from Sturrock et al. (2011, p. 140)

⁶⁰⁸ Verbatim from Sturrock et al. (2011, p. 138)

⁶⁰⁹ Verbatim from Kliejunas (2011, p. 15)

⁶¹⁰ Verbatim from Kliejunas (2011, p. 15)

⁶¹¹ Verbatim from Kliejunas (2011, p. 16)

⁶¹² Verbatim from Kliejunas (2011, p. 16). Kliejunas cites Manter & others (2000) for this information.

⁶¹³ Verbatim from Kliejunas (2011, p. 22). Kliejunas cites Werres & others (2001) for this information.

⁶¹⁴ Verbatim from Shafer et al. (2010, p. 185). Shafer et al. cite Anacker et al. (2008) for information on mild and wet conditions, and Rizzo & Garbelotto (2003) for information on heavy precipitation events.

⁶¹⁵ Verbatim from Shafer et al. (2010, p. 185). Shafer et al. cite Frankel (2008) for this information.

⁶¹⁶ Verbatim from Kliejunas (2011, p. 9)

period of needle wetness, temperature, and the quantity of spores available for infection.⁶¹⁷ Moisture is required for germination.⁶¹⁸ Ten or more consecutive hours of needle wetness are usually required for infection by *D. septosporum*.⁶¹⁹ The suitable temperature range for infection is 41-77 °F (5-25 °C), with an optimum of ~61-68 °F (16-20 °C).⁶²⁰ The optimum temperature for successful establishment following germination is approximately 54-64 °F (12-18 °C) when humidity is high.⁶²¹ Damage is typically limited to reduced tree vigor and growth in response to defoliation.⁶²² Mortality is rare but has occurred in stands with successive years of severe defoliation.⁶²³



Figure 19. White pine blister rust, caused by *Cronartium ribicola*, on sugar pine at Happy Camp, CA, USA. Source: Reproduced from Sturrock et al. (2011, Figure 2, p. 138) by authors of this report.

- **White pine blister rust** (Figure 19; *Cronartium ribicola*): Blister rust infection of pines results in branch dieback, reproductive failure, and tree mortality.⁶²⁴ The synergistic effects of *C. ribicola*, drought, increasing temperatures, and mountain pine beetle are considered the ultimate cause of the high mortality observed in many high-elevation populations of white pine.⁶²⁵ However, white pine blister rust is considered a cool weather disease (basidiospore germination – germination from a spore-bearing structure produced by certain fungi – and infection occurs from about 32 to 68 °F, 0 to 20 °C), with spread driven largely by moisture, air temperature, and air circulation.⁶²⁶ Since infection requires a cool, moisture-saturated environment, conditions suitable for *C. ribicola* to cause infection will decrease with fewer wet periods in spring or early summer.⁶²⁷ The probability of years when weather conditions especially favorable for new infections result in significant intensification and spread (wave years) will diminish as the climate becomes warmer and drier, resulting in less rust infection.⁶²⁸

- **Cytospora canker** (*Cytospora umbrina*): The pathogen is native and was first reported in Alaska in the 1930s.⁶²⁹ The

⁶¹⁷ Verbatim from Kliejunas (2011, p. 12). Kliejunas cites Bulman (1993) for this information.

⁶¹⁸ Verbatim from Kliejunas (2011, p. 12)

⁶¹⁹ Verbatim from Sturrock et al. (2011, p. 137). Sturrock et al. cite Gadgil (1974) and Bulman (1993) for this information.

⁶²⁰ Verbatim from Sturrock et al. (2011, p. 137). Sturrock et al. cite Bulman (1993) for this information.

⁶²¹ Verbatim from Kliejunas (2011, p. 12). Kliejunas cites Brown & Webber (2008) for this information.

⁶²² Verbatim from Kliejunas (2011, p. 10). Kliejunas cites Bingham & others (1971) and Patton (1997) for this information.

⁶²³ Verbatim from Kliejunas (2011, p. 10). Kliejunas cites Bradshaw (2004) for this information.

⁶²⁴ Verbatim from Kliejunas (2011, p. 25)

⁶²⁵ Verbatim from Kliejunas (2011, p. 25). Kliejunas cites Gibson & others (2008), Kegley & others (2004), Logan & Powell (2001), and Tomback & Achuff (2010) for this information.

⁶²⁶ Nearly verbatim from Sturrock et al. (2011, p. 138). Sturrock et al. cite Van Arsdel (1965) for this information.

⁶²⁷ Verbatim from Sturrock et al. (2011, p. 138)

⁶²⁸ Verbatim from Sturrock et al. (2011, p. 138). Sturrock et al. cite Kinloch (2003) for this information.

⁶²⁹ Verbatim from Kliejunas (2011, p. 30). Kliejunas cites Trummer (2006) for this information.

pathogen kills vascular tissues; causes elongated, girdling stem cankers; and frequently causes stem dieback and mortality.⁶³⁰ Temperature-induced drought stress may increase host susceptibility and disease severity.⁶³¹

- **Dwarf mistletoe** (*Arceuthobium* spp.): Dwarf mistletoes are parasitic flowering plants that infect conifers, producing characteristic aerial shoots that are leafless and yellow to orange or green to brown.⁶³² Dwarf mistletoes play a substantial role in mortality of trees that are stressed by drought or other factors.⁶³³
- **Armillaria root disease:** *Armillaria* species cause root rot in forests worldwide.⁶³⁴ *Armillaria* species can grow over a range of temperatures, from ~50-88 °F (10-31 °C), although the optimal temperature for many species is at ~68-72 °F (20-22 °C).⁶³⁵ Stand disturbances such as drought, temperature extremes, and soil compaction reduce host resistance to *Armillaria*.⁶³⁶ *Armillaria* itself makes trees more susceptible to bark beetle attack.⁶³⁷ Lack of precipitation decreases trees' resistance to *Armillaria* infection.⁶³⁸ Thus, the root pathogen *Armillaria* is more successful when hosts are stressed by drought.⁶³⁹

Observed Trends

Western North America

Of the hundreds of native bark beetle species in the western United States and Canada, few species (< 1%) attack and reproduce in live trees.⁶⁴⁰ Frequently referred to as aggressive bark beetles, these species can kill healthy trees and have the capacity to cause landscape-scale tree mortality (Table 18, Figure 20).⁶⁴¹

Recent bark beetle population eruptions have exceeded the frequencies, impacts, and ranges documented during the previous 125 years.⁶⁴² For example, current bark beetle outbreaks in western North American forests have reached levels not reported in the past, with affected areas in western U.S. states covering in excess of nearly 10 million acres (4 million hectares, ha) and approximately 35 million acres (14 million ha) in the western Canadian provinces, an area approximately equal to that of Washington State.⁶⁴³

⁶³⁰ Verbatim from Kliejunas (2011, p. 30)

⁶³¹ Verbatim from Kliejunas (2011, p. 31)

⁶³² Verbatim from Kliejunas (2011, p. 33). Kliejunas refers the reader to Figure 7 in the cited report for an image of the effects of dwarf mistletoe.

⁶³³ Verbatim from Kliejunas (2011, p. 34)

⁶³⁴ Verbatim from Kliejunas (2011, p. 37). Kliejunas cites Kile & others (1991) for this information.

⁶³⁵ Verbatim from Sturrock et al. (2011, p. 139). Sturrock et al. cite Rishbeth (1978) and Keca (2005, as cited in La Porta et al., 2008) for this information.

⁶³⁶ Verbatim from Kliejunas (2011, p. 40). Kliejunas cites Goheen & Otrrosina (1998) for this information.

⁶³⁷ Verbatim from Kliejunas (2011, p. 40)

⁶³⁸ Verbatim from Kliejunas (2011, p. 40)

⁶³⁹ Nearly verbatim from Kliejunas (2011, p. 46)

⁶⁴⁰ Verbatim from Bentz et al. (2010, p. 603)

⁶⁴¹ Verbatim from Bentz et al. (2010, p. 603)

⁶⁴² Verbatim from Raffa et al. (2008, p. 501)

⁶⁴³ Nearly verbatim from Edburg et al. (2012, p. 416). *Cascading impacts of bark beetle-caused tree mortality on coupled biogeophysical and biogeochemical processes*. Edburg et al. cite the USDA Forest Service (2010) for information on affected areas in the U.S. and Safranyik et al. (2010) for information on affected areas in Canada. Edburg et al. also refer the reader to Figure 1 in the cited article for information on the total area affected.

Although these bark beetle species are native to the coniferous forests of western North America, epidemics have been facilitated by recent climate change, including increased winter minimum and year-round temperatures and droughts; as a result, outbreaks of some species have moved to higher elevations and higher latitudes.⁶⁴⁴ In addition, warming trends have been associated with shifts in generation duration for populations of spruce beetle in Alaska, Utah, and Colorado, and mountain pine beetle in high-elevation forests.⁶⁴⁵ Further, the annual area affected by bark beetle infestations in North America is comparable to the average area burned by fire, suggesting that the impacts of these outbreaks on biogeophysical and biogeochemical processes are of a similar magnitude to that of fire.⁶⁴⁶

Bloomberg (1987) suggested that differences in incidence and severity of hemlock dwarf mistletoe among geographic areas (low in Alaska, moderate to high in British Columbia, and moderate in Washington and Oregon) reflect the effects of climate on seed production and spread, stand composition and growth rate, and local adaptations of dwarf mistletoe.⁶⁴⁷

Of the nine species of *Armillaria* root disease known in North America, *Armillaria solidipes* causes the greatest damage to conifers in the Western United States and Canada.⁶⁴⁸ In western North America, *A. solidipes* can cause major growth losses in Douglas-fir or true firs.⁶⁴⁹

Southcentral and Southeast Alaska

Estimates of mean fire return interval using soil charcoal data are an order of magnitude longer than the 50 years estimated between spruce beetle outbreaks in the region, and estimates from sedimentary charcoal are up to three times longer than the spruce beetle interval.⁶⁵⁰ This suggests that spruce beetles are by far the dominant form of natural disturbance in white/Lutz spruce forests in the region (i.e., the Kenai Peninsula).⁶⁵¹

In an analysis of climate variability and spruce beetle outbreaks, findings indicate that (1) major spruce beetle outbreaks in southcentral and southwest Alaska, as inferred from sustained growth releases (i.e.,

⁶⁴⁴ Verbatim from Edburg et al. (2012, p. 416). Edburg et al. cite Breshears et al. (2005) and Bentz et al. (2010) for information on epidemics being facilitated by recent climate change, Logan et al. (2010) for information on epidemics moving to higher elevations, and Safranyik et al. (2010) for information on epidemics moving to higher latitudes.

⁶⁴⁵ Verbatim from Bentz et al. (2010, p. 604). Bentz et al. cite Hansen et al. (2001) and Werner et al. (2006) for information on Alaska, Utah, and Colorado. Bentz et al. cite Bentz & Schen-Langenheim (2007) for information on high-elevation forests.

⁶⁴⁶ Verbatim from Edburg et al. (2012, p. 416). Edburg et al. cite Kurz et al. (2008), USDA Forest Service (2010), and Stinson et al. (2011) for information on the annual area affected by bark beetle being comparable to that affected by fire.

⁶⁴⁷ Verbatim from Kliejunas (2011, p. 36)

⁶⁴⁸ Verbatim from Kliejunas (2011, p. 37)

⁶⁴⁹ Verbatim from Klopfenstein et al. (2009, p. 2). *Approaches to predicting potential impacts of climate change on forest disease: an example with Armillaria root disease*. Klopfenstein et al. cite Kile & others (1991) for this information.

⁶⁵⁰ Nearly verbatim from Berg & Anderson (2006, p. 282). *Spruce beetle outbreaks on the Kenai Peninsula, Alaska, and Kluane National Park and Preserve, Yukon Territory: relationship to summer temperatures and regional differences in disturbance regimes*. Berg & Anderson cite Berg et al. (2006) for information on soil charcoal data for mean fire return interval and Anderson et al. (2002, *in press*) for information on sedimentary charcoal estimates of mean fire return interval.

⁶⁵¹ Verbatim from Berg & Anderson (2006, p. 282)

rapid growth of the trees surviving a spruce beetle attack, which is due to the thinned canopy and typically persists for decades until the canopy closes and growth is suppressed through competition) recorded across a range of sites, occurred in the 1810s, 1870s, 1910s, and 1970s and were synchronous across the period of record, and (2) these outbreaks tended to occur within multidecadal periods characterized by cool (-) phase Pacific Decadal Oscillation (PDO) conditions and, over shorter time scales, following one to a few years of warm (El Niño) phase El Niño-Southern Oscillation (ENSO) and drier-than-average summer conditions, as inferred from reconstructed climate indices.⁶⁵² The highly synchronized timing of spruce beetle outbreaks at interannual to multidecadal scales, and particularly the association between cool-phase PDO conditions and beetle disturbance, suggests that climate (i.e., temperature, precipitation) is a primary driver of outbreaks in the study area.⁶⁵³ For example, in a study of 23 sites, spruce beetle populations on the Kenai Peninsula grew from endemic to outbreak levels when summer temperatures over the previous 5 to 6 years were unusually warm; specifically, when the 5-year average summer temperature reached 50.5 °F (10.3 °C), the outbreak probability reached 50%.⁶⁵⁴

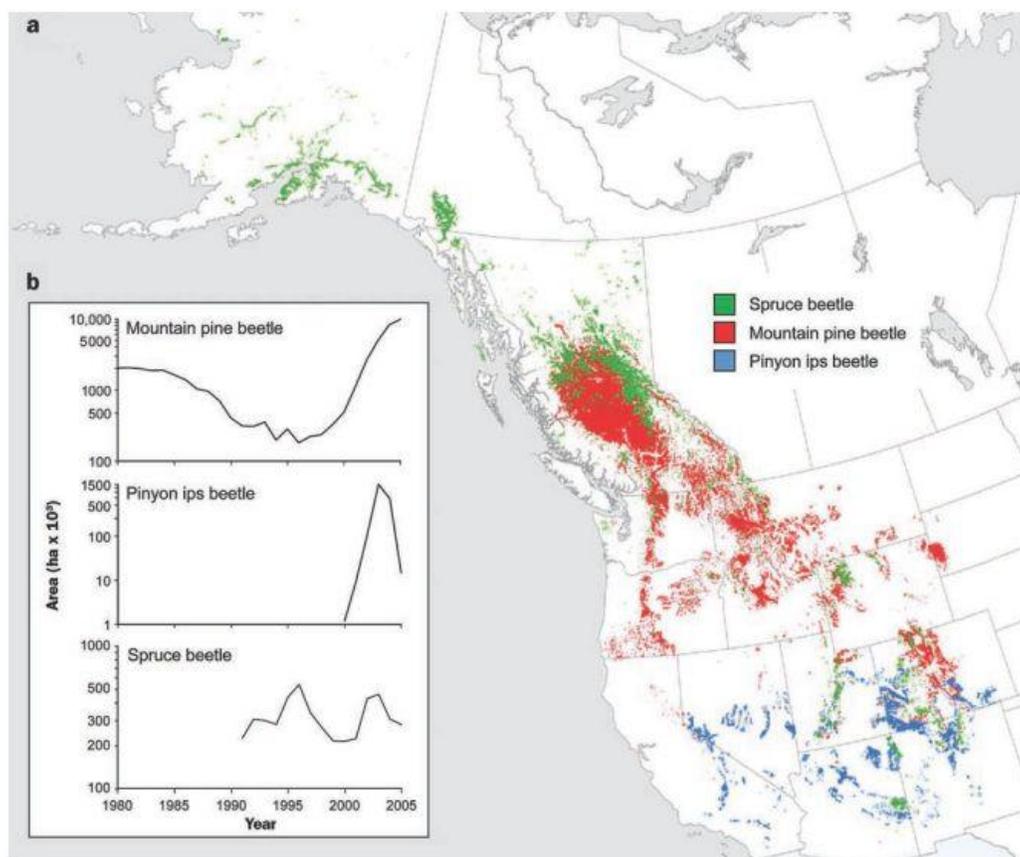


Figure 20. Recent mortality of major western conifer biomes to bark beetles. (a) Map of western North America showing regions of major eruptions by three species. (b) Sizes of conifer biome area affected by these three species over time. Data are from the Canadian Forest Service, the British Columbia Ministry of Forests and Range, and the US Forest Service.

Source: Reproduced from Raffa et al. (2008, Figure 1, p. 502) by authors of this report.

⁶⁵² Verbatim from Sherriff et al. (2011, p. 1467). *Climate variability and spruce beetle (Dendroctonus rufipennis) outbreaks in south-central and southwest Alaska.*

⁶⁵³ Verbatim from Sherriff et al. (2011, p. 1459)

⁶⁵⁴ Nearly verbatim from Berg et al. (2006, p. 228)

Additional information on the area affected by outbreaks, the mean interval between release events, the spatiotemporal synchrony in the severity of outbreaks, and the role of climate variability in outbreaks is available:

- **Area affected by outbreaks:** In southcentral and southwest Alaska, 3.7 million acres (1.5 million hectares) of spruce forest have been affected by the spruce beetle since 1989, and nearly half of the damage has occurred on the Alaska and Kenai Peninsulas.⁶⁵⁵ Spruce beetle damage dating from the 1990s or later was evident at 35 of 37 sites studied by Sherriff et al. (2011), with 76% of the sites showing high-severity infestations (>70% tree mortality and >50% of the surviving trees showing a release; 28 sites).⁶⁵⁶ Across a larger area, the spruce beetle spread through the Kenai Peninsula killing 80 percent of the spruce trees during the 1990's and continues to kill trees there today; it was the largest tree die-off ever recorded in North America.⁶⁵⁷
- **Mean and median interval between release events:** The mean interval between release events over a 250-year record (i.e., mid-1700s to present) was 48 years, in agreement with previously published regional estimates for the late 20th century (30–50 years).⁶⁵⁸ Another study found the mean and median return interval between statistically significant release events, which Berg et al. (2006) interpret as either local or regional spruce beetle outbreaks, was 52 and 45 years, respectively (study period: mid-1700s to present).⁶⁵⁹

Massive outbreaks as measured by substantial thinning events occur at longer intervals, depending on the availability of mature spruce and runs of warm summers.⁶⁶⁰ The southern Kenai Peninsula, for example, was last severely thinned in the late 1870s and early 1880s.⁶⁶¹ Across 23 sites on the Kenai Peninsula, all stands showed evidence of 1 to 5 thinning events with thinning occurring across several stands during the 1810s, 1850s, 1870-1880s, 1910s, and 1970-1980s, which Berg et al. (2006) interpreted as regional spruce beetle outbreaks.⁶⁶²

- **Spatiotemporal synchrony in outbreak severity:** All sites (i.e., the 37 sites studied by Sherriff et al., 2011) showed low-severity disturbances attributed to spruce beetle damage, most notably during the 1810s.⁶⁶³ During other major periods of disturbance (i.e., 1870s, 1910s, 1970s), the effects of spruce beetle outbreaks were of moderate or higher severity.⁶⁶⁴ Reconstructions (mid-1700s to present) indicate that the spruce beetle outbreak that occurred in Alaska in the 1990s was within the historical *geographic* range, but that it showed greater spatiotemporal synchrony, particularly in high-severity infestations (i.e., more sites record high-severity infestations), than at any other time in the past ~250 years.⁶⁶⁵

⁶⁵⁵ Verbatim from Sherriff et al. (2011, p. 1460)

⁶⁵⁶ Nearly verbatim from Sherriff et al. (2011, p. 1465). Sherriff et al. refer the reader to Appendix A: Table A1 in the cited article for this information.

⁶⁵⁷ Nearly verbatim from Kelly et al. (2007, p. 53). Kelly et al. cite Inkley et al. (2004) for this information.

⁶⁵⁸ Nearly verbatim from Sherriff et al. (2011, p. 1467). Sherriff et al. cite Holsten et al. (2001) for information on the previously published regional estimates of the mean interval between release events.

⁶⁵⁹ Nearly verbatim from Berg et al. (2006, p. 223). Berg et al. refer the reader to Figure 6 in the cited article for this information.

⁶⁶⁰ Nearly verbatim from Berg & Anderson (2006, p. 282)

⁶⁶¹ Verbatim from Berg & Anderson (2006, p. 282). Berg & Anderson cite Berg et al. (2006) for this information.

⁶⁶² Nearly verbatim from Berg et al. (2006, p. 219)

⁶⁶³ Nearly verbatim from Sherriff et al. (2011, p. 1459)

⁶⁶⁴ Verbatim from Sherriff et al. (2011, p. 1459)

⁶⁶⁵ Nearly verbatim from Sherriff et al. (2011, p. 1469). Emphasis in original.

- **Role of climate variability in outbreaks:** At interannual time scales, ENSO and PDO reconstructions revealed the strongest associations with spruce beetle outbreaks during and following years recorded as warm-phase ENSO and cool-phase PDO; i.e., spruce beetle outbreaks tended to initiate during and following years of late-summer drought (low August precipitation), warm (El Niño) phases of ENSO, and cool phases of PDO.⁶⁶⁶ Over multidecadal time scales (up to ~40 years), cool-phase PDO conditions tended to precede beetle outbreaks, regardless of the phase of ENSO.⁶⁶⁷

Recently, Volney and Fleming (2000) found that spruce budworm in Alaska have successfully completed their life cycle in one year, rather than the previous two.⁶⁶⁸ Earlier warming spring temperatures allow a longer active growing season and higher temperatures directly accelerate the physiology and biochemical kinetics of the insects' life cycle.⁶⁶⁹

The affected area (i.e., of Sitka spruce trees infected with Sitka spruce aphids) near Sitka and the frequency of aphid outbreaks increased after 1970, probably due to shorter and warmer winters.⁶⁷⁰

Cytospora canker of thinleaf alder is currently epidemic in the southern Rocky Mountains, Alaska, and other areas of western North America.⁶⁷¹ Dieback and mortality of thinleaf alder within riparian areas is occurring in Colorado and adjacent areas and in south-central and interior Alaska.⁶⁷² Sitka alder, and to a lesser degree green alder, are also affected in Alaska.⁶⁷³

Information on the damage from and ecological implications of hemlock dwarf mistletoe, which infects western hemlock, is available:

- Longer growing seasons and reduced snow will favor both the host (i.e., western hemlock) and parasite (i.e., hemlock dwarf mistletoe);
- Competitive advantages offered by climate changes will likely be mitigated by the disease.⁶⁷⁴

Although the frequency and intensity of windstorms are difficult to predict, wind-protected landscapes support old-growth stands with multi-aged structures where stem decays and other disease agents produce

⁶⁶⁶ Verbatim from Sherriff et al. (2011, p. 1468). Sherriff et al. refer the reader to Figure 4b and Appendix B: Figure B1a in the cited article for information on initiation related to late-summer drought, to Figure 4c and Appendix B: figure B1d in the cited article for information on ENSO, and to Appendix B: Figure B1c in the cited article for information on PDO.

⁶⁶⁷ Verbatim from Sherriff et al. (2011, p. 1459)

⁶⁶⁸ Verbatim from Running & Mills (2009, p. 10)

⁶⁶⁹ Verbatim from Running & Mills (2009, p. 10-11). Running & Mills cite Logan et al. (2003) for this information.

⁶⁷⁰ Nearly verbatim from Kelly et al. (2007, p. 54)

⁶⁷¹ Verbatim from Kliejunas (2011, p. 30). Kliejunas refers the reader to Figure 7 in the cited report for an image of cytospora canker of thinleaf alder. Kliejunas cites Trummer (2006) and Worrall (2009) for information on the epidemic.

⁶⁷² Verbatim from Kliejunas (2011, p. 30)

⁶⁷³ Verbatim from Kliejunas (2011, p. 30). Kliejunas cites USDA FS (2007) for this information.

⁶⁷⁴ Nearly verbatim from Wolken et al. (2011, Table 2, p. 13). Wolken et al. cite Hennon et al. (2011) and Muir & Hennon (2007) for this information.

fine-scale disturbances involving the death of individual or small groups of trees.⁶⁷⁵ Currently, stem-decay fungi consume an estimated 31% of the volume of live trees.⁶⁷⁶

Southwest Yukon Territory

Over the last 250 years, spruce beetle outbreaks occurred commonly among spruce forests on the Kenai Peninsula (Alaska), at a mean return interval of 52 years, and rarely among spruce forests in the Kluane National Park and Preserve region where cold winter temperatures and fire appear to more strongly regulate spruce beetle population size.⁶⁷⁷ More specifically, with the exception of the periods of 1934–1942 and 1994–2004, the white spruce forests examined in the Kluane region had not experienced a major spruce beetle outbreak within the last three centuries.⁶⁷⁸ Additional information on these outbreaks is available:

- **1930s-1940s outbreak:** Among the four Kluane stands, Berg et al. (2006) found strong evidence of a 1930–1940s outbreak in one stand, including still standing beetle-scarred snags, and weak evidence of this outbreak in the other three stands.⁶⁷⁹ The 1934–1942 outbreak in the Kluane region occurred during the extremely warm summers of the 1930s.⁶⁸⁰ Of the four Kluane stands, only Papineau Road showed a substantial growth release, confirming an outbreak reported from the 1940s.⁶⁸¹ The other three Kluane stands showed small but statistically significant releases in the 1930 and 1940s, as well as other releases not correlated among stands.⁶⁸² Surviving trees on the Papineau Road site exhibited strong releases with many still growing today at more than twice the historical average growth rate for the stand.⁶⁸³
- **1990s to early 2000s outbreak:** At all four sites at least moderate infestations were observed in the 1990s and early 2000s.⁶⁸⁴ Spruce beetle outbreaks in the Kluane region appeared to be initiated and maintained by periods of warm summer temperature, as evidenced by the 1994–2005 outbreaks following the unusually high summer temperatures from 1989 to 2004.⁶⁸⁵

Western British Columbia

Historically, the range of mountain pine beetle has been limited by climate.⁶⁸⁶ Summer temperature

⁶⁷⁵ Verbatim from Wolken et al. (2011, p. 17). Wolken et al. cite Hennon (1995) and Hennon & McClellan (2003) for this information.

⁶⁷⁶ Verbatim from Wolken et al. (2011, p. 17). Wolken et al. cite Farr et al. (1976) for this information.

⁶⁷⁷ Nearly verbatim from Berg et al. (2006, p. 219)

⁶⁷⁸ Verbatim from Berg et al. (2006, p. 224)

⁶⁷⁹ Verbatim from Berg et al. (2006, p. 227)

⁶⁸⁰ Nearly verbatim from Berg et al. (2006, p. 228). Berg et al. cite Szeicz & MacDonald (1995) and Wilson & Luckman (2003) for this information.

⁶⁸¹ Verbatim from Berg et al. (2006, p. 223). Berg et al. cite Furniss (1950) and Downing (1957) for this information.

⁶⁸² Verbatim from Berg et al. (2006, p. 223)

⁶⁸³ Verbatim from Berg et al. (2006, p. 223). Berg et al. refer the reader to Figure 5 in the cited article for this information.

⁶⁸⁴ Verbatim from Berg et al. (2006, p. 224)

⁶⁸⁵ Verbatim from Berg et al. (2006, p. 228)

⁶⁸⁶ Verbatim from Safranyik et al. (2010, p. 420). *Potential for range expansion of mountain pine beetle into the boreal forest of North America*. Safranyik et al. cite Safranyik et al. (1975), Carroll et al. (2004), and Aukema et al. (2008) for this information.

regimes that preclude a univoltine (i.e., producing one generation per year) life cycle and (or) minimum winter temperatures of -40°F (-40°C) or below explain much of the beetle's past distribution (Figure 21).⁶⁸⁷ A comparison of annual surveys of mountain pine beetle infestations with maps of the historical distribution of climatically suitable habitats shows that climatic conditions have become more favorable to the mountain pine beetle over large portions of western Canada during the past 30 years.⁶⁸⁸ This has enabled populations to expand into formerly climatically unsuitable habitats, especially toward higher elevations and more northerly latitudes.⁶⁸⁹

The presence of bark beetle outbreaks in areas with a historically unsuitable climate, in part a consequence of climate change, provided an opportunity to assess the hypothesis that the mountain pine beetle has higher reproductive success in lodgepole pine trees growing in areas that have not previously experienced frequent outbreaks.⁶⁹⁰ The mean number of brood beetles produced per attacking female was significantly affected by historic climatic suitability, increasing as suitability decreased.⁶⁹¹ There was a significant negative effect of attack density on brood productivity, as expected.⁶⁹² There was no significant interaction between historic climatic suitability and attack density.⁶⁹³

In B.C., 124 insect, 4 plant disease, and 144 plant invasive alien species associated with

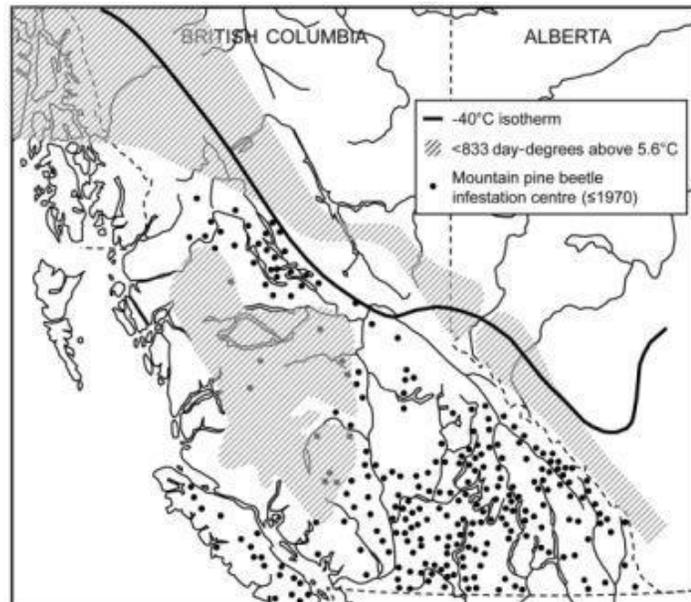


Figure 21. Historical climatic limits to the northern and eastern distribution of mountain pine beetle. Data points represent the observed distribution of infestations up to and including 1970; shading indicates regions where, on average (1941–1970), there were fewer than 833 day-degrees above 5.6°C within a growing season, and the heavy line denotes the isotherm where -40°C occurred, on average (1941–1970), on at least 1 day each winter (data from the Canadian Forest Service Forest Insect and Disease Survey and Environment Canada's Meteorological Service). *Source: Reproduced from Safranyik et al. (2010, Figure 4, p. 420) by authors of this report.*

⁶⁸⁷ Nearly verbatim from Safranyik et al. (2010, p. 420). Safranyik et al. cite Safranyik et al. (1975), Powell et al. (2000), and Logan & Powell (2001) for information on summer temperature limiting a univoltine life cycle, and Safranyik et al. (1975), Mock et al. (2007), and Figure 4 in the cited article for information on minimum winter temperature effects on beetle distribution.

⁶⁸⁸ Verbatim from Safranyik et al. (2010, p. 420). Safranyik et al. cite Carroll et al. (2004) for this information.

⁶⁸⁹ Verbatim from Safranyik et al. (2010, p. 420–421). Safranyik et al. cite Carroll et al. (2004) for this information.

⁶⁹⁰ Nearly verbatim from Cudmore et al. (2010, p. 1036). *Climate change and range expansion of an aggressive bark beetle: evidence of higher beetle reproduction in naïve host tree populations.*

⁶⁹¹ Nearly verbatim from Cudmore et al. (2010, p. 1040). Cudmore et al. refer the reader to Figure 2 in the cited article for this information. *Note: Cudmore et al. used a mixed model ANOVA for data analysis. Reported statistics are: $F = 8.79$, $df = 3$, 8.8 , $P = 0.005$.*

⁶⁹² Nearly verbatim from Cudmore et al. (2010, p. 1040). *Note: Cudmore et al. used a mixed model ANOVA for data analysis. Reported statistics are: $F = 22.68$, $df = 1$, 13.7 , $P < 0.001$.*

⁶⁹³ Nearly verbatim from Cudmore et al. (2010, p. 1040). Cudmore et al. refer the reader to Figure 3 in the cited article for this information. *Note: Cudmore et al. used a mixed model ANOVA for data analysis. Reported statistics are: $F = 0.709$, $df = 3$, 79.7 , $P = 0.549$.*

forest and rangelands have been identified.⁶⁹⁴ The extent of the insect distribution within the province and their impacts are largely unknown.⁶⁹⁵ White pine blister rust has caused widespread mortality of western white pine and whitebark pine throughout almost all of their natural populations.⁶⁹⁶

A disease of lodgepole pine, *Dothistroma* needle blight, is expanding, causing extensive mortality of pine in the northwestern part of the province.⁶⁹⁷ A survey of 101,313 acres (41,000 hectares, ha) in three forest districts from 2002 to 2004 detected the disease across 93,900 acres (38,000 ha), with mortality occurring on 6,672 acres (2700 ha).⁶⁹⁸ Even mature lodgepole pine trees were severely affected and dying.⁶⁹⁹ In this case, a local trend of increasing summer precipitation appears to be responsible.⁷⁰⁰ Woods and others (2005) found a strong positive relationship between the frequency of warm rain events and disease severity.⁷⁰¹ Further, although drought stress facilitated progression from an incipient to epidemic mountain pine beetle population in British Columbia, a significant correlation with precipitation was no longer found after the beetle population became self-amplifying.⁷⁰² Elevated temperatures, which directly influence bark beetle population success, were associated with drought conditions that affected tree stress.⁷⁰³ In addition, although lodgepole pine is native, the species has been planted extensively since the early 1980s, increasing host abundance.⁷⁰⁴

In southern British Columbia, Hood (1982) observed a positive correlation between precipitation, particularly spring rainfall, and relative abundance of *P. gaeumannii* (i.e., Swiss needle cast, a fungal foliar disease of Douglas-fir).⁷⁰⁵ On coastal sites in B.C., *A. solidipes* (i.e., an *Armillaria* root disease) was prevalent on sites with slightly dry soils, and occurred at low frequency on sites with moist soils.⁷⁰⁶

Pacific Northwest

Mountain pine beetle infestations have historically occurred frequently and extensively throughout the Pacific Northwest.⁷⁰⁷ Climate change, in particular warming and drought, affects bark beetle life stage development rates, winter mortality, and host tree susceptibility.⁷⁰⁸ Across the western U.S., stand

⁶⁹⁴ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 73)

⁶⁹⁵ Nearly verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 75)

⁶⁹⁶ Nearly verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 75)

⁶⁹⁷ Nearly verbatim from B.C. Ministry of Environment (2007, p. 160)

⁶⁹⁸ Verbatim from Kliejunas (2011, p. 11). Kliejunas cites Worrall (2010) for this information.

⁶⁹⁹ Verbatim from Kliejunas (2011, p. 11)

⁷⁰⁰ Verbatim from B.C. Ministry of Environment (2007, p. 160). B.C. MoE cites Woods et al. (2005) for this information.

⁷⁰¹ Verbatim from Kliejunas (2011, p. 12)

⁷⁰² Verbatim from Bentz et al. (2010, p. 605). Bentz et al. cite Raffa et al. (2008) for this information.

⁷⁰³ Nearly verbatim from Bentz et al. (2010, p. 605)

⁷⁰⁴ Nearly verbatim from Kliejunas (2011, p. 12)

⁷⁰⁵ Nearly verbatim from Kliejunas (2011, p. 17)

⁷⁰⁶ Nearly verbatim from Kliejunas (2011, p. 40)

⁷⁰⁷ Verbatim from Littell et al. (2010, p. 132). Littell et al. cite Wellner (1978) and Logan & Powell (2001) for this information.

⁷⁰⁸ Verbatim from Littell et al. (2010, p. 132). Littell et al. cite Logan & Powell (2001), Carroll et al. (2004), and Oneil (2006) for this information.

structural conditions make host species susceptible to beetle attack, and future climate change is predicted to increase climate suitability at higher elevations.⁷⁰⁹

The balsam woolly adelgid is a European insect that first appeared in Oregon in the 1920s.⁷¹⁰ By the 1950s and 1960s dramatic outbreaks of balsam woolly adelgid occurred in the Cascades and caused true fir mortality over thousands of acres.⁷¹¹ True fir species are most vulnerable to balsam woolly adelgid infestations when growing at the lower ends of their elevation ranges where milder temperatures occur.⁷¹² A factor favoring adelgid survival and increased damage is warmer than average summer temperatures.⁷¹³ Since then (i.e., the 1960s), this insect has spread over much of the fir type in Oregon and tree mortality has subsided to lower levels.⁷¹⁴ The long-term impacts have been substantial and include eliminating grand fir at low elevations in the Willamette Valley and the disappearance of subalpine fir from some high elevation areas where it is an important pioneer tree species.⁷¹⁵

Occurrence of Swiss needle cast in the Pacific Northwest is positively correlated with degree-day accumulation during winter and leaf wetness hours during spring to autumn.⁷¹⁶ More severe disease symptoms and greater fungal colonization are commonly observed on lower elevation sites near the coast, suggesting the possible involvement of maritime fog.⁷¹⁷ Within the epidemic area (i.e., coastal Washington, Oregon, and California), needle retention varies from approximately 1.5 to 2.6 years.⁷¹⁸ Normal needle retention in healthy coastal form Douglas-fir is approximately four years.⁷¹⁹ Disease tends to be more severe in sites nearer the coast, at lower elevations, and on southern aspect slopes, gradually diminishing to the east.⁷²⁰ In an earlier study, Hood (1982) found more *P. gaeumannii* (i.e., Swiss needle cast) in southern British Columbia and western Washington in coastal forests of Vancouver Island and the Olympic Peninsula, with lower levels in the rain shadow of eastern Vancouver Island and the interior, and attributed the difference mainly to precipitation patterns.⁷²¹

Childs (1960) reported that death of conifer branches in the Pacific Northwest following an unusually hot summer in 1958 and an unusually dry summer in 1959 was extensive in trees stressed by dwarf mistletoe and other agents.⁷²² Childs (1960) also suggested that the death of branches infected by dwarf mistletoe

⁷⁰⁹ Verbatim from Littell et al. (2010, p. 132). Littell et al. cite Hicke & Jenkins (2008) for information on stand structural conditions and host species susceptibility. Littell et al. cite Hicke et al. (2006) for information on future climate suitability at higher elevations.

⁷¹⁰ Verbatim from Flowers & Kanaskie (2007a, p. 1)

⁷¹¹ Verbatim from Flowers & Kanaskie (2007a, p. 1)

⁷¹² Verbatim from Flowers & Kanaskie (2007a, p. 2)

⁷¹³ Verbatim from Flowers & Kanaskie (2007a, p. 2)

⁷¹⁴ Verbatim from Flowers & Kanaskie (2007a, p. 1)

⁷¹⁵ Verbatim from Flowers & Kanaskie (2007a, p. 1)

⁷¹⁶ Nearly verbatim from Sturrock et al. (2011, p. 138). Sturrock et al. cite Manter et al. (2005) for this information.

⁷¹⁷ Verbatim from Stone et al. (2008, p. 172). Stone et al. cite Rosso & Hansen (2003) for this information.

⁷¹⁸ Nearly verbatim from Stone et al. (2008, p. 171). *Predicting effects of climate change on Swiss needle cast disease severity in Pacific Northwest forests*. Stone et al. cite Hansen et al. (2000) for this information.

⁷¹⁹ Verbatim from Stone et al. (2008, p. 171)

⁷²⁰ Verbatim from Stone et al. (2008, p. 171). Stone et al. cite Hansen et al. (2000), Manter et al. (2003b), and Rosso & Hansen (2003) for this information.

⁷²¹ Nearly verbatim from Stone et al. (2008, p. 172)

⁷²² Verbatim from Kliejunas (2011, p. 35)

may reduce inoculum (i.e., the means of inoculation, or infestation) and thus reduce dwarf mistletoe spread.⁷²³

Another present-day concern in the Pacific Northwest (Oregon, Washington, and northern California) involves a new exotic insect pest of small fruits, *Drosophila suzukii*.⁷²⁴

Western Washington

For information on western Washington, please see the previous section on the Pacific Northwest.

Western Oregon

Mountain pine beetle is the most important insect pest in Oregon, affecting 348,400 acres per year (140,992 hectares per year) on average from 2004 to 2008.⁷²⁵ Another important disease that is strongly climate sensitive is sudden oak death (caused by the non-native pathogen *Phytophthora ramorum*), which has been spreading northward from California into southwestern Oregon forests since 2001.⁷²⁶ For the non-native pathogen *P. ramorum* which causes sudden oak death, Kanaskie and others (2008) attributed an unexpected expansion of the disease from sites where eradication efforts were being conducted to two consecutive years with an unusually wet spring and early summer.⁷²⁷ Hansen and others (2008) reported that rain in late May following a dry April triggered an infection event at two sites, resulting in dieback, subsequent sprouting of tanoak, and numerous new *P. ramorum* bole infections.⁷²⁸

A dendrochronological study showed that growth suppression owing to the Swiss needle cast is not a recent phenomenon on the Oregon coast.⁷²⁹ The average growth reduction owing to Swiss needle cast for six study sites ranged from 18% to 50% in the years 1590-2011, which was consistent with the range of growth losses found in Oregon and New Zealand.⁷³⁰ Tree-ring records at all six study sites indicated that Swiss needle cast intensity peaked in 1984-1986 because of a prior decade of warmer winters and milder, wetter summers, which favored spore dispersal, germination, and needle colonization.⁷³¹ Disease intensity peaked in 1984-1986 at all study sites, followed either by a decline to at or below historic levels at warmer, less-humid study sites owing to decreasing needle wetness in summer, or an increase to unprecedented levels from 1984 to 2007 at a cooler, more humid site owing to increasing winter and summer temperatures.⁷³² Specifically, the peak impact (i.e., on Douglas-fir) of Swiss needle cast for the six study sites ranged from 31% to 100% in the years 1984-1986, about double the historic average impact at each site.⁷³³

⁷²³ Verbatim from Kliejunas (2011, p. 35)

⁷²⁴ Nearly verbatim from Hixon et al. (2010, p. 273)

⁷²⁵ Verbatim from Shafer et al. (2010, p. 183). Shafer et al. cite Nelson et al. (2009) for this information.

⁷²⁶ Verbatim from Shafer et al. (2010, p. 185)

⁷²⁷ Nearly verbatim from Kliejunas (2011, p. 22)

⁷²⁸ Verbatim from Kliejunas (2011, p. 22)

⁷²⁹ Nearly verbatim from Lee et al. (2013, p. 685). *Tree-ring analysis of the fungal disease Swiss needle cast in western Oregon coastal forests.*

⁷³⁰ Nearly verbatim from Lee et al. (2013, p. 685). Lee et al. cite Maguire et al. (2002) and Shaw et al. (2011) for information on Oregon, and Kimberley et al. (2011) for information on New Zealand.

⁷³¹ Verbatim from Lee et al. (2013, p. 685-686)

⁷³² Verbatim from Lee et al. (2013, p. 689)

⁷³³ Nearly verbatim from Lee et al. (2013, p. 686)

However, another study found that since the early 1990s, a severe, unprecedented epidemic of Swiss needle cast has affected the coastal fog belt zone of Oregon, where Douglas-fir was not a dominant species in presettlement forests.⁷³⁴ Based on annual area surveys conducted by the Swiss Needle Cast Cooperative at Oregon State University, the spatial extent of infected forests increased from 130,966 acres (53,000 hectares, ha) in 1996 to 518,921 acres (210,000 ha) in 2012 at a rate of about 2.0 miles per year (3.2 kilometers per year).⁷³⁵ Symptoms including chlorosis (i.e., abnormal reduction or loss in the green color of leaves), premature needle loss, growth reduction, and abundant fruiting of the pathogen on 1- and 2-year-old needles are evident from Coquille and Bandon on the southern Oregon coast to Shelton, Washington, on Puget Sound; damage is concentrated in plantations near Tillamook, Oregon.⁷³⁶

Occurrence of the disease in the Pacific Northwest is positively correlated with degree-day accumulation during winter and leaf wetness hours from spring through autumn (warm winters and wet summers).⁷³⁷ The pathogen occurs over about 1.2 million acres (500,000 ha) of Douglas-fir in Oregon.⁷³⁸ Approximately 395,369 acres (160,000 ha) are severely affected with Swiss needle cast, and some landowners in these areas are converting their Douglas-fir plantations to spruce and hemlock.⁷³⁹ Mean and maximum decreases in basal area growth in Oregon are 20% and 55%, respectively.⁷⁴⁰ Douglas-fir radial growth was reduced by 85% at a severely diseased site.⁷⁴¹ Vertical growth can decrease by about 25%.⁷⁴² Wood density and proportion of latewood to earlywood were higher in stands heavily infested (needle retention less than 2 years) with Swiss needle cast than in healthier stands.⁷⁴³

Northwest California

In the United States, environmental impacts of *P. ramorum* (i.e., the non-native pathogen causing sudden oak death) have been greatest in coastal woodlands in California and southwestern Oregon.⁷⁴⁴ Epidemic mortality of coast live oak occurred 1 to 2 years after high spring rainfall in the El Niño years of 1998 and 2005.⁷⁴⁵ Mortality of tanoak and oaks are resulting in changes in forest composition, loss of habitat for animals, increases in soil erosion, and a substantial increase in fuel loads near heavily populated urban-woodland interfaces.⁷⁴⁶

⁷³⁴ Nearly verbatim from Kliejunas (2011, p. 15). Kliejunas cites Hansen & others (2000) for this information.

⁷³⁵ Verbatim from Lee et al. (2013, p. 688)

⁷³⁶ Verbatim from Kliejunas (2011, p. 15). Kliejunas cites Hansen & others (2000) for this information.

⁷³⁷ Verbatim from Kliejunas (2011, p. 17). Kliejunas cites Manter & others (2005) for this information.

⁷³⁸ Verbatim from Kliejunas (2011, p. 16)

⁷³⁹ Verbatim from Kliejunas (2011, p. 16). Kliejunas cites Hansen & others (2002) for this information.

⁷⁴⁰ Verbatim from Kliejunas (2011, p. 16). Kliejunas cites Maguire & others (2002) and Mainwaring & others (2005) for this information.

⁷⁴¹ Verbatim from Kliejunas (2011, p. 16). Kliejunas cites Black & others (2005) for this information.

⁷⁴² Verbatim from Kliejunas (2011, p. 16)

⁷⁴³ Verbatim from Kliejunas (2011, p. 16). Kliejunas cites Johnson & others (2005) for this information.

⁷⁴⁴ Nearly verbatim from Kliejunas (2011, p. 21)

⁷⁴⁵ Verbatim from Kliejunas (2011, p. 22). Kliejunas cites Davidson & others (2005) and Rizzo & others (2005) for this information.

⁷⁴⁶ Verbatim from Kliejunas (2011, p. 21)

Future Projections

Note: Please see Box 5 (p. 184) for a discussion of some of the modelling approaches presented in this section.

Western North America

Bentz et al. (2010) analyzed the influence of future temperature patterns on mountain pine beetle success within its current range in the western United States and Canada using models describing the insect's seasonality and tolerance to cold (Figure 22).⁷⁴⁷ In a comparison of three models of climatic suitability for mountain pine beetle range expansion, in the near future (2001-2030), overall climate suitability is expected to intensify in southern and central B.C. and shift north into the western boreal region, while the remainder of the boreal forest will remain unsuitable, even though a univoltine (i.e., producing one generation of beetles per year) life cycle for the mountain pine beetle is possible (2001-2030 vs. 1961-1990; CGCM1 run with 1% annual increase in CO₂ starting in 2000).⁷⁴⁸ In the recent past (1971-2000) these areas (i.e., of climatic suitability) were predominantly in southern and central B.C., southern and west-central Alberta, and southern Saskatchewan.⁷⁴⁹

Modeled results suggest that projected warming across the western U.S. will lead to a decrease in overall modeled area of adaptive seasonality of mountain pine beetle (1994-2100 vs. 1895-1993 run with CGCM1 and HADCM2 using gridded daily temperatures from the Vegetation/Ecosystem Modeling and Analysis Project).⁷⁵⁰ By the end of the time period (i.e., by 2100), Hicke et al. (2011) estimated that only about 2.5 million acres (1 million hectares, ha) in the western U.S. will have thermally suitable conditions for outbreak, compared to 49-74 million acres (20-30 million ha) historically.⁷⁵¹ At the highest elevations, predicted warmer conditions will result in increases in the area of adaptive seasonality.⁷⁵² However, the area of adaptive seasonality will decrease after 2040 in the 8202-9843 foot bin (2500-3000 meter bin; a bin refers to binning temperatures and area by elevation), and after 2060 for the highest elevation bin.⁷⁵³ *For additional information on long-term patterns of beetle population dynamics in relationship to climate and forest conditions, please see Chapter IV.3 (Information Gaps).*

⁷⁴⁷ Nearly verbatim from Bentz et al. (2010, p. 608)

⁷⁴⁸ Nearly verbatim from Safranyik et al. (2010, p. 425). Safranyik et al. refer the reader to Figure 5 in the cited article for this information.

⁷⁴⁹ Nearly verbatim from Safranyik et al. (2010, p. 425). Safranyik et al. refer the reader to Figure 5 in the cited article for this information.

⁷⁵⁰ Nearly verbatim from Hicke et al. (2011, p. 11). *Changing temperatures influence suitability for modeled mountain pine beetle (Dendroctonus ponderosae) outbreaks in the western United States.*

⁷⁵¹ Nearly verbatim from Hicke et al. (2011, p. 6)

⁷⁵² Nearly verbatim from Hicke et al. (2011, p. 1)

⁷⁵³ Nearly verbatim from Hicke et al. (2011, p. 6)

Table 18. Bark beetle species that have the capacity to cause landscape-scale tree mortality in the western United States and Canada within the NPLCC region.

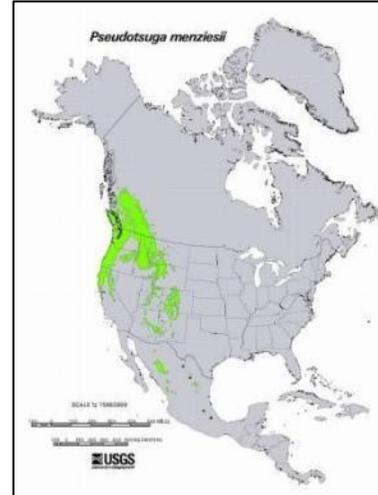
California fivespined ips (*Ips paraconfusus*)

Major host species: Knobcone pine, lodgepole pine, Coulter pine, Jeffrey pine, sugar pine, ponderosa pine, Monterey pine, Torrey pine, and others

Range: West of the crests of the Sierra Nevada and Cascade Mountains, from southern California to northern Oregon. Recently found in Washington, mostly along the Columbia River both east and west of the Cascades, and as far north as Toledo.

Sources: Bentz et al. (2010), Murray et al. (2012), Shultz & Bedard (1987)

Douglas-fir beetle (*Dendroctonus Pseudotsugae*)

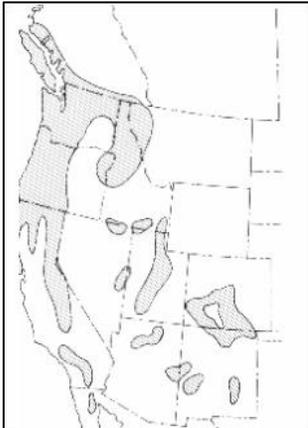


Major host species: Douglas-fir

Range: The beetle can be found almost anywhere Douglas-fir is found. Douglas-fir range shown at left.

Sources: Bentz et al. (2010), Flowers & Kanaskie (2007b), Schmitz & Gibson (1996), Image reproduced from USGS by authors of this report

Fir engraver (*Scolytus ventralis*)



Major host species: White fir, grand fir, and red fir

Range: Shown at left.

Sources: Bentz et al. (2010), Image reproduced from Ferrell (1986, Fig. 2, p. 2) by authors of this report, USFS (2011a)

Jeffrey pine beetle (*Dendroctonus jeffreyi*)

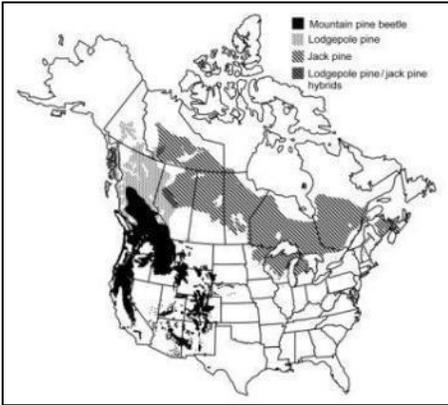


Major host species: Jeffrey pine

Range: Shown at left.

Sources: Bentz et al. (2010), Image reproduced from Smith et al. (2009, Fig. 3, p. 3) by authors of this report.

Mountain pine beetle (*Dendroctonus ponderosae*)

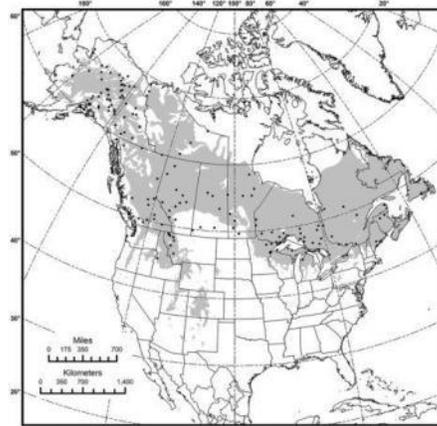


Major host species: Whitebark pine, Rocky Mountain bristlecone pine, foxtail pine, lodgepole pine, limber pine, sugar pine, western white pine, ponderosa pine, and others

Range: Northern Mexico through the Pacific Northwest to northwest Alberta. U.S. and Canada range shown in black at left.

Sources: Bentz et al. (2010), Image reproduced from Safranyik et al. (2010, Fig. 1, p. 417) by authors of this report, Sambaraju et al. (2012)

Northern spruce engraver (*Ips perturbatus*)



Major host species: Engelmann spruce, white spruce, Lutz spruce, black spruce, and Sitka spruce

Range: Black circles show beetle distribution. Range of white and Engelmann spruce is shown in grey.

Sources: Bentz et al. (2010), Image reproduced from Burnside et al. (2011, Fig. 2, p. 2) by authors of this report.

Spruce beetle (*Dendroctonus rufipennis*)



Major host species: Engelmann spruce, white spruce, and Sitka spruce

Range: Shown at left.

Sources: Bentz et al. (2010), Image reproduced from Holsten et al. (1999, Figure 2) by authors of this report.

Western balsam bark beetle (*Dryocoetes confuses*)

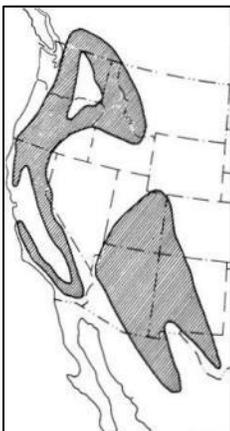


Major host species: Subalpine fir and others

Range: The beetle is found throughout the range of subalpine fir, shown at left.

Sources: Bentz et al. (2010), Image reproduced from USGS by authors of this report.,Kegley (2006), USFS (2011b)

Western pine beetle (*Dendroctonus brevicomis*)



Major host species: Coulter pine and ponderosa pine

Range: Shown at left.

Sources: Bentz et al. (2010), Image reproduced from DeMars & Roettgering (1982, Fig. 2, p. 2) by authors of this report.

Table Source: Modified from Bentz et al. (2010, Table 1, p. 603) by authors of this report.

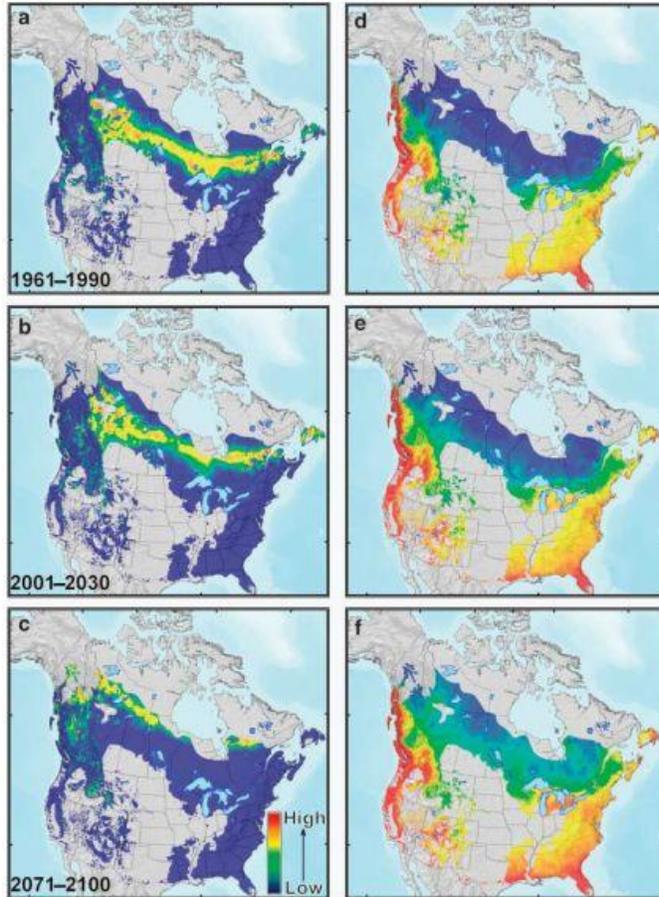


Figure 22. Predicted probability of mountain pine beetle adaptive seasonality (a-c) and cold survival (d-f) across the range of pine species in the United States and Canada during three climate normals periods: (a) and (d) 1961-1990; (b) and (e) 2001-2030; and (c) and (f) 2071-2100. Mountain pine beetle outbreak populations are currently restricted to pine forests in the western United States, central British Columbia, and west-central Alberta. Based solely on the modeled response of mountain pine beetle to temperature (2001-2030 and 2071-2100 vs. 1961-1990; CRCM v. 4.2.0 runs ADJ and ADL run under A2), results suggest that by the end of this century, probability of range expansion across Canada and into central and eastern U.S. forests will be low to moderate. *Source: Reproduced from Bentz et al. (2010, Figure 3, p. 609) by authors of this report.*

In another mountain pine beetle study, Figure 24 compares the areas designated as vulnerable for two tree species (i.e., lodgepole and jack pine; vulnerable is defined as having <50% modeled probability of species' occurrence in 1976-2006 compared to the modeled distribution in 1950-1975; see Box 5) with the areas predicted by the Safranyik et al. (2010) mountain pine beetle index to have a risk (i.e., of beetle range expansion) greater than moderate for the 2001-2030 and 2010-2040 projected climatic conditions (vs. 1961-1990; CGCM1 run under moderate BAU scenario⁷⁵⁴).⁷⁵⁵ Areas of vulnerable forest (i.e., of lodgepole and jack pine forest) that coincide with those favorable for beetle expansion are presented in Figure 23.⁷⁵⁶ Specific results include:

- **Area affected:** 15,444 square miles (mi²; 40,000 square kilometers, km²) of lodgepole pine forest are projected to be susceptible to beetle attack during the period from 2001-2030, with an increase to 17,375 mi² (45,000 km²) in the 2010-2040 period (vs. 1950-1975; CGCM3, BAU scenario).⁷⁵⁷
- **Geography affected:** For lodgepole pine, the areas of vulnerability and high mountain pine beetle climatic suitability occupy interior British Columbia and extend along the western edge of lodgepole pine's distribution, which occurs in three distinct regions (see Figure 23).⁷⁵⁸ By 2010-2040, the area suitable for the beetle is projected to increase along with an increase in vulnerable forests.⁷⁵⁹

⁷⁵⁴ Safranyik et al. (2010, p. 422)

⁷⁵⁵ Nearly verbatim from Coops et al. (2012, p. 168). *Modeling lodgepole and jack pine vulnerability to mountain pine beetle expansion into the western Canadian boreal forest.*

⁷⁵⁶ Nearly verbatim from Coops et al. (2012, p. 168)

⁷⁵⁷ Verbatim from Coops et al. (2012, p. 168)

⁷⁵⁸ Verbatim from Coops et al. (2012, p. 168)

⁷⁵⁹ Verbatim from Coops et al. (2012, p. 168)

In addition, although spruce beetle outbreak potential will be enhanced by higher temperatures throughout the century, reductions in the range of Engelmann spruce in the western United States, also as a result of climate change, could cause an overall reduction in long-term spruce beetle impacts in that region (Figure 25).⁷⁶⁰

Current understanding of both the conditions required for a bark beetle outbreak and of anticipated global changes allows Raffa et al. (2008) to hypothesize how anthropogenic activities may lead to regime shifts in which the frequency, severity, location, and extent of eruptions exceed what they can infer about historical outbreak patterns.⁷⁶¹ Potential processes and manifestations of a regime shift include:

- More frequent favorable temperatures, which enabled spruce beetle outbreaks in coastal Alaska;
- Eruptions in regions where previous likelihoods of surpassing critical thresholds were low, as with the current mountain pine beetle outbreak in central British Columbia and at high elevations throughout the Rocky Mountains;
- Geographic range expansion across existing host species, as with mountain pine beetle in British Columbia;
- Movement into evolutionarily or partially naïve hosts with geographic range expansion, as with mountain pine beetle in lodgepole–jack pine hybrids in Alberta (and ultimately jack pine across the boreal forest, and its potential as a corridor to nonadapted red pine and white pine in the Great Lakes region);
- Expansion to new host species within historic geographic ranges, as with the current high mortality to spruce by mountain pine beetle in British Columbia, which may be viewed as an extreme progression of the declining host discrimination that normally contributes to eruptions;
- Extensive tree mortality by beetle species historically were more locally eruptive, such as the pinyon ips; and,
- Enhanced likelihood of external drivers increasing synchronicity among disturbances such as drought, both reducing tree resistance against bark beetles and favoring the frequency and severity of fire.⁷⁶²

Under a climate change scenario of warmer and drier future conditions, Sturrock et al. (2011) predict that diseases caused by pathogens directly affected by climate (e.g. *Dothistroma* needle blight) will have a reduced or unchanged impact on their hosts, but an increased impact under a scenario of warmer and wetter conditions.⁷⁶³ For diseases caused by pathogens indirectly affected by climate (e.g. *Armillaria* root disease) and for decline diseases, in general, Sturrock et al. (2011) predict an increased impact on hosts under a climate-change scenario of warmer and drier future conditions and a reduced or unchanged impact under warmer and wetter future conditions.⁷⁶⁴

⁷⁶⁰ Verbatim from Bentz et al. (2010, p. 607). Bentz et al. cite Rehfeldt et al. (2006) for information on the future distribution of Engelmann spruce.

⁷⁶¹ Nearly verbatim from Raffa et al. (2008, p. 5110)

⁷⁶² Nearly verbatim from Raffa et al. (2008, p. 5110)

⁷⁶³ Nearly verbatim from Sturrock et al. (2011, p. 144)

⁷⁶⁴ Nearly verbatim from Sturrock et al. (2011, p. 144)

Specific projections for several forest pathogens in Western North America are available (Table 19):

- ***Dothistroma* needle blight:** Using slight variations of the CLIMEX (a model used to predict the effects of climate on species) parameter estimates used by Watt and others (2009), Venette found that climatic conditions that support *Dothistroma* (i.e., a fungal foliar disease of lodgepole and other pine species) are likely to persist in the western U.S. through 2080, even if *Dothistroma* is assumed to be heat-sensitive (additional information on climate model not provided).⁷⁶⁵ Increases in precipitation may be more important than increases in temperature for increasing the spread and impact of the disease.⁷⁶⁶ For example, the favorable effect of warming on *Dothistroma* blight may lessen if decreased summer rainfall accompanies the warming.⁷⁶⁷
- **Swiss needle cast:** A decrease in precipitation would likely decrease the probability of damage to Douglas-fir from *P. gaeumannii* (i.e., Swiss needle cast, a fungal foliar disease).⁷⁶⁸ Predicted warmer temperatures, along with sufficient moisture, will favor the pathogen and increase disease incidence on Douglas-fir.⁷⁶⁹
- **Sudden oak death:** Continued warming would increase areas suitable climatically for the pathogen, resulting in increased mortality if the pathogen (i.e., *P. ramorum*, which causes sudden oak death) is introduced to those areas.⁷⁷⁰ However, moisture must be sufficient for pathogen sporulation and infection.⁷⁷¹ Increased precipitation during spring is likely to be associated with increased prevalence of the pathogen in areas where it already occurs and expansion of the pathogen to new locations.⁷⁷² Venette (2009) used the CLIMEX model to quantify the potential change in distribution of habitat and in habitat quality for *P. ramorum* on the basis of climate scenarios.⁷⁷³ The model suggested that high-quality habitat in the contiguous United States currently extends along the west coast from approximately Monterey, California, to the vicinity of Puget Sound, Washington.⁷⁷⁴ On the basis of projections from the Canadian General Circulation Model-1 (CGCM1), Venette projected that the extent of high-quality habitat will decrease substantially in the Eastern United States, but will increase in Washington, Oregon, and California.⁷⁷⁵ By 2050, habitat will extend from Los Angeles, California, to the Puget Sound area in Washington.⁷⁷⁶ Inland expansion of habitat by 2080 is projected to be modest.⁷⁷⁷
- **White pine blister rust:** A warmer climate, along with drier environmental conditions, would reduce rust sporulation and infection.⁷⁷⁸ Although increases in precipitation likely increase habitat quality for the pathogen, projected increases in temperature do not.⁷⁷⁹

⁷⁶⁵ Nearly verbatim from Kliejunas (2011, p. 13). Kliejunas cites Venette (2010) for this information.

⁷⁶⁶ Verbatim from Kliejunas (2011, p. 14)

⁷⁶⁷ Nearly verbatim from Kliejunas (2011, p. 13)

⁷⁶⁸ Verbatim from Kliejunas (2011, p. 17)

⁷⁶⁹ Verbatim from Kliejunas (2011, p. 17)

⁷⁷⁰ Nearly verbatim from Kliejunas (2011, p. 24)

⁷⁷¹ Verbatim from Kliejunas (2011, p. 24)

⁷⁷² Verbatim from Kliejunas (2011, p. 23)

⁷⁷³ Verbatim from Kliejunas (2011, p. 23)

⁷⁷⁴ Verbatim from Kliejunas (2011, p. 23)

⁷⁷⁵ Verbatim from Kliejunas (2011, p. 23)

⁷⁷⁶ Verbatim from Kliejunas (2011, p. 23)

⁷⁷⁷ Verbatim from Kliejunas (2011, p. 23)

⁷⁷⁸ Verbatim from Kliejunas (2011, p. 29)

⁷⁷⁹ Verbatim from Kliejunas (2011, p. 29)

- **Cytospora canker of alder:** Warmer temperatures and drier conditions will stress the host, increasing its susceptibility to infection and to canker growth.⁷⁸⁰ Wetter conditions may reduce the host moisture stress, slowing or stopping canker growth.⁷⁸¹
- **Dwarf mistletoe:** As climate changes, the distribution of dwarf mistletoes is expected to follow the shift in distribution of their hosts.⁷⁸² Because cold temperatures limit the ranges of many dwarf mistletoes, increases in temperature likely will result in range extensions.⁷⁸³ Increases in temperature will increase dwarf mistletoe survival and host infection.⁷⁸⁴ Decreases in precipitation will likely increase host stress, increasing damage from the pathogen.⁷⁸⁵ However, extremely dry conditions may result in host mortality, resulting in a decrease in survival and infection of dwarf mistletoe.⁷⁸⁶
- **Armarillia spp. root disease:** The incidence of Armillaria root disease is likely to increase as temperatures increase and precipitation decreases, especially when hosts are stressed by moisture deficiency.⁷⁸⁷ A drier climate would, in general, stress hosts more than a wetter climate, and thus increase host susceptibility.⁷⁸⁸ Such increases not only will decrease tree growth and increase direct mortality, but may increase the incidence or severity of insect outbreaks on stressed trees.⁷⁸⁹ *Armillaria sinapina*, typically regarded as a weak pathogen of diverse hosts, is projected to cause more disease as incidence of stressed hosts increases.⁷⁹⁰

⁷⁸⁰ Verbatim from Kliejunas (2011, p. 32)

⁷⁸¹ Verbatim from Kliejunas (2011, p. 32)

⁷⁸² Verbatim from Kliejunas (2011, p. 35)

⁷⁸³ Verbatim from Kliejunas (2011, p. 35-36)

⁷⁸⁴ Verbatim from Kliejunas (2011, p. 35)

⁷⁸⁵ Verbatim from Kliejunas (2011, p. 35)

⁷⁸⁶ Verbatim from Kliejunas (2011, p. 35)

⁷⁸⁷ Verbatim from Kliejunas (2011, p. 40). Kliejunas cites Shaw & Kile (1991) and the U.S. Office of Technology Assessment (1993) for information on the the increasing incidence of *Armillaria* as temperatures increase and precipitation decreases.

⁷⁸⁸ Verbatim from Kliejunas (2011, p. 41)

⁷⁸⁹ Verbatim from Kliejunas (2011, p. 41). Kliejunas cites Battes & others (2006) for this information.

⁷⁹⁰ Verbatim from Kliejunas (2011, p. 41). Kliejunas cites Morrison & others (1985) for information on *A. sinapina* being a weak pathogen, and Klopfenstein & others (2009b) for information on projections for more disease as host stress increases.

Table 19. Future risk potential of disease damage from forest pathogens under two climate change scenarios.*

Pathogen	Typical Host(s)	Future Risk Potential**	
		Warmer-drier	Warmer-wetter
<i>Dothistroma</i> needle blight (<i>D. septosporum</i> , <i>D. pini</i>)	Pine species, especially lodgepole pine	Low	Moderate
<i>P. gaeumannii</i> , Swiss needle cast	Douglas-fir	Low	Moderate
<i>P. ramorum</i> , sudden oak death	Coast live oak, tanoak, European beech, others	Moderate	Very high
<i>C. ribicola</i> , white pine blister rust	Eastern, western, & southwestern white pine, sugar pine, whitebark pine, limber pine, foxtail pine, Rocky Mountain bristlecone pine	Moderate	Moderate
<i>C. umbrina</i> , cytospora canker of alder	Thinleaf alder, Sitka alder, green alder	High	Moderate
Dwarf mistletoe	Pines, spruces, larches, douglas-firs, firs, hemlocks, and the cypress family	High	High
<i>Armillaria</i> root disease	Many conifer species, occasionally hardwoods	Very high	High

*Climate change scenarios refer to a warmer-drier or warmer-wetter future. Models were not used in this analysis.
 **Risk potential is estimated as the likelihood of increased disease damage multiplied by the potential consequences of increased disease damage (Kliejunas 2011, p. 4).
 Source: Kliejunas (2011). Table created by authors of this report.

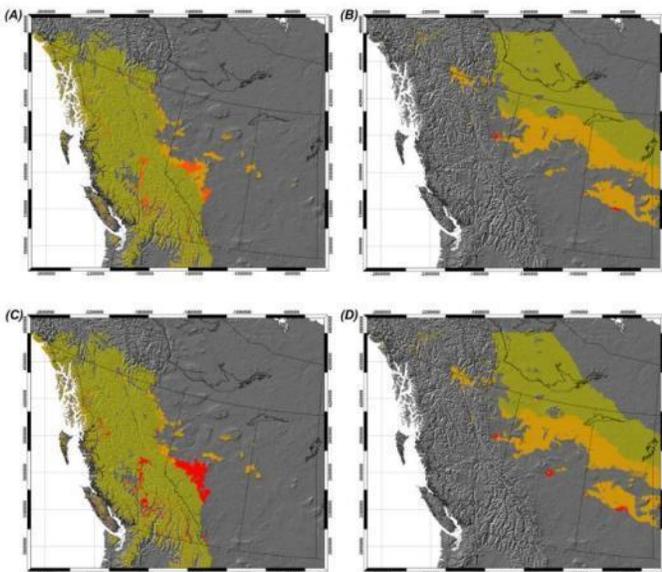


Figure 24. Tree species' ranges (green) overlaid with the vulnerable areas (orange) as well as where climatic conditions are moderate or higher for mountain pine beetle (red) for (A) lodgepole pine and (B) jack pine using 2001-2030 climate and (C-D) 2010-2040 climate. (For interpretation of the references to color in this figure legend, Coops et al. (2012) refer the reader to the web version of the cited article).
 Source: Reproduced from Coops et al. (2012, Figure 6, p. 169) by the authors of this report.

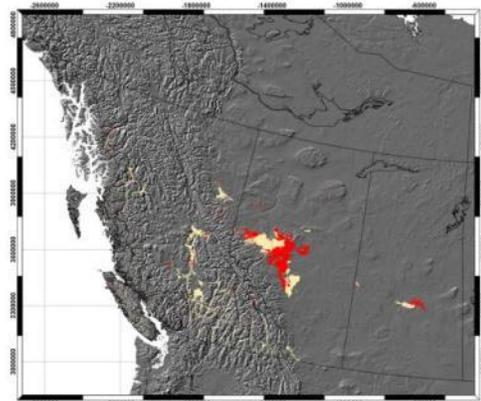


Figure 23. Areas where climatic conditions for mountain pine beetle expansion are greater than or equal to moderate and coincide with where the tree hosts (i.e., lodgepole and jack pine) are deemed vulnerable for 2001-2030 climate (tan) and 2010-2040 climate (red). (For interpretation of the references to color in this figure legend, Coops et al. (2012) refer the reader to the web version of the cited article).
 Source: Reproduced from Coops et al. (2012, Figure 7, p. 169) by the authors of this report.

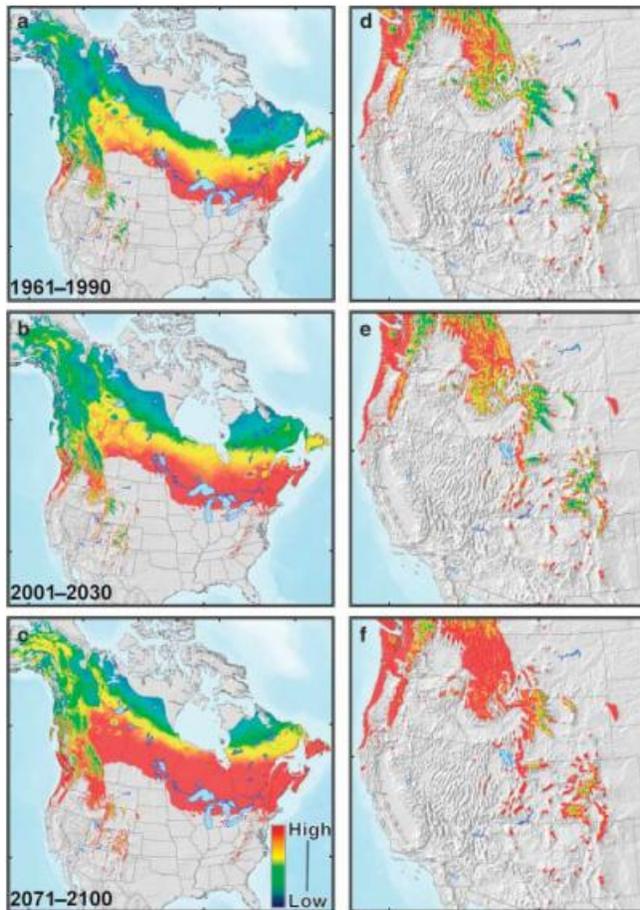


Figure 25. Predicted probability of spruce beetle offspring developing in a single year in spruce forests across the range of this insect in North America during three climate normal periods: (a) 1961-1990, (b) 2001-2030, and (c) 2071-2100, and only in the western United States in (d) 1961-1990, (e) 2001-2030, and (f) 2071-2100. Higher probability of one-year life-cycle duration translates to higher probability of population outbreak and increased levels of spruce-beetle-caused tree mortality. Model results (2001-2030 and 2071-2100 vs. 1961-1990; CRCM v. 4.2.0 runs ADJ and ADL run under A2) are shown only for areas estimated to be 20th-century spruce habitat (from Little 1971).

Source: Reproduced from Bentz et al. (2010, Figure 1, p. 607) by authors of this report.

Southcentral and Southeast Alaska

Higher winter temperatures will facilitate movement of Sitka aphids toward the mainland and expand the area and frequency of attack.⁷⁹¹ Lodgepole pines in Haines and Skagway may soon be infected (i.e., by mountain pine beetle), and the closely related shore pine, common in the bogs of southeastern Alaska, could be impacted if the pine beetles switch hosts.⁷⁹² Mountain pine beetles have moved up in elevation at nearly twice the rate of their host forests and are expected to shift to even higher latitudes and elevations.⁷⁹³ Models predict that western balsam bark beetle outbreaks will occur nearly 100 feet (~30 meters) higher for every 1.8°F (1.0 °C) increase in temperature.⁷⁹⁴

Following the sequential and large outbreaks of the 1850s, 1870–1880s, and 1910s on the Kenai Peninsula, spruce beetle outbreaks did not occur widely again until the 1970s.⁷⁹⁵ This suggests that it may take decades before spruce forests on the Kenai Peninsula mature following the 1990s outbreak and again become susceptible to another large spruce beetle outbreak.⁷⁹⁶ However, if the recent warming trend continues, endemic levels of spruce beetles will likely be high enough to perennially thin the forests as soon as the trees reach susceptible size.⁷⁹⁷

Southwest Yukon Territory

If this warming trend persists (i.e., of summer temperatures), spruce beetle outbreaks may continue to increase in their frequency and

⁷⁹¹ Verbatim from Kelly et al. (2007, p. 54)

⁷⁹² Nearly verbatim from Kelly et al. (2007, p. 54-55)

⁷⁹³ Verbatim from Kelly et al. (2007, p. 55). Kelly et al. cite Williams & Liebhold (2002) for this information.

⁷⁹⁴ Nearly verbatim from Kelly et al. (2007, p. 54). Kelly et al. cite Williams & Liebhold (2002) for this information.

⁷⁹⁵ Nearly verbatim from Berg et al. (2006, p. 219)

⁷⁹⁶ Verbatim from Berg et al. (2006, p. 219)

⁷⁹⁷ Verbatim from Berg et al. (2006, p. 219)

intensity and expand into areas and to tree species that have been uncommonly infested.⁷⁹⁸

Western British Columbia

The resilience and condition of the forests will be tested by climate-induced spread of insects, diseases, and invasive species.⁷⁹⁹ The range and impacts of insect pests and diseases, especially of forest trees, is expected to expand.⁸⁰⁰ There are at least twelve native insect species that have the potential for significant detrimental impact on B.C. forests.⁸⁰¹ These include western spruce budworm and spruce bark beetle.⁸⁰² In addition, Douglas-fir bark beetle and western balsam bark beetle are also high priority.⁸⁰³

Non-native pests are also expected to expand their range in the province.⁸⁰⁴ Insects such as the Asian gypsy moth, the Asian long-horned beetle, and the European wood wasp have the potential to spread in southern B.C., causing more damage as the climate warms.⁸⁰⁵ The same is true of leaf and root diseases, such as sudden oak death and needle blights, which are likely to become more widespread in a warmer and wetter climate.⁸⁰⁶

In a study of the spatial outbreak patterns of mountain pine beetle, Sambaraju et al.'s (2012) results imply that temperature effects on the tree-killing behavior of mountain pine beetle will be especially manifested through winter weather patterns.⁸⁰⁷ These include cold snaps, which may cause a 69–87% decrease in the odds of finding beetle killed-trees in a given area, and large, sudden drops in daily winter temperatures (results acquired under a combination of four simulated climate change and two climatic variability scenarios using adapted terms from a spatial-temporal logistic regression model and the peak year of the current outbreak, 2005, as a case study).⁸⁰⁸ Sambaraju et al.'s (2012) results also reveal that forested regions at high elevation and latitudes further north of the current range of the mountain pine beetle in British Columbia could become outbreak-prone due to climate change.⁸⁰⁹ Small shifts in temperature resulted in occurrences of new areas of outbreaks first at higher elevations (1.8 °F and 3.6 °F; 1 °C and 2 °C) and then at northern latitudes (7.2 °F; 4 °C) (Figure 26).⁸¹⁰ Specifically:

- Increasing mean temperatures caused increases in the net numbers of higher risk cells.⁸¹¹ The percentage of reduced risk cells occurring at elevations ≤ 4921 feet (≤ 1500 meters, m) was

⁷⁹⁸ Nearly verbatim from Berg et al. (2006, p. 230). Berg et al. cite Juday et al. (2005) for this information.

⁷⁹⁹ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 32)

⁸⁰⁰ Verbatim from B.C. Ministry of Environment (MoE) (2007, p. 160)

⁸⁰¹ Verbatim from Murdock et al. (2013, p. 76)

⁸⁰² Verbatim from Murdock et al. (2013, p. 76)

⁸⁰³ Verbatim from Murdock et al. (2013, p. 76)

⁸⁰⁴ Verbatim from B.C. Ministry of Environment (2007, p. 161)

⁸⁰⁵ Verbatim from B.C. Ministry of Environment (2007, p. 161). B.C. MoE cites Hunt et al. (2006) for this information.

⁸⁰⁶ Nearly verbatim from B.C. Ministry of Environment (2007, p. 161). B.C. MoE cites Brasier (2005) for this information.

⁸⁰⁷ Nearly verbatim from Sambaraju et al. (2012, p. 217). *Climate change could alter the distribution of mountain pine beetle outbreaks in western Canada.*

⁸⁰⁸ Verbatim from Sambaraju et al. (2012, p. 217)

⁸⁰⁹ Nearly verbatim from Sambaraju et al. (2012, p. 220)

⁸¹⁰ Nearly verbatim from Sambaraju et al. (2012, p. 220)

⁸¹¹ Verbatim from Sambaraju et al. (2012, p. 217). Sambaraju et al. refer the reader to Figures 5a and 5b in the cited article for this information.

higher under a 7.2 °F (4 °C) scenario, when compared to a 1.8 °F (1 °C) or a 3.6 °F (2 °C) scenario.⁸¹²

- Conversely, the percentage of cells with increased outbreak risk at elevations > 4921 feet (> 1500 m) was higher for 1.8 °F (1 °C) mean temperature increase scenario compared to a 3.6 °F (2 °C) or a 7.2 °F (4 °C) scenario.⁸¹³

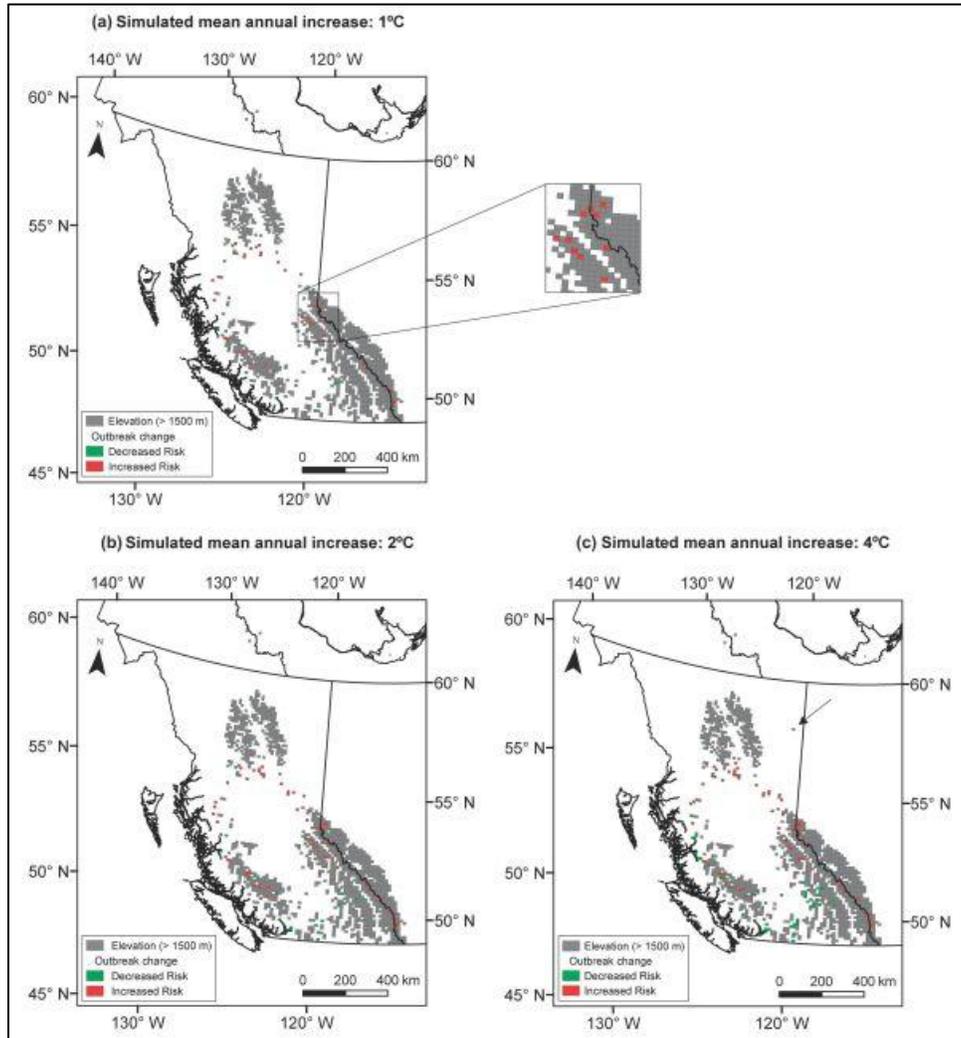


Figure 26. Elevational and latitudinal changes in median outbreak probabilities for mountain pine beetle under four simulated climate change scenarios at a variability of 1 °C. Cells colored differently under (a) 1 °C, (b) 2 °C, and (c) 4 °C mean temperature increases indicate areas where median probability for that particular cell increased or decreased to the next higher (red cells) or lower (green cells) risk class, respectively, compared to a 0 °C temperature increase scenario. Arrow in (c) points to a grid cell (in red) at $-120.8^{\circ}\text{W}/58.0^{\circ}\text{N}$ that showed a 15% increase in outbreak risk under a 4 °C mean temperature increase.

Source: *Reproduced from Sambaraju et al. (2012, Figure 4, p. 220) by authors of this report.*

⁸¹² Nearly verbatim from Sambaraju et al. (2012, p. 217). Sambaraju et al. refer the reader to Figure 5a in the cited article for this information.

⁸¹³ Nearly verbatim from Sambaraju et al. (2012, p. 217). Sambaraju et al. refer the reader to Figure 5b in the cited article for this information.

The potential influence of climate on pest outbreak risk was also modeled using an approach that maps out the future projected locations of the range of present-day climate associated with presence of the species of interest (2020s, 2050s, & 2080s vs. 1961-1990 run with CGCM3, A2 run 5 and HadGEM1, A1B run 1).⁸¹⁴ Results are available for western spruce budworm and spruce bark beetle:

- **Western spruce budworm:** The warm/wet scenario (i.e., CGCM3 A2 run 5) shows increasing western spruce budworm outbreak risk in central and northwestern B.C. and decreases from high to medium risk in many interior southern valleys.⁸¹⁵ The hot/dry scenario (i.e., HadGEM1 A1B run 1) indicates a smaller area of increasing western spruce budworm risks than the warm/wet scenario.⁸¹⁶ A considerable portion of B.C. has no historical analogue climate (in B.C.) by the 2080s.⁸¹⁷
- **Spruce bark beetle (Figure 27):** In the warm/wet scenario (i.e., CGCM3 A2 run 5), small areas of decreased spruce bark beetle risk in central B.C. and increased risk in northwestern B.C.

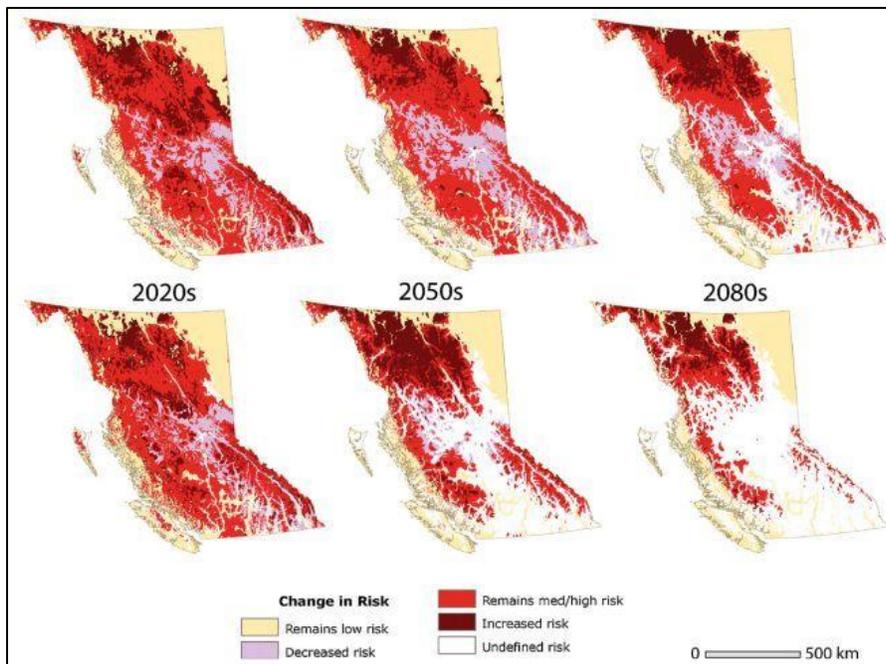


Figure 27. Projected spruce bark beetle outbreak risk: top row: warm/wet projection (CGCM3 A2 run 5), bottom row: hot/dry projection (HadGEM A1B run 1) for 2020s (left), 2050s (middle), and 2080s (right).

Source: Reproduced from Murdock et al. (2013, Figure 5, p. 84) by authors of this report.

during the 2020s and 2050s give way to a considerable area of undefined risk by the 2080s in central valleys as climatic conditions change sufficiently to have no analogue within the historically observed range of spruce bark beetle outbreaks in B.C.⁸¹⁸ In the hot/dry scenario (i.e., HadGEM1 A1B run 1), risk of spruce bark beetle outbreaks shows small increases and a shift to undefined, no historically observed analogue climates at an even quicker pace and

⁸¹⁴ Verbatim from Murdock et al. (2013, p. 78). *Pest outbreak distribution and forest management impacts in a changing climate in British Columbia.*

⁸¹⁵ Nearly verbatim from Murdock et al. (2013, p. 82). Murdock et al. refer the reader to Figure 4, top panel, in the cited article for this information.

⁸¹⁶ Nearly verbatim from Murdock et al. (2013, p. 82)

⁸¹⁷ Verbatim from Murdock et al. (2013, p. 82). Murdock et al. refer the reader to Figure 4, bottom panel, in the cited article for this information.

⁸¹⁸ Nearly verbatim from Murdock et al. (2013, p. 82). Murdock et al. refer the reader to Figure 5, top panel, in the cited article for this information.

bigger scale than western spruce budworm.⁸¹⁹

Pacific Northwest

In the Pacific Northwest, where the mean annual temperature currently is below the optimum (77 °F; 25 °C) for *Armillaria* (i.e., a root disease) growth, increases in temperature are likely to result in increased prevalence and rate of spread of root disease.⁸²⁰ Forecasts of future climate trends for the Pacific Northwest also suggest a probable expansion of the area affected by Swiss needle cast beyond the western Coast Range (i.e., of Washington, Oregon, and California) as winter temperatures and spring precipitation continue to increase, resulting in greater disease pressure on Douglas-fir stands further inland.⁸²¹

Two implications derived from climate models are that, as average temperatures increase, there will be a subsequent increase in the geographic range of the fly (*Drosophila suzukii*) and the number of generations per year.⁸²²

Western Washington

Due to climatic stress on host trees, mountain pine beetle outbreaks may increase in frequency and levels of tree mortality.⁸²³ Mountain pine beetles will reach higher elevations due to an increase in favorable temperature conditions for the beetles in these areas as the region warms.⁸²⁴ Conversely, this species may become less of a threat at middle and lower elevations as the region warms, due to less favorable temperature conditions.⁸²⁵ Other insect species may emerge in areas that are no longer suitable for the mountain pine beetle.⁸²⁶

Western Oregon

Rising temperatures will cause adaptive seasonality (for mountain pine beetle) to decrease in low elevation forests, which in some model simulations results in a distinct overall projected decrease in the area attacked by mountain pine beetle.⁸²⁷ High elevation forests, however, are likely to experience an increase in adaptive seasonality and hence of mountain pine beetle attacks in the coming decades, increasing the pressure on high elevation pine species such as whitebark pine.⁸²⁸ Later in the 21st century, adaptive seasonality is expected to also decline in high elevation forests, if warming continues as projected.⁸²⁹

⁸¹⁹ Nearly verbatim from Murdock et al. (2013, p. 82). Murdock et al. refer the reader to Figure 5, bottom panel, in the cited article for this information.

⁸²⁰ Nearly verbatim from Kliejunas (2011, p. 41). Kliejunas cites IPCC (2001) for this information.

⁸²¹ Nearly verbatim from Stone et al. (2008, p. 175)

⁸²² Nearly verbatim from Hixon et al. (2010, p. 273). Hixon et al. refer to Damus (2009) for information on climate models projecting the potential geographic range and population dynamics of *D. suzukii*.

⁸²³ Verbatim from Littell et al. (2010, p. 154)

⁸²⁴ Verbatim from Littell et al. (2010, p. 154)

⁸²⁵ Verbatim from Littell et al. (2010, p. 154)

⁸²⁶ Verbatim from Littell et al. (2010, p. 154)

⁸²⁷ Nearly verbatim from Shafer et al. (2010, p. 184). Shafer et al. cite Williams & Liebhold (2002), Hicke et al. (2006), and Littell et al. (2009b) for this information.

⁸²⁸ Verbatim from Shafer et al. (2010, p. 184)

⁸²⁹ Verbatim from Shafer et al. (2010, p. 184). Shafer et al. cite Hicke et al. (2006) for this information.

In the Oregon Coast Range, Swiss needle cast (caused by the fungus *Phaeocryptopus gaeumannii*), a foliage disease of Douglas-fir, was found to be highly sensitive to winter temperature with an average predicted increase of 9.2% in infected needles per 1.8 °F (1 °C) increase in temperature.⁸³⁰ Under future climate change scenarios, Swiss needle cast impacts are likely to increase along the coast from northern Oregon to British Columbia, New Zealand, and elsewhere where June-July precipitation is much higher than the *P. gaeumannii*-limiting threshold of 3.94 inches (110 mm), and decrease along the coast from California to southern Oregon and elsewhere where summer precipitation is at or below the threshold.⁸³¹

More extreme weather conditions projected for the future could facilitate sudden oak death in Oregon.⁸³²

Northwest California

Despite the rapid spread of sudden oak death and its severe impacts on oak populations, relatively little is known about how composition of the vegetation should change in affected forests.⁸³³ Unsurprisingly, these changes include declines in oak basal area.⁸³⁴ Where oaks co-occur with California bay laurels, bays are expected to increase.⁸³⁵ In other areas, oaks co-occur with redwoods, so redwoods are expected to increase.⁸³⁶

Information Gaps

Research should identify herbivores (i.e., herbivorous insects) and pathogens that are likely to be key agents of forest disturbance in the next fifty years.⁸³⁷ Integrated continental surveys are needed to determine the sensitivity of different types of pests and diseases to environmental change and the potential for increased outbreaks of insect herbivores and pathogens at the margins of their existing ranges.⁸³⁸ To understand the interactions between forest disturbance and management, how the genetic diversity of host plants will determine the future epidemiology of forest pathogens needs further exploration.⁸³⁹ Critical evaluations of known patterns of species change and yield following past climate changes are needed, along with models of succession that incorporate disturbance processes.⁸⁴⁰

An analysis of the dynamics of bark beetle eruptions suggests that future research needs to comprehensively address six elements:

- Identifying thresholds and key variables that trigger changes in the relative strengths of various feedbacks;

⁸³⁰ Verbatim from Shafer et al. (2010, p. 185). Shafer et al. cite Manter et al. (2005) for this information.

⁸³¹ Verbatim from Lee et al. (2013, p. 689). Lee et al. cite Hood (1982) for information on the 3.94 inch (100 mm) threshold.

⁸³² Verbatim from Shafer et al. (2010, p. 185)

⁸³³ Nearly verbatim from Sandel et al. (2012, p. 24)

⁸³⁴ Verbatim from Sandel et al. (2012, p. 24)

⁸³⁵ Verbatim from Sandel et al. (2012, p. 24-25). Sandel et al. cite Moritz et al. (2008) and Brown & Allen-Diaz (2009) for this information.

⁸³⁶ Verbatim from Sandel et al. (2012, p. 25). Sandel et al. cite Moritz et al. (2008) for this information.

⁸³⁷ Nearly verbatim from Dale et al. (2008, p. 732)

⁸³⁸ Verbatim from Dale et al. (2008, p. 732)

⁸³⁹ Nearly verbatim from Dale et al. (2008, p. 732)

⁸⁴⁰ Verbatim from Dale et al. (2008, p. 732)

- Understanding underlying mechanisms and factors promoting the concurrence of multiple causalities;
- Using historical patterns to analyze existing drivers and to predict future system states;
- Characterizing thresholds beyond which changes are most likely irreversible;
- Estimating potential endogenous responses arising from herbivores, hosts, symbionts, and natural enemies, by studying their phenotypic plasticities, intraspecific variation, and likely evolutionary changes; and,
- Integrating our understanding of multiple factors into a framework for predicting future eruptions.⁸⁴¹

Raffa et al. (2008) further propose that applying evolutionary models within a framework of threshold theory can improve the ability to anticipate regime shifts.⁸⁴²

Approaches that are currently available for predicting climate influences on forest disease provide a solid foundation for forest planning.⁸⁴³ However, further refinements will improve accuracy and utility of these approaches.⁸⁴⁴ Of critical need is more information on the current distribution of accurately identified pathogens.⁸⁴⁵ Prediction models can be further improved by including additional information, such as more precise climate data, other geographic information (e.g., slope, aspect, topography), and other environmental data (e.g., soil type, habitat type).⁸⁴⁶ Once climatic influences on host and pathogen distribution are better understood, information is frequently needed to determine the climatic conditions, seasonal/annual weather, and microclimates that are suitable for the development of disease.⁸⁴⁷ Continued surveys and research can provide necessary information for refining predictions of climate influence on diverse forest diseases.⁸⁴⁸ An integration of diverse tools and data is necessary to improve predictions for climatic influence on forest disease.⁸⁴⁹

Because land-cover patterns can affect atmospheric circulation and cloud formation, changes in forest structure in the aftermath of fire, wind or ice storms, hurricanes, landslides, drought, and pest outbreaks may alter weather or climate conditions.⁸⁵⁰ This interaction needs to be studied and better understood.⁸⁵¹

⁸⁴¹ Nearly verbatim from Raffa et al. (2008, p. 513)

⁸⁴² Nearly verbatim from Raffa et al. (2008, p. 513)

⁸⁴³ Verbatim from Klopfenstein et al. (2009, p. 8)

⁸⁴⁴ Verbatim from Klopfenstein et al. (2009, p. 8)

⁸⁴⁵ Verbatim from Klopfenstein et al. (2009, p. 8)

⁸⁴⁶ Verbatim from Klopfenstein et al. (2009, p. 8)

⁸⁴⁷ Verbatim from Klopfenstein et al. (2009, p. 8)

⁸⁴⁸ Nearly verbatim from Klopfenstein et al. (2009, p. 8)

⁸⁴⁹ Verbatim from Klopfenstein et al. (2009, p. 9)

⁸⁵⁰ Verbatim from Dale et al. (2008, p. 732). Dale et al. cite Segal et al. (1988) for information on the effects of atmospheric circulation and cloud formation on land-cover patterns.

⁸⁵¹ Verbatim from Dale et al. (2008, p. 732)

Discussion: Direct & Indirect Effects of Climate Change on Bark Beetles

The time required to complete a generation varies among bark beetle genera, species within a genus, populations within a species, and individuals within a population.⁸⁵² Some species, such as the western pine beetle, and the piñon ips, produce more than one generation per year.⁸⁵³ Others, including the spruce beetle and mountain pine beetle, require one, two, or even three years to produce a single generation, depending on the temperature profile at a particular locale within their large geographic ranges.⁸⁵⁴

Direct effects of climate change on bark beetle population dynamics will occur predominantly through the influence of temperature on life-history strategies that (a) maintain adaptive developmental timing leading to synchronized population emergence and life-cycle timing, and (b) facilitate cold tolerance and avoidance of low-temperature-induced mortality:⁸⁵⁵

- **Developmental timing:** Although little is known about specific temperature-dependent developmental processes of many bark beetle species, research suggests that at least two predominant strategies, diapause and direct temperature control, have evolved to maintain appropriate life-cycle timing.⁸⁵⁶ Each strategy may be differentially affected by climate change:⁸⁵⁷
 - **Diapause** is a dynamic, endocrine-mediated and environmentally driven dormancy that occurs at a specific life stage.⁸⁵⁸ The effect of climate change on these species (i.e., fir engraver, spruce beetle, Douglas fir beetle, eastern larch beetle, and pine engraver, all indigenous to western North America) will depend on the life stage in which diapause occurs.⁸⁵⁹ For example, high summer temperatures prevent facultative (i.e., optional) prepupal diapauses of the spruce beetle, resulting in beetles that complete their life cycles in a single year, compared with two years when the diapause is invoked, potentially leading to exponential population growth.⁸⁶⁰ Conversely, an obligatory adult diapause initiated by low temperatures, as in spruce beetles and Douglas-fir beetles, could be disrupted by higher minimum temperatures.⁸⁶¹
 - **Direct temperature control:** Temperature pattern throughout a life cycle is critical to appropriate seasonality, and predicted rises in temperature could affect both developmental thresholds and rates in multiple life stages.⁸⁶² Additional fitness parameters potentially affected include higher adult longevity and prolonged adult emergence and flight.⁸⁶³
- **Cold tolerance:** Cold tolerance for these insects (i.e., those listed previously) is therefore greatest during the winter months, and lowest during periods of glycerol synthesis and catabolism (i.e., the

⁸⁵² Verbatim from Bentz et al. (2010, p. 603)

⁸⁵³ Verbatim from Bentz et al. (2010, p. 603)

⁸⁵⁴ Verbatim from Bentz et al. (2010, p. 603)

⁸⁵⁵ Verbatim from Bentz et al. (2010, p. 603)

⁸⁵⁶ Verbatim from Bentz et al. (2010, p. 604)

⁸⁵⁷ Verbatim from Bentz et al. (2010, p. 604)

⁸⁵⁸ Verbatim from Bentz et al. (2010, p. 604)

⁸⁵⁹ Nearly verbatim from Bentz et al. (2010, p. 604)

⁸⁶⁰ Nearly verbatim from Bentz et al. (2010, p. 604). Bentz et al. cite Hansen & Bentz (2003) for this information.

⁸⁶¹ Verbatim from Bentz et al. (2010, p. 604)

⁸⁶² Verbatim from Bentz et al. (2010, p. 604)

⁸⁶³ Verbatim from Bentz et al. (2010, p. 604)

breakdown of complex molecules into simpler molecules) in autumn and spring, respectively, suggesting a direct correlation between increasing minimum temperatures associated with climate change and a reduction in cold-induced beetle mortality.⁸⁶⁴

Bark beetle population success will be influenced indirectly by the effects of climate on community associates, host-tree vigor, and host abundance:⁸⁶⁵

- **Community associates:** Because benefits to the mountain pine beetle are not the same for each fungal species, shifts in temperature and precipitation associated with climate change could indirectly affect mountain pine beetle population dynamics through direct effects on fungal symbionts (e.g., *Grosmannia clavigera* and *Ophiostoma montium*).⁸⁶⁶ Other community associates and trophic interactions, including avian predators and insect parasitoids and predators, undoubtedly will also be influenced by abiotic factors associated with climate change.⁸⁶⁷
- **Host-tree physiology:** The indirect negative effects of enhanced CO₂ on bark beetle growth and survival are, at least in part, outweighed by other climate-change-induced effects on host trees, including reduced defenses.⁸⁶⁸ Although the mechanisms connecting drought stress to bark beetle outbreaks are not well understood in western North America ecosystems, it is clear that effects will vary regionally and by bark beetle-host species complex because of differences in critical feedbacks driving beetle population dynamics, as well as physiological differences among tree species.⁸⁶⁹ However, drought-induced alterations to tree defensive capacity ultimately reduce the threshold number of beetles necessary for a successful mass attack, thereby relaxing the constraints on critical thresholds that must be surpassed for bark beetle outbreaks to occur.⁸⁷⁰
- **Host-tree distribution:** Bark beetles are inextricably linked to their host trees, and will undoubtedly influence the formation of new western North American coniferous forests as predicted broad-scale tree migrations occur this century.⁸⁷¹ For example, although spruce beetle outbreak potential will be enhanced by higher temperatures throughout the century, reductions in the range of Engelmann spruce in the western United States, also as a result of climate change, could cause an overall reduction in long-term spruce beetle impacts in that region (Figure 25).⁸⁷² *Please see Chapter VI, Sections 2 through 4 for additional information on changes in tree distribution.*

⁸⁶⁴ Nearly verbatim from Bentz et al. (2010, p. 605)

⁸⁶⁵ Verbatim from Bentz et al. (2010, p. 605)

⁸⁶⁶ Nearly verbatim from Bentz et al. (2010, p. 605)

⁸⁶⁷ Verbatim from Bentz et al. (2010, p. 605)

⁸⁶⁸ Verbatim from Bentz et al. (2010, p. 605)

⁸⁶⁹ Verbatim from Bentz et al. (2010, p. 605)

⁸⁷⁰ Verbatim from Bentz et al. (2010, p. 605)

⁸⁷¹ Verbatim from Bentz et al. (2010, p. 611)

⁸⁷² Verbatim from Bentz et al. (2010, p. 607). Bentz et al. cite Rehfeldt et al. (2006) for information on the future distribution of Engelmann spruce.

5. Altered patterns of landslides, ice & wind storms, and avalanches

Both slow and rapid movements of soil, rock, and associated vegetation are triggered directly by climate factors and indirectly by climate-influenced processes (e.g., stream-bank erosion) and by non-climate factors such as earthquakes and volcanism.⁸⁷³ Triggering climatic events include snowmelt and intense rainfall, including that associated with hurricanes.⁸⁷⁴ Landslide frequency and extent are influenced by precipitation amount and intensity; snow accumulation, melt rate, and distribution; and roads and other land uses.⁸⁷⁵ The potential for a site to slide is influenced by slope steepness, properties of soil and rock, and hydrologic factors.⁸⁷⁶ Vegetation influences the likelihood of sliding through the soil-stabilizing effects of root systems and the effects of vegetation structure and composition on hydrology.⁸⁷⁷

Ice storms are caused by rain falling through sub-freezing air masses close to the ground; those air masses supercool the raindrops, which freeze on impact.⁸⁷⁸ Ice accumulation can vary dramatically with topography, elevation, aspect, and areal extent of the region where conditions favor glaze formation.⁸⁷⁹ Depending on forest stand composition, amount and extent of ice accumulation, and stand history, damage can range from light and patchy to total breakage of all mature stems.⁸⁸⁰ Effects on forest stands include shifts in overstory composition in favor of more resistant tree species, loss of stand growth until leaf area is restored, and damage to stem form.⁸⁸¹ Damaged stems are then more susceptible to the impacts of insects and disease.⁸⁸² Recently thinned stands can be highly vulnerable because crowns have spread into the new space but branch strength has not developed.⁸⁸³ Several tree species can survive within areas frequented by ice storms.⁸⁸⁴ Even though the weather conditions producing ice storms are well understood, it is not known how changes in climate will affect the frequency, intensity, location, or areal extent of ice storms.⁸⁸⁵

Key Terms in this Section

Denudation: *long-term wearing away of the earth's surface by weathering, erosion, and mass wasting*

Ice Storm: *an occurrence of freezing precipitation resulting in either structural damage or at least 0.25 inch (~0.64 cm) of ice accumulation*

Landslide: *the downward and outward movement of slope-forming materials including rock, soil, and/or artificial till, which may fall, topple, slide, spread, or flow during a slide event*

Sources: Joyce et al. (2001); National Weather Service (2009); USGS (2004)

⁸⁷³ Verbatim from Dale et al. (2008, p. 729)

⁸⁷⁴ Verbatim from Dale et al. (2008, p. 729)

⁸⁷⁵ Verbatim from Dale et al. (2008, p. 729)

⁸⁷⁶ Verbatim from Dale et al. (2008, p. 729)

⁸⁷⁷ Verbatim from Dale et al. (2008, p. 729)

⁸⁷⁸ Verbatim from Dale et al. (2008, p. 728)

⁸⁷⁹ Verbatim from Joyce et al. (2001, p. 502)

⁸⁸⁰ Verbatim from Joyce et al. (2001, p. 502). Joyce et al. cite Irland (1998) for this information.

⁸⁸¹ Verbatim from Dale et al. (2008, p. 729). Dale et al. cite Irland (2000) for this information.

⁸⁸² Verbatim from Dale et al. (2008, p. 729). Dale et al. cite Smith (2000) for this information.

⁸⁸³ Verbatim from Dale et al. (2008, p. 729)

⁸⁸⁴ Verbatim from Dale et al. (2008, p. 729)

⁸⁸⁵ Verbatim from Joyce et al. (2001, p. 502)

Locations of big blowdown patches may occur more often in areas highly susceptible to maritime windstorm activity.⁸⁸⁶ Windstorms can cause heavy mortality, produce canopy disruption, reduce tree density and size structure, and change local environmental conditions.⁸⁸⁷ Consequently, the disturbance may trigger advance regeneration, seed germination, and accelerated seedling growth.⁸⁸⁸ These effects can change successional patterns, gap dynamics, and other ecosystem-level processes.⁸⁸⁹ The relationship between wind strength and severity of disturbance is not constant across different forests and species; although shallow-rooted species and thinned stands may be especially vulnerable to wind events, multiple factors influence tree response to high winds.⁸⁹⁰

Understanding the causes of landslides, ice and wind storms, and avalanches

Climate change effects on landslides reflect changes in the delivery of water to soils through altered precipitation and snow hydrology.⁸⁹¹ Because climate change is expected to vary geographically and with elevation, landslide responses will vary with similar complexity.⁸⁹² Landslides are expected to be less frequent in areas where GCM scenarios predict reduced overall precipitation or reduced snowmelt because of warming trends, limiting snow accumulation.⁸⁹³ The most socially and ecologically significant landslides are triggered by intense precipitation.⁸⁹⁴ Thus climate change that increases storminess, and hence soil saturation, will increase landslide occurrence.⁸⁹⁵ Landslides remove soil and vegetation from steep slopes and damage forests on gentler slopes where landslide deposits come to rest.⁸⁹⁶ Landslides in forest landscapes can also damage aquatic resources and threaten public safety.⁸⁹⁷ Yet it is important to recognize that landslides are natural components of terrestrial and aquatic ecosystems.⁸⁹⁸

Though weather conditions producing ice storms are well understood, it is unclear how changes in climate will affect their frequency, intensity, regional location, or areal extent.⁸⁹⁹ However, atmospheric warming will most likely shift the locations of prevailing ice storms northward.⁹⁰⁰

Small-scale wind events are products of mesoscale climatic circumstances and thus may be affected by climate changes, although the type and amount of alteration in windstorm characteristics cannot be predicted because these smaller-scale events are below the resolution of today's GCMs.⁹⁰¹

⁸⁸⁶ Nearly verbatim from Harcombe et al. (2004, p. 80)

⁸⁸⁷ Verbatim from Dale et al. (2008, p. 728)

⁸⁸⁸ Verbatim from Dale et al. (2008, p. 728). Dale et al. cite Peterson & Pickett (1995) for this information.

⁸⁸⁹ Verbatim from Dale et al. (2008, p. 728)

⁸⁹⁰ Verbatim from Dale et al. (2008, p. 728)

⁸⁹¹ Verbatim from Dale et al. (2008, p. 729). Dale et al. cite Buma & Dehn (1998) for this information.

⁸⁹² Verbatim from Dale et al. (2008, p. 729)

⁸⁹³ Verbatim from Dale et al. (2008, p. 729). Dale et al. cite Buma & Dehn (1998) and Dehn (forthcoming) for this information.

⁸⁹⁴ Verbatim from Dale et al. (2008, p. 729)

⁸⁹⁵ Verbatim from Dale et al. (2008, p. 729)

⁸⁹⁶ Verbatim from Dale et al. (2008, p. 729)

⁸⁹⁷ Verbatim from Dale et al. (2008, p. 729)

⁸⁹⁸ Verbatim from Dale et al. (2008, p. 729)

⁸⁹⁹ Verbatim from Dale et al. (2008, p. 729)

⁹⁰⁰ Verbatim from Dale et al. (2008, p. 729)

⁹⁰¹ Verbatim from Dale et al. (2008, p. 728)

Observed Trends

Western North America

Landslide processes exhibit very strong geographic patterns.⁹⁰² Pacific coastal mountains are particularly prone to sliding because of weak rocks, steep slopes, and high precipitation from frontal storms in these tectonically active areas.⁹⁰³

Southcentral and Southeast Alaska

Wind-generated disturbance is the principal disturbance affecting the dynamics of coastal temperate rainforests of southeast Alaska.⁹⁰⁴ A disturbance continuum driving forest processes exists over southeast Alaska, spanning landscapes ranging from those buffeted by recurrent large-scale wind disturbance to those protected from catastrophic wind where autogenic, gap-phase processes operate.⁹⁰⁵ Studies indicate that blowdowns in southeast Alaska range widely in size (1 to 1,000 acres) and disproportionately occur as smaller patches (typically less than 50 acres, or approximately 20 hectares) as depicted by size distributions on Chichagof Island.⁹⁰⁶

For example, windthrow has affected >20% of the forests on Kuiu Island.⁹⁰⁷ Many large catastrophic wind storms have affected Kuiu Island in the last 400 years.⁹⁰⁸ These catastrophic storms affect some portion of Kuiu Island every 100 years, well within the lifespan of dominant forest species.⁹⁰⁹

Forest susceptibility to blowdown may be highest during wet, stormy periods, when gusty conditions are prevalent and soil stability is reduced by saturation.⁹¹⁰ In southeast Alaska, productive western hemlock and western hemlock-Sitka spruce forests are the least windfirm.⁹¹¹ These productive forests are particularly susceptible to blowdown because of large, top-heavy canopies and tall tree heights.⁹¹² In contrast, cedar-dominated forests (western redcedar and Alaska-cedar) growing on wet sites are most

⁹⁰² Verbatim from Joyce et al. (2001, p. 499)

⁹⁰³ Verbatim from Joyce et al. (2001, p. 499)

⁹⁰⁴ Verbatim from Kramer et al. (2001, p. 2750). *Abiotic controls on long-term windthrow disturbance and temperate rain forest dynamics in southeast Alaska*. Kramer et al. cite Veblen & Alaback (1996) for this information.

⁹⁰⁵ Verbatim from Nowacki & Kramer (1998, p. 15). *The effects of wind disturbance on temperate rain forest structure and dynamics of southeast Alaska*. Nowacki & Kramer cite Kramer (1997) for information on the disturbance continuum. Nowacki & Kramer refer the reader to Figure 6 in the cited report for information on landscapes buffeted by recurrent large-scale wind disturbance and to Figure 7 in the cited report for information on landscapes protected from catastrophic wind.

⁹⁰⁶ Nearly verbatim from Nowacki & Kramer (1998, p. 8). Nowacki & Kramer refer the reader to Table 2 in the cited report for information on the size of blowdowns and to Figure 4 for the size distributions on Chichagof Island.

⁹⁰⁷ Nearly verbatim from Kramer et al. (2001, p. 2760)

⁹⁰⁸ Verbatim from Kramer et al. (2001, p. 2760)

⁹⁰⁹ Verbatim from Kramer et al. (2001, p. 2760)

⁹¹⁰ Verbatim from Nowacki & Kramer (1998, p. 9). Nowacki & Kramer cite Foster (1988) and Harris (1989) for this information.

⁹¹¹ Verbatim from Nowacki & Kramer (1998, p. 9)

⁹¹² Verbatim from Nowacki & Kramer (1998, p. 9). Nowacki & Kramer cite Foster (1988), Foster & Boose (1992), and Lohmander & Helles (1987) for this information.

windfirm.⁹¹³ The windfirmness of wetland forests, where canopies are rather open and trees are short and tapered, has been recognized elsewhere.⁹¹⁴

Harris (1989) working on Prince of Wales and associated Islands and Kramer (1997) on Kuiu Island found blowdowns to be concentrated on certain topographic locations.⁹¹⁵

- **South-facing slopes:** Areas prone to blowdown often were south-facing slopes directly exposed to prevailing winds.⁹¹⁶
- **East- and west-facing slopes:** Blowdown patches frequently extend onto east- and west-facing slopes where winds tend to accelerate as they round mountain flanks.⁹¹⁷
- **Areas impeding airflow:** In general, trees growing on topographic features impeding airflow are quite susceptible to blowdown.⁹¹⁸ In particular, high-intensity blowdowns frequently occur on exposed areas, often on hilltops and along ridge noses.⁹¹⁹

Harris (1989) concluded that areas least prone to large-scale blowdown occur within wind shadows along north- and northwest-facing slopes or in the lee (northward, in this case) of high mountains that deflect wind.⁹²⁰

Western British Columbia

Guthrie and Brown (2008) estimated the variability in landslide rates on Vancouver Island over the Holocene and suggested that increases in landslide rates doubled during shifts from drier to wetter periods (Table 20).⁹²¹ Based on a mean landslide size, it is estimated that debris slides and flows eroded an average of 0.2 ft/ft² (0.7 m/m²) across Vancouver Island during the last 10,000 years.⁹²²

In more recent history, large rock slides appear to have responded to warming trends of the past few decades by destabilizing from snow and ice melt and increasing freeze thaw processes.⁹²³ Larger soil slides are more common during long periods (years to decades) of above-average precipitation, likely from soil saturation.⁹²⁴ Prolonged periods of increased precipitation or temperature have increased the vulnerability of slopes to failure in these areas, whereas large or intense storms are often the trigger.⁹²⁵ Shifts in landslide rates attributed to changes in climatic regimes are thought to be of a similar order of

⁹¹³ Verbatim from Nowacki & Kramer (1998, p. 9)

⁹¹⁴ Verbatim from Nowacki & Kramer (1998, p. 9). Nowacki & Kramer cite Foster & Boose (1992) for this information.

⁹¹⁵ Verbatim from Nowacki & Kramer (1998, p. 8). Nowacki & Kramer refer the reader to Table 2 in the cited report for this information.

⁹¹⁶ Verbatim from Nowacki & Kramer (1998, p. 8)

⁹¹⁷ Verbatim from Nowacki & Kramer (1998, p. 8). Nowacki & Kramer cite Harris (1989) for this information.

⁹¹⁸ Verbatim from Nowacki & Kramer (1998, p. 8). Nowacki & Kramer cite Harris (1989) for this information.

⁹¹⁹ Verbatim from Nowacki & Kramer (1998, p. 8). Nowacki & Kramer cite Harris (1989) for this information.

⁹²⁰ Verbatim from Nowacki & Kramer (1998, p. 8)

⁹²¹ Nearly verbatim from Pike et al. (2010, p. 704)

⁹²² Nearly verbatim from Guthrie & Brown (2008, p. 32)

⁹²³ Nearly verbatim from Pike et al. (2010, p. 704). Pike et al. cite Egginton (2005) and Geertsema et al. (2007) for this information.

⁹²⁴ Verbatim from Pike et al. (2010, p. 704). Pike et al. cite Egginton (2005) and Geertsema et al. (2007) for this information.

⁹²⁵ Verbatim from Pike et al. (2010, p. 704)

magnitude or smaller when compared to landslide responses to forest management in the 20th century.⁹²⁶ Septer and Schwab (1995) summarized extreme rainstorm and landslide events in northwest British Columbia over the 1881–1991 period.⁹²⁷ Since 1900, the following changes in annual landslide frequency and size have been observed for northern British Columbia and Vancouver Island (Table 20):

- **Landslide frequency:** In northern British Columbia, shallow slides and debris flows have occurred during infrequent large storms.⁹²⁸ On Vancouver Island by 50 years ago, the island wide total landslide rate was an estimated 303 landslides per year, with the rate increasing to modern levels of about 402 landslides per year or 0.024 landslides/(yr*mi²) (0.015 landslides (yr*km²)).⁹²⁹ The figures for Vancouver Island reveal that the average landslide rate (below the alpine zone) in the last 50 years is close to twice the highest average landslide rate in the last 10,000 years.⁹³⁰
- **Landslide size:** In an analysis of landslide characteristics on the west coast of Vancouver Island, results indicate average denudation rates of 5,122 cubic feet per year per square mile (ft³ yr⁻¹ mi⁻²; 56 cubic meters per year per square kilometer), and higher natural rates of failure than analogous regions in coastal British Columbia.⁹³¹ In contrast, the landslide rates are substantially less than those from forested watersheds.⁹³²

Information on disturbance from erosion in glacial areas, snow avalanches, and wind storms is also available:

- **Erosion in glacial areas:** Though the relationship to climate variability and change in the region is not completely understood, in recently exposed glacial forefield areas, sediment production rates have increased from both primary erosion of exposed slopes and remobilization of stored channel deposits.⁹³³
- **Snow avalanches:** Mountainous terrain and heavy snowfall throughout northwest British Columbia leave many slopes susceptible to snow avalanches.⁹³⁴ Climatic conditions such as heavy snowfall, followed by warm weather and rainfall, trigger large catastrophic snow avalanches.⁹³⁵

⁹²⁶ Verbatim from Pike et al. (2010, p. 704). Pike et al. cite Campbell & Church (2003) and Guthrie & Brown (2008) for this information.

⁹²⁷ Verbatim from Pike et al. (2010, p. 704). *Note from authors of this report: Septer & Schwab produced a chronological catalogue of all events from 1891-1991 (see Septer & Schwab, pp. 7-173). Summary of events by disturbance type was not provided for landslides or snow avalanches, but was provided for major storm and flood categories (see Septer & Schwab, Appendix 7, pp. 190-191) and by river, creek, and lake (see Septer & Schwab, Appendix 6, pp. 183-189).*

⁹²⁸ Verbatim from Pike et al. (2010, p. 704)

⁹²⁹ Nearly verbatim from Guthrie & Brown (2008, p. 31)

⁹³⁰ Nearly verbatim from Guthrie & Brown (2008, p. 31)

⁹³¹ Nearly verbatim from Guthrie & Evans (2004, p. 1321)

⁹³² Verbatim from Guthrie & Evans (2004, p. 1321)

⁹³³ Verbatim from Pike et al. (2010, p. 704). Pike et al. cite Orwin & Smart (2004) and Schiefer & Gilbert (2007) for this information.

⁹³⁴ Nearly verbatim from Septer & Schwab (1995, p. 5).

⁹³⁵ Verbatim from Septer & Schwab (1995, p. 5).

- **Wind storms:** Large-scale, catastrophic forest blowdown has, historically, been relatively rare in B.C., with return intervals of 300 to 500 plus years.⁹³⁶ Windstorms are more frequent on the coast than in the interior, and the tree mortality due to wind events also varies regionally, ranging from up to 80 percent in affected stands of wet coastal forests to less than 15 percent in interior Ponderosa pine forests.⁹³⁷ Disturbance regimes of wet coastal forests are currently dominated by fine-scale gap dynamics, with frequent events that affect only small numbers of trees.⁹³⁸

Table 20. Rate and size of landslides over time on Vancouver Island, BC.
Table created by authors of this report.

Landslide Rate/Size			Time Period	Sources
Annual # of landslides	Annual # of landslides per square mile (per km ²)	Annual cubic feet per square mile (cubic meters per km ²)		
121	0.007 (0.005)	N/A	8-10 millenia before present (BP)	Guthrie & Brown (2008)
221	0.01 (0.008)	N/A	4-6 millenia BP	
191	0.01 (0.007)	N/A	0-3 millenia BP	
191	0.01 (0.007)	N/A	7 millenia BP	
303	0.018 (0.011)	N/A	50-99 years BP	
402	0.024 (0.015)	N/A	0-49 years BP	
N/A	N/A	5122 (56)		Guthrie & Evans (2004)

Western Washington

Information needed.

Western Oregon

In the Neskowin Crest Research Area, located along the central coast of Oregon in a Sitka spruce-western hemlock zone, a large blowdown patch was the dominant wind-related feature, covering approximately 15% of the study area.⁹³⁹ Aerial photographs of the area between 1953 and 1993, maps, visual inspection of the area, and modeling provide information on patterns in forest structure and their causes over time, including distribution, composition, and the timing and rate of wind-related disturbance:

⁹³⁶ Verbatim from Pojar (2010, p. 22). Pojar cites Lertzman et al. (1996) and Wong et al. (2003) for this information.

⁹³⁷ Verbatim from Pojar (2010, p. 22). Pojar cites Franklin et al. (1987) for this information.

⁹³⁸ Verbatim from Pojar (2010, p. 22). Pojar cites Lertzman et al. (1996) and Daniels & Gray (2006) for this information.

⁹³⁹ Nearly verbatim from Harcombe et al. (2004, p. 78)

- **Distribution:** Most of the large blowdown patch (67%) observed between 1953 and 1993 fell within the area predicted to have maximum blowdown probability by the WINDSTORM model, which was concentrated on south faces of secondary ridges west of the main north-south ridge which bisects the study area.⁹⁴⁰ The approximately 67% of the patch within the predicted highest probability of blowdown covered 28% of the entire predicted area.⁹⁴¹ In other words, of the area most susceptible to blowdown according to the WINDSTORM model, 28% was characterized as a blowdown patch, and this comprised the majority of the observed blowdown patch (67%).
- **Composition:** Visual inspection of recent photographs of the area showed that the large blowdown patch was quite heterogeneous by 1993.⁹⁴² It was mostly made up of patches of small stems of varying sizes, which represented post-windthrow regeneration varying in date of origin, with remnant patches or individuals of the pre-blowdown second growth, and possibly even a very small number of old trees (>145 years).⁹⁴³ Increment cores taken in this patch showed breast-height ages that dated recruitment to the 1940s or even earlier, possibly as a result of small canopy gaps.⁹⁴⁴
- **Timing and rate of wind-related disturbance:** The blowdown patch first appeared at a stand age of about 100 years when it was approaching maximum stand height of ~164 feet (50 m) and was in the late stem-exclusion stage.⁹⁴⁵ The rate of growth of the blowdown patch increased over time.⁹⁴⁶ The blowdown patch also appeared over time by repeated windthrow.⁹⁴⁷ Several patches in the susceptible area appeared at different times and seemed to grow at different rates, not always along the north edge.⁹⁴⁸ Furthermore, there were small gaps in other parts of the study area that did not grow rapidly.⁹⁴⁹ For these reasons, the researchers suggest that, in this case, susceptibility to blowdown is more a consequence of location than of presence of edges, though the edges undoubtedly influenced the rate and local pattern of blowdown.⁹⁵⁰

Northwest California

Information needed.

⁹⁴⁰ Nearly verbatim from Harcombe et al. (2004, p. 76). Harcombe et al. refer the reader to Figure 5 in their article. Further, they state WINDSTORM is “a maritime windstorm susceptibility model developed in southeast Alaska” and that “maritime windstorm activity in coastal Oregon is similar in many ways to that of southeast Alaska. Both are driven by temperature instability between two large semi permanent air masses, the east Pacific High and the Aleutian Low, the result being the development of occasional large extra-tropical cyclonic windstorms” (p. 74).

⁹⁴¹ Nearly verbatim from Harcombe et al. (2004, p. 78)

⁹⁴² Nearly verbatim from Harcombe et al. (2004, p. 75)

⁹⁴³ Verbatim from Harcombe et al. (2004, p. 75)

⁹⁴⁴ Verbatim from Harcombe et al. (2004, p. 75). Harcombe et al. cite Greene et al. (1992) for information on recruitment.

⁹⁴⁵ Nearly verbatim from Harcombe et al. (2004, p. 78)

⁹⁴⁶ Verbatim from Harcombe et al. (2004, p. 79)

⁹⁴⁷ Nearly verbatim from Harcombe et al. (2004, p. 79)

⁹⁴⁸ Nearly verbatim from Harcombe et al. (2004, p. 79)

⁹⁴⁹ Verbatim from Harcombe et al. (2004, p. 79)

⁹⁵⁰ Nearly verbatim from Harcombe et al. (2004, p. 79)

Future Projections

Western North America

Increases in extremes of precipitation intensity, rain-on-snow during mid-winter melt, and transport of moisture in atmospheric rivers are all likely mechanisms for increasing sufficient pore water pressure or hillslope, thus increasing the risk of landslides, erosion, and gully formation for individual storms.⁹⁵¹

Direct effects of some climatic changes on sediment yield and mass wasting may be overshadowed by longer term, indirect effects through vegetation response.⁹⁵² Although decreasing precipitation in some places might suggest reduced risks of erosion or landslides, this change may have indirect effects on mortality and thinning of vegetation and fire risk; these effects could have much greater consequences for erosion and landslides, through reductions in root reinforcement of soil and greater exposure of soil to precipitation effect and runoff.⁹⁵³

Southcentral and Southeast Alaska

Glaciers melting and the associated rebound of the land (isostatic rebound) may produce a myriad of impacts including increased frequency of earthquakes.⁹⁵⁴ Based on evidence from former melting events, it is predicted that isostatic rebound may decrease fault stability margin and increase thrust faulting events such as earthquakes and aftershocks.⁹⁵⁵ These changes in glacial ice loading can affect seismicity and regional tectonics and contribute to changes in hydrologic patterns, erosion, sedimentation, and changes to shorelines.⁹⁵⁶ Glacier Bay National Park contains some of the fastest measured rates of uplift in the world.⁹⁵⁷

Western British Columbia

Future changes in geomorphic processes will be driven primarily through changes in precipitation and temperature regimes.⁹⁵⁸ Recent trends are expected to continue.⁹⁵⁹ Information on landslides, disturbance related to glacial recession, snow avalanches, and wind storms is available:

- **Landslides:** Landslide response to climate change in coastal British Columbia will largely follow the projected peak flow response in rain-dominated and hybrid streams.⁹⁶⁰

⁹⁵¹ Verbatim from Ryan et al. (2012, p. 35). Ryan et al. cite Easterling et al. (2000a) and Karl & Knight (1998) for information on extremes of precipitation intensity, Hamlet & Lettenmaier (2007), Lettenmaier & Gan (1990) and Wenger et al. (2011) for information on rain-on-snow events, and Dettinger (2011) and Ralph et al. (2006) for information on atmospheric rivers.

⁹⁵² Verbatim from Ryan et al. (2012, p. 35). Ryan et al. cite Bull (1991), Collins & Bras (2008), Goode et al. (2011), Istanbuloglu & Bras (2006), Kirkby & Cox (1995), Langbein & Schumm (1958), and Tucker & Bras (1998) for this information.

⁹⁵³ Verbatim from Ryan et al. (2012, p. 35)

⁹⁵⁴ Verbatim from Jezierski et al. (2010, p. 12)

⁹⁵⁵ Verbatim from Jezierski et al. (2010, p. 12). Jezierski et al. cite Sauber & Molnia (2004) for this information.

⁹⁵⁶ Verbatim from Jezierski et al. (2010, p. 12). Jezierski et al. cite Motyka et al. (2007) for this information.

⁹⁵⁷ Verbatim from Jezierski et al. (2010, p. 12)

⁹⁵⁸ Verbatim from Pike et al. (2010, p. 726)

⁹⁵⁹ Nearly verbatim from Pike et al. (2011, p. 726)

⁹⁶⁰ Nearly verbatim from Pike et al. (2011, p. 727)

- **Disturbance related to glacial recession:** Ongoing glacial recession will continue to promote periglacial processes in recently deglaciated areas.⁹⁶¹ This includes increased geomorphic hazards such as outburst flooding, rock debuitressing, slope failures on over-steepened slopes, changes to sediment production, and suspended sediment fluxes.⁹⁶²
- **Snow avalanches:** Increased storm intensities during the winter may lead to increased avalanche activity.⁹⁶³ Countering this process will be warmer-than-present winter temperatures which, in general, will result in lower temperature gradients within snowpacks, and therefore increased slope stability.⁹⁶⁴ In some areas, the winter snow line may migrate high enough so that lower-elevation areas do not exceed threshold snow depths sufficient to initiate avalanches.⁹⁶⁵ This upward migration of the snow line, and encroachment of vegetation into avalanche paths, may lead to a corresponding upslope shift in avalanche runout zones.⁹⁶⁶ This process is most likely to be pronounced in coastal British Columbia, and particularly at or near the current tree line.⁹⁶⁷
- **Wind storms:** Climate warming will increase the intensity of atmospheric convective processes and thus the frequency and intensity of windstorms.⁹⁶⁸ Northern Vancouver Island, areas of the central and northern B.C. mainland coast, and parts of Haida Gwaii are most susceptible to big blows.⁹⁶⁹ Frequency of catastrophic blowdown could increase to approximate wind disturbance regimes in parts of southeast Alaska.⁹⁷⁰ Large windthrow events there can have return intervals of less than 300 years, can dominate the disturbance regime, and are a major determinant of forest structure.⁹⁷¹ Windstorms are often accompanied by increased precipitation, a combination that can destabilize soils and increase the frequency of landslides.⁹⁷²

Pacific Northwest

In the Pacific Northwest, much of the small, rapid landsliding occurs during rain-on-snow events in a broad elevation band where snow accumulates and melts several times in an average year.⁹⁷³ A simple warming without change in overall annual precipitation would be expected to result in reduced sliding by limiting the amount of snow (and its associated snowmelt) available to augment the rainfall reaching the soil.⁹⁷⁴

Western Washington

Information needed.

⁹⁶¹ Verbatim from Pike et al. (2010, p. 727)

⁹⁶² Verbatim from Pike et al. (2010, p. 727). Pike et al. cite Moore et al. (2009) for this information.

⁹⁶³ Verbatim from Pike et al. (2010, p. 727)

⁹⁶⁴ Verbatim from Pike et al. (2010, p. 727)

⁹⁶⁵ Verbatim from Pike et al. (2010, p. 727)

⁹⁶⁶ Verbatim from Pike et al. (2010, p. 727)

⁹⁶⁷ Verbatim from Pike et al. (2010, p. 727)

⁹⁶⁸ Verbatim from Pojar (2010, p. 22)

⁹⁶⁹ Verbatim from Pojar (2010, p. 22)

⁹⁷⁰ Verbatim from Pojar (2010, p. 22)

⁹⁷¹ Verbatim from Pojar (2010, p. 22). Pojar cites Nowacki & Kramer (1998) for this information.

⁹⁷² Verbatim from Pojar (2010, p. 22). Pojar cites Schwab (1998) for this information.

⁹⁷³ Verbatim from Dale et al. (2008, p. 729)

⁹⁷⁴ Verbatim from Dale et al. (2008, p. 729)

Western Oregon

Information needed.

Northwest California

Information needed.

Information Gaps

In southcentral and southeast Alaska, information is needed on observed trends and future projections for landslides, ice storms, and avalanches. Information on future wind storm projections is also needed. In western British Columbia, information is needed on observed trends and future projections for on ice storms. In western Washington, information is needed on observed trends for landslides, ice and wind storms, and avalanches. Information is also needed on future projections for avalanches, ice storms, and wind storms. In western Oregon, information is needed on observed trends for landslides, ice storms, and avalanches. Information is also needed on future projections for avalanches, ice storms, and wind storms. In northwest California, information is needed on observed trends for landslides, ice and wind storms, and avalanches. Information is also needed on future projections for landslides, ice and wind storms, and avalanches.

Specific research needs that should improve the understanding of how climate change affects landslide, avalanche, storm, and wind-related forest disturbances include:

- **Understanding climatological conditions that initiate disturbance:** Although there is a significant understanding of erosion and landslide processes, the ability to predict or manage high-risk areas is limited by uncertainty in predicting changes in precipitation amount, frequency, and location of extreme rainfall events.⁹⁷⁵ Therefore, a key information need is improved projections of changes in precipitation amount, and spatial and temporal distribution of extreme events.⁹⁷⁶ For long-term climate change projections, improved resolution in climate models is needed so that regional patterns can be projected.⁹⁷⁷ Better monitoring is needed to improve the characterization of ice accumulation in relation to storm characteristics and associated weather, especially the delineation of areas by amount of ice accumulation.⁹⁷⁸ Once the relationship between climate and disturbances has been quantified, more-accurate predictions of disturbances can be developed to minimize their impact.⁹⁷⁹
- **Understanding the effects of disturbances on microclimate:** Because land-cover patterns can affect atmospheric circulation and cloud formation, changes in forest structure in the aftermath of fire, wind or ice storms, hurricanes, landslides, drought, and pest outbreaks may alter weather or climate conditions.⁹⁸⁰ This interaction needs to be studied and better understood.⁹⁸¹ Another

⁹⁷⁵ Nearly verbatim from Ryan et al. (2012, p. 35)

⁹⁷⁶ Nearly verbatim from Ryan et al. (2012, p. 36)

⁹⁷⁷ Verbatim from Dale et al. (2008, p. 731)

⁹⁷⁸ Verbatim from Dale et al. (2008, p. 732)

⁹⁷⁹ Verbatim from Dale et al. (2008, p. 732)

⁹⁸⁰ Verbatim from Dale et al. (2008, p. 732). Dale et al. cite Segal et al. (1988) for information on the effects of atmospheric circulation and cloud formation on land-cover patterns.

⁹⁸¹ Verbatim from Dale et al. (2008, p. 732)

important interaction needing additional research is the effect of drought on adjustments of forest canopy leaf area and belowground allocation of carbon to hydrologic flowpaths and root reinforcement of soil.⁹⁸² Further, a key information need is improved understanding of the effects of tree mortality and changing species composition on soil stability.⁹⁸³

- **Quantifying impacts of disturbances on forests:** There is a paucity of basic information on the frequency, intensity, and spatial extent of some disturbances and their impacts on forests.⁹⁸⁴ This problem is especially severe for landslides, ice storms, and small wind events.⁹⁸⁵ For example, reconstructive studies should be done to determine the long-term influence of successive ice storms on forests.⁹⁸⁶ Such analysis also allows exploration of interactions between disturbances and delayed responses.⁹⁸⁷
- **Interactions between forest disturbances and management:** Some management practices have been developed to cope with the physical disturbances of droughts, hurricanes, and wind events.⁹⁸⁸ However, additional research could expand options for management.⁹⁸⁹

⁹⁸² Nearly verbatim from Ryan et al. (2012, p. 35)

⁹⁸³ Nearly verbatim from Ryan et al. (2012, p. 36)

⁹⁸⁴ Verbatim from Dale et al. (2008, p. 732)

⁹⁸⁵ Verbatim from Dale et al. (2008, p. 732)

⁹⁸⁶ Verbatim from Dale et al. (2008, p. 732)

⁹⁸⁷ Verbatim from Dale et al. (2008, p. 732)

⁹⁸⁸ Verbatim from Dale et al. (2008, p. 732). Dale et al. cite Savill (1993) for this information.

⁹⁸⁹ Verbatim from Dale et al. (2008, p. 732)

Discussion: Disturbance Interactions

Overall, interactions among ecological disturbance and stressors likely cause larger effects on ecosystems than any individual disturbance or stressor.⁹⁹⁰ Disturbance interactions may rapidly bring ecosystems to thresholds.⁹⁹¹ A notable threshold response to multiple stressors is the reproductive cycle of mountain pine beetle, whose outbreaks have killed mature trees across millions of hectares of pine in western North America.⁹⁹² Adaptive seasonality, combined with drought-caused and age-related vulnerability of the host species, has brought an abrupt increase in mortality of lodgepole pine across the West.⁹⁹³ *Chapter IV.4 provides additional information on this topic.* Thus, climate-induced increases in wildfire occurrence and insect outbreaks across large landscapes will potentially cause rapid changes in the structure and function of forest ecosystems (Table 21).⁹⁹⁴

In the context of the effects of climate change on ecosystems, sensitivity to disturbance interactions is extended to environmental drivers not usually identified as disturbances.⁹⁹⁵ For example, extreme temperatures, drought, and air pollution put forest ecosystems under stress, which may increase their vulnerability to “true” disturbances such as fire, insect outbreaks, and pathogens.⁹⁹⁶ Key information needs include additional empirical data on stress interactions in a wide range of forest ecosystems and a transition from qualitative to quantitative analyses and models of how stressors and disturbances interact to affect forest ecosystems.⁹⁹⁷

Table 21. Characteristics of continuous versus abrupt thresholds.		
Cause/Response	Predictable	Unexpected
Continuous	A tipping point is known from previous experience or modeling, and trends in the controlling factor(s) are measured. Example: gradual loss of habitat toward a point at which metapopulation models predict extirpation.	Controlling factor is changing gradually, but ecosystem effects or interactions of response variables are too complex to predict. Example: increases in an invasive nonnative species with unknown effects on biotic interactions of natives or grazing pressure.
Abrupt	Pulses in a controlling factor precipitate an inevitable response. Example: large disturbance or invasion (perhaps unprecedented) changes structure and composition of a landscape with a loss of 90 percent of potential nesting trees for northern spotted owls.	Pulses in a controlling factor (or very likely multiple controls) are expected to produce surprises. Example: changing fire frequency and mountain pine beetle outbreaks may have sudden consequences for vegetation, animals, or landscape pattern.

Source: Reproduced from Ryan et al. (2012, Table 2.4, p. 37) by authors of this report.

⁹⁹⁰ Nearly verbatim from Ryan et al. (2012, p. 42)

⁹⁹¹ Verbatim from Ryan et al. (2012, p. 36). Ryan et al. cite Groffman et al. (2006) for this information.

⁹⁹² Verbatim from Ryan et al. (2012, p. 38). Ryan et al. cite Logan & Powell (2001) for information on the reproductive cycle of mountain pine beetle.

⁹⁹³ Nearly verbatim from Ryan et al. (2012, p. 38). Ryan et al. cite Hicke et al. (2006) for this information.

⁹⁹⁴ Verbatim from Ryan et al. (2012, p. 42)

⁹⁹⁵ Verbatim from Ryan et al. (2012, p. 38)

⁹⁹⁶ Verbatim from Ryan et al. (2012, p. 38)

⁹⁹⁷ Nearly verbatim from Ryan et al. (2012, p. 42)

V. Implications for Ecological Processes and Ecosystem Services

Biodiversity, ecosystems, and ecosystem services are already under stress from a variety of sources (for example, land use and land cover change, extraction of natural resources, biological disturbances, and pollution); in most cases, these interacting stressors have had a greater effect on the overall health of these systems than climate change.⁹⁹⁸ Forests, for example, provide critical refuges for terrestrial biodiversity, are a central component of the earth's biogeochemical systems, and are a source of ecosystem services essential for human wellbeing.⁹⁹⁹ In turn, the terrestrial biosphere affects the climate through a variety of biophysical, biogeochemical, and biogeographical pathways that act over a range of spatial and temporal scales.¹⁰⁰⁰ Forest processes regulate the flux and apportionment of carbon, water, nutrients, and other constituents within a forest ecosystem.¹⁰⁰¹ These processes operate at spatial scales from leaf to landscape and control responses of forest ecosystems, such as forest productivity, to environmental factors such as temperature, precipitation, and atmospheric concentrations of CO₂.¹⁰⁰² Interactions between processes can amplify or mute the overall effects of changes in complex forest ecosystems.¹⁰⁰³ The predominance of negative and positive feedbacks within and between processes will determine the stability or instability of the system.¹⁰⁰⁴

Climate change effects are projected to be an increasingly important source of stress in the future.¹⁰⁰⁵ Ecosystems that are already being affected by other stressors are likely to have faster and more acute reactions to climate change.¹⁰⁰⁶ Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations, the following implications of climate change for terrestrial ecosystems in the NPLCC region have been identified:

1. Altered nutrient cycling and productivity
2. Altered soil attributes

The following structure will be used to present information on the implications of climate change for the NPLCC region's terrestrial ecosystems:

- **Observed Trends** – observed changes for southcentral and southeast Alaska, western British Columbia, Pacific Northwest, and northwest California. For context, summary information on observed changes globally or for western North America is also provided.

⁹⁹⁸ Verbatim from Staudt et al. (2012, p. 5-1). *Impacts of climate change on already stressed biodiversity, ecosystems, and ecosystem services.*

⁹⁹⁹ Verbatim from Sturrock et al. (2011, p. 133). *Climate change and forest diseases.* Sturrock et al. cite Shvidenko et al. (2005) for this information.

¹⁰⁰⁰ Nearly verbatim from Arora & Boer (2005, p. 39). *A parameterization of leaf phenology for the terrestrial ecosystem component of climate models.*

¹⁰⁰¹ Verbatim from Joyce et al. (2001, p. 494)

¹⁰⁰² Verbatim from Joyce et al. (2001, p. 494)

¹⁰⁰³ Verbatim from Ryan et al. (2012, p. 36)

¹⁰⁰⁴ Verbatim from Ryan et al. (2012, p. 36)

¹⁰⁰⁵ Nearly verbatim from Staudt et al. (2012, p. 5-1)

¹⁰⁰⁶ Verbatim from Staudt et al. (2012, p. 5-1)

- **Future Projections** – projected direction and/or magnitude of change for southcentral and southeast Alaska, western British Columbia, Pacific Northwest, and northwest California. For context, summary information on future projections globally or for western North America is also provided.
- **Information Gaps** – information and research needs identified by literature searches, as well as our summary of the sections missing information in this chapter.

1. Altered nutrient cycling & productivity

Carbon storage in forest ecosystems results from the balance between growth of wood, foliage, and roots and their death or shedding and subsequent decomposition.¹⁰⁰⁷ Disturbance is the largest factor changing the balance between production and decomposition, but chronic changes in temperature, precipitation, CO₂, and nitrogen deposition over large areas can also alter the U.S. forest carbon balance.¹⁰⁰⁸

Carbon dioxide enrichment of the atmosphere will likely have direct and indirect effects on ecosystems processes and species distributions.¹⁰⁰⁹ At the ecosystem scale, introduced species as well as outbreaks of native insects and diseases can alter natural cycles and disturbance regimes, such as nutrient cycles, and fire frequency and intensity.¹⁰¹⁰ Climate change-induced perturbations in forest distribution, growth rates, and risk of wildfire, invasive species, and disease are impacting the rates of carbon sequestration and expectations for length of storage.¹⁰¹¹

Several factors could contribute to increased ecosystem productivity.¹⁰¹² If moisture is adequate, plants grow faster at warmer temperatures and with elevated levels of atmospheric CO₂ – but only up to a point.¹⁰¹³ For example, tree species have temperature optima above which growth rates level off or decline.¹⁰¹⁴ Available nitrogen can become a limiting factor in a CO₂-enriched environment.¹⁰¹⁵ Because plants exposed to relatively high levels of CO₂ can partially close their stomata, thus reducing water loss and lengthening their growing season, longer warmer summers with more CO₂ could

Key Terms in this Section

C₃ plants: *plants producing a three-carbon compound during photosynthesis such as trees*

C₄ plants: *plants producing a four-carbon compound during photosynthesis such as grasses*

Carbon cycle: *the movement of carbon through the environment; ecosystems store carbon primarily as above- and below-ground wood and biomass, necromass (litter, woody debris), and organic carbon in the soil; ecosystems release carbon primarily through respiration, decay, and burning*

Net ecosystem production: *net gain or loss of carbon from an ecosystem; equal to the net primary production minus the carbon lost through heterotrophic respiration (i.e., conversion of organic matter to CO₂ by organisms other than plants)*

Net primary productivity: *the increase in plant biomass or carbon in a given area; equal to gross primary production minus carbon lost through autotrophic respiration (i.e., respiration by photosynthetic organisms, e.g. plants)*

Nitrogen cycle: *the natural movement of nitrogen through the environment, including the atmosphere, plants, animals, and microorganisms that live in soil and water*

Sources: U.S. EPA (2013); IPCC (2001)

¹⁰⁰⁷ Verbatim from Ryan et al. (2012, p. 43)

¹⁰⁰⁸ Verbatim from Ryan et al. (2012, p. 43)

¹⁰⁰⁹ Verbatim from Hixon et al. (2010, p. 326)

¹⁰¹⁰ Verbatim from Joyce et al. (2001, p. 498). Joyce et al. cites Mack and D'Antonio (1998) for this information.

¹⁰¹¹ Verbatim from Kareiva et al. (2012, p. 4-11). *Impacts of climate change on ecosystem services.*

¹⁰¹² Verbatim from Pojar (2010, p. 23)

¹⁰¹³ Verbatim from Pojar (2010, p. 23). Pojar cites Levitt (1980) for information on plant growth with adequate moisture and elevated temperature and CO₂ conditions.

¹⁰¹⁴ Verbatim from Pojar (2010, p. 23). Pojar cites Smith & Hinckley (1995), Woodward (1987), D'Arrigo et al. (2004), and Lloyd & Bunn (2007) for this information.

¹⁰¹⁵ Verbatim from Pojar (2010, p. 23). Pojar cites Oren et al. (2001) and Rich et al. (2006) for this information.

also result in more growth.¹⁰¹⁶ Gains in aggregate yield of tree biomass could, however, be offset by nutrient limitations, maladaptation to changing environmental conditions, and losses due to other factors related to climate change, including increased fire, insect and disease outbreaks, severe weather events, thaw-freeze damage, and increased moisture stress in some areas.¹⁰¹⁷

In addition, photosynthesis increases with increasing atmospheric concentrations of CO₂ and with temperature, resulting in increased growth of plants.¹⁰¹⁸ Plants reach maximum photosynthesis between about 350 and 550 ppm atmospheric CO₂, depending on differences in mechanisms of photosynthesis.¹⁰¹⁹ Photosynthesis levels off at higher concentrations of CO₂.¹⁰²⁰ Regardless of CO₂ concentrations, maximum photosynthesis tends to occur between about 85 °F and 115 °F (29 °C and 46 °C), and declines rapidly at higher temperatures.¹⁰²¹

Plants that use C₄ photosynthesis tend to dominate under conditions of high temperatures and low CO₂ concentrations.¹⁰²² C₃ plants are competitively superior to C₄ plants under conditions of increasing CO₂ atmospheric concentrations and increasing temperatures.¹⁰²³ Plants that use the C₃ pathways (e.g., pine, fir, hardwoods, shrubs) are usually competitively superior to C₄ plants under conditions of higher atmospheric CO₂ concentrations, and conifers are competitively superior to deciduous species.¹⁰²⁴

Biological processes that convert nutrients held in organic matter to available mineral forms are generally temperature-dependent.¹⁰²⁵ Soil organic carbon and soil nitrogen are both easily removed by wind and water erosion, which can lead to feedbacks to the atmosphere.¹⁰²⁶ Nitrogen availability is closely tied to the water cycle and it controls photosynthetic rates and thus forest productivity, as well as carbon allocation and resulting canopy development.¹⁰²⁷ Nitrogen can limit carbon uptake even when water is readily available, but when water is limiting, plants cannot take up available nitrogen unless they develop

¹⁰¹⁶ Verbatim from Pojar (2010, p. 23-24). Pojar cites Ainsworth & Rogers (2007) for information on plant stomata closing in response to relatively high levels of CO₂.

¹⁰¹⁷ Nearly verbatim from Pojar (2010, p. 24). Pojar cites Wang et al. (2006) for information on nutrient limitations and maladaptation to changing environmental conditions. Pojar cites Spittlehouse & Stewart (2003), Johnston & Williamson (2005), and Campbell et al. (2008) for information on the losses due to other factors related to climate change.

¹⁰¹⁸ Nearly verbatim from deVos, Jr. & McKinney (2007, p. 7). *Potential impacts of global climate change on abundance and distribution of elk and mule deer in western North America.*

¹⁰¹⁹ Verbatim from deVos, Jr. & McKinney (2007, p. 7)

¹⁰²⁰ Verbatim from deVos, Jr. & McKinney (2007, p. 7)

¹⁰²¹ Verbatim from deVos, Jr. & McKinney (2007, p. 7). deVos, Jr. & McKinney cite Mooney (1986) and Schulze et al. (2002) for this information.

¹⁰²² Verbatim from deVos, Jr. & McKinney (2007, p. 7)

¹⁰²³ Verbatim from deVos, Jr. & McKinney (2007, p. 7)

¹⁰²⁴ Nearly verbatim from deVos, Jr. & McKinney (2007, p. 8). deVos, Jr. & McKinney cite Schulze et al. (2002), Howerly (2006), and Koch (2006) for this information.

¹⁰²⁵ Verbatim from Ryan et al. (2012, p. 46)

¹⁰²⁶ Verbatim from Peterman & Bachelet (2012, p. 171). *Climate change and forest dynamics: a soils perspective.*

¹⁰²⁷ Verbatim from Peterman & Bachelet (2012, p. 168). Peterman & Bachelet cite Field et al. (1983) and Lajtha & Whitford (1989) for information on nitrogen availability being closely tied to the water cycle. Peterman & Bachelet cite Miller & Miller (1976), Brix (1981), Keyes & Grier (1981), Linder & Rook (1984), Nadelhoffer et al. (1985), Linder (1987), Myers (1988), Sanantonio (1989), and Raison & Stottlemeyer (1991) for information on the role of nitrogen in photosynthesis, forest productivity, carbon allocation, and canopy development.

symbiotic relationships with a nitrogen fixer.¹⁰²⁸ For this reason, the sizes of the soil carbon and nitrogen pools are good indicators of any change in the local soil nitrogen-supplying capacity.¹⁰²⁹ When fires burn forest litter and understory, immobilized nitrogen in the biomass gets released to the atmosphere.¹⁰³⁰ Other forest nitrogen outputs include biomass loss from harvest, erosion, leaching and gaseous transfers.¹⁰³¹

Observed Trends

Global

Globally, forests, grasslands, wetlands and tundra function as large terrestrial reservoirs of carbon, part of the Earth's feedback system that until recently maintained fairly stable concentrations of atmospheric CO₂.¹⁰³² Forest ecosystems contain more than half of the world's terrestrial carbon, and account for approximately 80% of the carbon exchange between terrestrial ecosystems and the atmosphere.¹⁰³³ The biosphere (the global aggregate of aquatic—especially oceans—and terrestrial ecosystems) removes 50 to 60 percent of human-caused greenhouse gas emissions (fossil fuel and land use emissions), curbing more intense global climate change.¹⁰³⁴

Terrestrial net primary production (NPP), the initial step of the carbon cycle in which carbon is fixed as biomass, increased from 1982 through 1999, in part due to eased climatic constraints on plant growth.¹⁰³⁵ However, global NPP slightly decreased for 2000-2009 by -0.55 Petagrams of carbon (Pg C; 1 Pg = 1,000,000,000,000,000 grams).¹⁰³⁶ In the northern hemisphere, 65% of vegetated land area had increased NPP, including large areas of North America, Western Europe, Indian, China, and the Sahel.¹⁰³⁷ Regions with decreased NPP include Eastern Europe, central Asia, and high latitudes of west Asia.¹⁰³⁸

Review papers show that annual net carbon uptake (sequestration) is generally low or negative in forests less than 20 years old (because of high rates of decomposition following stand-initiating disturbances), reaches a peak rate in intermediate-aged forests (that is, 30 to 120 years), and declines but reaches

¹⁰²⁸ Verbatim from Peterman & Bachelet (2012, p. 168). Peterman & Bachelet cite Charley (1972), Ludwig (1979), and Reynolds & Cunningham (1981) for this information.

¹⁰²⁹ Verbatim from Peterman & Bachelet (2012, p. 168). Peterman & Bachelet cite Ayanaba et al. (1976), Shurer (1985), and Powlson & Prookes (1987) for this information.

¹⁰³⁰ Verbatim from Peterman & Bachelet (2012, p. 169). Peterman & Bachelet cite Raison et al. (1985) and O'Connell (1989) for this information.

¹⁰³¹ Verbatim from Peterman & Bachelet (2012, p. 169). Peterman & Bachelet cite Raison et al. (1985) for this information.

¹⁰³² Verbatim from Pojar (2010, p. 53)

¹⁰³³ Nearly verbatim from Pojar (2010, p. 53). Pojar cites Wilson & Hebda (2008) for this information.

¹⁰³⁴ Nearly verbatim from Pojar (2010, p. 53). Pojar cites Solomon et al. (2007) for this information.

¹⁰³⁵ Verbatim from Zhao & Running (2010, p. 940). Zhao et al. cite Nemani et al. (2003) for this information.

¹⁰³⁶ Nearly verbatim from Zhao & Running (2010, p. 940). Zhao & Running refer the reader to Figures 1 and 3, and Table S3, in the cited article for this information. Zhao & Running state the global average annual total NPP is 53.5 Pg Carbon per year.

¹⁰³⁷ Nearly verbatim from Zhao & Running (2010, p. 941)

¹⁰³⁸ Verbatim from Zhao & Running (2010, p. 941)

equilibrium or remains positive in forests older than 120-160 years.¹⁰³⁹ However, old forests store much more carbon in living matter, standing and downed wood, and in the soil, than do younger forests.¹⁰⁴⁰

Long-term monitoring of old-growth forests provides mixed evidence as to whether their total carbon storage capacity is changing; many old-growth forests throughout the world appear to be net carbon sinks; however, this effect is diminished at larger spatiotemporal scales of measurement.¹⁰⁴¹

Southcentral and Southeast Alaska

Total carbon in the Tongass National Forest (southeast Alaska; soil, aboveground living biomass, and roots and dead woody debris) is estimated to be 2.8 ± 0.5 Petagrams (Pg).¹⁰⁴² In all, 66% of the total carbon in the Tongass is in the soils, 30% is in aboveground biomass (15% in live trees, 6% in seedlings and saplings, 3% in standing dead wood, 6% in coarse woody debris, less than 1% in small woody debris, and 1% in understory vegetation), and 4% is in roots.¹⁰⁴³ The carbon stock in the Tongass forest and soils (2.8 Pg) comprises 7.7% of the carbon in the forests and soils of the conterminous United States (36.7 Pg) and 0.25% of the carbon in the Earth's forest vegetation and soils (1,146 Pg).¹⁰⁴⁴

Organic soils are known to be significant sources of dissolved organic carbon for streams in northern forested ecosystems.¹⁰⁴⁵ Soils in southeastern Alaska contain an estimated 1.2 billion metric tons of carbon.¹⁰⁴⁶ That estimate, however, excludes the deep, unfrozen peat deposits found in the organic soils of the region, and may underestimate actual carbon stored in forested soils.¹⁰⁴⁷ Also, current survey methods may underestimate the carbon storage in southeastern Alaskan soils.¹⁰⁴⁸

Despite the extent of peatlands that occur within Pacific coastal temperate rainforest watersheds, there is little information describing how dissolved organic matter (DOM) storage and export patterns are related to soil saturation and temperature in the region.¹⁰⁴⁹ In 2004 and 2005, D'Amore et al. (2010) measured soil water tables, soil temperatures, and redox potential and compared these measurements to fluctuations

¹⁰³⁹ Verbatim from Pojar (2010, p. 59). Pojar cites Harmon et al. (2004), Pregitzer & Euskirchen (2004), Paw et al. (2004), Gough et al. (2008), Luysaert et al. (2008), Lewis et al. (2009), Phillips et al. (2008), Keith et al. (2009), and Hudiberg et al. (2009) for this information.

¹⁰⁴⁰ Nearly verbatim from Pojar (2010, p. 60). Pojar cites Pregitzer & Euskirchen (2004) and Van Tuyl et al. (2005) for this information.

¹⁰⁴¹ Verbatim from Anderson-Teixeira et al. (2012, p. 9). *Altered dynamics of forest recovery under a changing climate*. Anderson-Teixeira et al. cite Baker et al. (2004), Luysaert et al. (2007), Chave et al. (2008), and Lewis et al. (2009) for information on old-growth forests as net carbon sinks. Anderson-Teixeira et al. cite Clark (2002), Feeley et al. (2007a), and Chave et al. (2008) for information on the diminished effect at larger spatiotemporal scales of measurement.

¹⁰⁴² Nearly verbatim from Leighty et al. (2006, p. 1059). *Effects of management on carbon sequestration in forest biomass in southeast Alaska*. Note: The carbon estimate (2.8 Pg) is reported with its 95% confidence interval (± 0.5). Leighty et al. refer the reader to Table 1 in the cited article for this information.

¹⁰⁴³ Verbatim from Leighty et al. (2006, p. 1059)

¹⁰⁴⁴ Verbatim from Leighty et al. (2006, p. 1059)

¹⁰⁴⁵ Verbatim from Kelly et al. (2007, p. 50). Kelly et al. cite Mulholland & Kuenzler (1979) for this information.

¹⁰⁴⁶ Verbatim from Kelly et al. (2007, p. 50). Kelly et al. cite Alexander et al. (1989) and Leighty et al. (2006) for this information.

¹⁰⁴⁷ Verbatim from Kelly et al. (2007, p. 50). Kelly et al. cite Harrison et al. (2003) for this information.

¹⁰⁴⁸ Verbatim from Kelly et al. (2007, p. 50). Kelly et al. cite D'Amore et al. (2002) and D'Amore (in prep) for this information.

¹⁰⁴⁹ Verbatim from D'Amore et al. *Controls on dissolved organic matter concentrations in soils and streams from a forested wetland and sloping bog in southeast Alaska*. (2010, p. 249)

in dissolved organic carbon (DOC) and nitrogen (DON) concentrations in a forested wetland and sloping bog in southeast Alaska (near the mouth of McGinnis Creek) to address this key information gap.¹⁰⁵⁰ Key findings include:

- **DOC concentrations:** DOC concentrations ranged from 5 to 140 mg C l⁻¹ (milligrams carbon per liter) in wetland soils, 11 to 46 mg C l⁻¹ in streams, and varied greatly in response to changes in water table, redox potential and soil temperature.¹⁰⁵¹ In addition, DOC concentrations peaked before the mid-summer temperature maximum at the forested wetland in 2005.¹⁰⁵²
- **DON concentrations:** DON concentrations ranged from 0.03 to 2.4 mg N l⁻¹ (milligrams nitrogen per liter) in wetland soils, 0.2 to 0.6 mg N l⁻¹ in streams, and concentrations also reflected seasonal changes in physical measures.¹⁰⁵³
- **Distribution of DOC and DON:** Depth to water table and soil temperature were significant factors related to the concentration of DOC in forested wetland soils and streams, while soil temperature was a significant factor that influenced stream DOC and DON concentrations.¹⁰⁵⁴ Comparing soil solution and stream DOM concentrations indicated that nitrogen is retained in bogs, while both dilution and biotic/abiotic retention mechanisms control DOM export in forested wetlands.¹⁰⁵⁵
- **Carbon storage:** The forested wetland and bog soils had about the same carbon storage to 3.28 feet (1 meter) depth (approximately 11 kilograms of carbon per square meter), but size distribution of the material varied as indicated by the rubbed fibre analysis.¹⁰⁵⁶ Both the bog and forested wetland sites had soils that reflect the results of Holocene peatland development and contained deep (>1.6 foot, >0.5 meter) and concentrated (>35%) organic carbon stocks that were extensive reservoirs or organic matter.¹⁰⁵⁷

The high soil moisture conditions of coastal temperate forests lead to the limitation of forest productivity on sites and the accumulation of soil organic material.¹⁰⁵⁸ From 1988 to 2000 in Alaska, years with relatively early seasonal thawing showed generally greater leaf area index and annual productivity, while years with delayed seasonal thawing showed corresponding reductions in canopy cover and productivity.¹⁰⁵⁹ The PEM-derived (i.e., biome-specific production efficiency model) gross primary productivity and net primary productivity values for Alaska and northwest Canada averaged 597 [\pm 173.7 (s)] and 301 [\pm 107.4 (s)] grams of carbon per square meter per year, respectively.¹⁰⁶⁰ Mean annual

¹⁰⁵⁰ Nearly verbatim from D'Amore et al. (2010, p. 249)

¹⁰⁵¹ Verbatim from D'Amore et al. (2010, p. 249)

¹⁰⁵² Verbatim from D'Amore et al. (2010, p. 256). D'Amore et al. refer the reader to Figure 5D in the cited article for this information.

¹⁰⁵³ Verbatim from D'Amore et al. (2010, p. 249)

¹⁰⁵⁴ Verbatim from D'Amore et al. (2010, p. 249)

¹⁰⁵⁵ Verbatim from D'Amore et al. (2010, p. 249)

¹⁰⁵⁶ Verbatim from D'Amore et al. (2010, p. 252)

¹⁰⁵⁷ Verbatim from D'Amore et al. (2010, p. 252). D'Amore et al. refer the reader to Table 1 in the cited article for this information.

¹⁰⁵⁸ Verbatim from Wolken et al. (2011, p. 17). Wolken et al. cite Neiland (1971) for this information.

¹⁰⁵⁹ Nearly verbatim from Kimball et al. (2006, p. 2)

¹⁰⁶⁰ Nearly verbatim from Kimball et al. (2006, p. 12). Kimball et al. refer the reader to Figure 5 and Table 1 in the cited article for this information.

productivity within boreal forest areas was approximately 12.2% greater than regional average conditions, while arctic tundra annual productivity was 21.3% lower than the regional mean.¹⁰⁶¹

Western British Columbia

There is consensus that temperate rainforests (coastal and interior) and southern montane forests, which have faster-growing and bigger trees, sequester and store more carbon per hectare than slower growing, northern forests.¹⁰⁶² In total 18 billion tons of carbon are estimated to be stored by B.C.'s forest ecosystems, nearly 1000 times the province's annual emissions of greenhouse gases.¹⁰⁶³ The carbon stored in the trees, roots and soils of these forests averages 125 tons per acre (311 tons per hectare).¹⁰⁶⁴ However, carbon storage estimates vary by region and forest type:

- **Pacific Maritime and Montane Cordillera Ecozones:** The Carbon Budget Model for Canada's Forests (1999) estimates B.C.'s Pacific Maritime and Montane Cordillera ecozones store on average ~142 tons of carbon per acre (~350 tons of carbon per hectare).¹⁰⁶⁵ Individual forest ecosystems in these ecozones can store considerably more than the average, from 243 to 526.1 tons of carbon per acre (600 to 1300 tons of carbon per hectare).¹⁰⁶⁶
- **Temperate old-growth rainforests:** Old-growth forests steadily accumulate carbon for centuries and store vast quantities of it, up to 445.2 tons per acre (1100 tons per hectare) in B.C.'s temperate rainforests – some of the highest storage capacities in the world.¹⁰⁶⁷

B.C.'s peatlands cover approximately 6% of the province – mostly in the north and on the outer coast – and are estimated to store 6.8 billion tons of carbon and to sequester about 1.5 million tons of carbon per year.¹⁰⁶⁸ Three northern wetland complexes are mostly peatlands (Fort Nelson Lowland in northeast B.C., Hecate Lowland on the central and north coast, and the Argonaut Plain on northeast Haida Gwaii), carbon-rich wetland ecosystems with massive deposits of peat at least 40 cm thick.¹⁰⁶⁹

In cooler months, high daytime atmospheric vapor pressure deficit rarely restricts photosynthesis in any zone (i.e., in any biogeoclimatic zone in B.C.).¹⁰⁷⁰ As temperature increases, high daytime atmospheric vapor pressure deficit increases exponentially and often imposes limitations on stomatal conductance during the summer.¹⁰⁷¹ Throughout the province, high daytime atmospheric vapor pressure deficit currently restricts photosynthesis on average between 30% and 40% during the summer months (i.e., as reported by results from the 3-PG process-based model).¹⁰⁷²

¹⁰⁶¹ Verbatim from Kimball et al. (2006, p. 12)

¹⁰⁶² Verbatim from Pojar (2010, p. 62). Pojar cites Keith et al. (2009) for this information.

¹⁰⁶³ Nearly verbatim from Pojar (2010, p. 53). Pojar cites Wilson & Hebda (2008) for this information.

¹⁰⁶⁴ Nearly verbatim from Pojar (2010, p. 53)

¹⁰⁶⁵ Nearly verbatim from Pojar (2010, p. 60). Pojar cites Kurz & Apps (1999) for this information.

¹⁰⁶⁶ Verbatim from Pojar (2010, p. 60). Pojar cites Trofymow & Blackwell (1998) and Fredeen et al. (2005) for this information.

¹⁰⁶⁷ Nearly verbatim from Pojar (2010, p. 57)

¹⁰⁶⁸ Nearly verbatim from Pojar (2010, p. 54). Pojar cites Wilson & Hebda (2008) for this information.

¹⁰⁶⁹ Nearly verbatim from Pojar (2010, p. 54)

¹⁰⁷⁰ Nearly verbatim from Coops et al. (2010, p. 521)

¹⁰⁷¹ Verbatim from Coops et al. (2010, p. 521)

¹⁰⁷² Nearly verbatim from Coops et al. (2010, p. 521)

Pacific Northwest

Potential carbon stores in the Pacific Northwest are among the highest for forests in the world.¹⁰⁷³

In 14 mid- to late-successional stands in the northwest U.S., the distribution and amounts of organic matter, carbon, and nitrogen in woody residue and soil components varied considerably among forest types and locations.¹⁰⁷⁴ The highest totals were found in the high-rainfall areas of western Oregon (Table 22).¹⁰⁷⁵ Combined, woody residue, forest floor, and soil wood contained greater than 50% of the soil carbon to a mineral-soil depth of approximately 12 inches (30 cm) in 13 of the 14 stands, while the 0-3.9 inch (0-10 cm) soil depth contained more carbon than the 3.9-12 inch (10-30 cm) depth in nearly half the stands.¹⁰⁷⁶ In contrast to carbon, nitrogen pools were much larger in the mineral soil than in the surface organic layers.¹⁰⁷⁷ Specific results for two stands in the southern Oregon Cascades and Oregon Coast Range are provided in Table 22.

Northwest California

Information needed.

¹⁰⁷³ Verbatim from Shafer et al. (2010, p. 188). Shafer et al. cite Smithwick et al. (2002) and Homann et al. (2005) for this information.

¹⁰⁷⁴ Nearly verbatim from Page-Dumroese & Jurgenson (2006, p. 2275). *Soil carbon and nitrogen pools in mid- to late-successional forest stands of the northwestern United States: potential impact of fire*. Page-Dumroese & Jurgenson refer the reader to Table 3 in the cited article for this information.

¹⁰⁷⁵ Nearly verbatim from Page-Dumroese & Jurgenson (2006, p. 2275)

¹⁰⁷⁶ Nearly verbatim from Page-Dumroese & Jurgenson (2006, p. 2275-2276)

¹⁰⁷⁷ Verbatim from Page-Dumroese & Jurgenson (2006, p. 2276). Page-Dumroese & Jurgenson refer the reader to Table 3 in the cited article for this information.

Table 22. Distribution of woody residue and soil organic matter, carbon, and nitrogen in two mid- to late-successional stands in the southern Oregon Cascades and Oregon Coast Range, including fine roots in the forest floor, soil wood, and mineral soil pools.						
<i>Oregon Cascades</i> (<i>Douglas-fir/Oregon grape stand</i>)	Organic Matter		Carbon		Nitrogen	
	Soil (Mg ha ⁻¹)*	Distribution (%)	Soil (Mg ha ⁻¹)	Distribution (%)	Soil (Mg ha ⁻¹)	Distribution (%)
Woody residue	78 (10)	17	36 (9)	12	166 (14)	5
Forest floor	127 (12)	27	72 (46)	23	201 (30)	7
Soil wood	50 (9)	11	27 (2)	9	95 (37)	3
Mineral soil (0-3.9", 0-10 cm)	105 (7)	22	83 (22)	26	1112 (49)	37
Mineral soil (3.9-12; 10-30 cm)	108 (15)	23	94 (13)	30	1432 (52)	48
Total	468	100	312	100	3006	100
<i>Oregon Coast Range</i> (<i>Sitka spruce/ red alder stand</i>)	Soil (Mg ha ⁻¹)	Distribution (%)	Soil (Mg ha ⁻¹)	Distribution (%)	Soil (Mg ha ⁻¹)	Distribution (%)
Woody residue	228 (12)	22	130 (8)	30	249 (17)	6
Forest floor	157 (14)	15	77 (38)	18	183 (32)	5
Soil wood	111 (26)	11	51 (6)	12	84 (6)	2
Mineral soil (0-3.9", 0-10 cm)	307 (11)	29	117 (12)	27	1405 (35)	36
Mineral soil (3.9-12; 10-30 cm)	244 (15)	23	55 (13)	13	1999 (42)	51
Total	1047	100	430	100	3920	100

*Megagrams per hectare
Note: Values are given as the mean with the standard error of the mean in parentheses
Source: Modified from Page-Dumroese & Jurgenson (2006, Table 3, p. 2277-2279) by authors of this report.

Future Projections

Global

Because responses to CO₂ enrichment may differ among species and locations, a wide range of responses to increased atmospheric CO₂ should be expected worldwide.¹⁰⁷⁸ For mature forests, in large part because of this uncertainty (i.e., in whether elevated CO₂ will increase biomass and productivity in mature forests), it remains unclear whether the net carbon balance of mature forests will increase in response to CO₂ fertilization.¹⁰⁷⁹ The ability of forests to sustain increased net primary productivity (NPP) under

¹⁰⁷⁸ Verbatim from Sturrock et al. (2011, p. 133)

¹⁰⁷⁹ Nearly verbatim from Anderson-Teixeira et al. (2013, p. 5). Anderson-Teixeira refer the reader to Figure 3 in the cited article for this information.

elevated CO₂ as they age – and, ultimately, the potential for mature forests to increase carbon storage under elevated CO₂ – depends in large part upon biogeochemistry.¹⁰⁸⁰

Western North America

Western U.S. forests are responsible for 20% to 40% of total U.S. carbon sequestration.¹⁰⁸¹ In a modeling study of projected future changes in vegetation across western North America (2070-2099 vs. 1961-1990; CESM run with its DGVM under A2), the projected total carbon loss in the simulations is 5.8 Gigatons of carbon (GtC), with 57% (3.3 GtC) lost from the vegetation stock and 43% (2.5 GtC) from the soil carbon stock (Figure 28).¹⁰⁸² The net impact is about a 50% decrease in projected ecosystem carbon storage in this region.¹⁰⁸³ Specific results for the vegetation, soil, and total carbon stocks include:

- **Vegetation carbon stock:** The model results indicate that by 2100, there may be a 3.3 GtC (or 35%) reduction in the vegetation carbon, where 27% of the land is covered by forests (here, forests are defined as the regions with more than 90% tree coverage) owing to the transition from forests to grasses and shrubs.¹⁰⁸⁴ The projected loss of forest carbon from 2005 to 2100 is equivalent to 16 years of fossil fuel emissions from the United States.¹⁰⁸⁵
- **Soil carbon stock:** In addition to vegetation carbon loss, there may be an additional 2.5 GtC (or 13%) soil carbon loss because of both increased necromass and accelerated decomposition rates with higher temperatures.¹⁰⁸⁶
- **Total carbon stock:** The total loss from vegetation changes and soil is also about 15% of the total 37.2 GtC carbon pools over the continental U.S. as reported by Potter et al. (2006).¹⁰⁸⁷

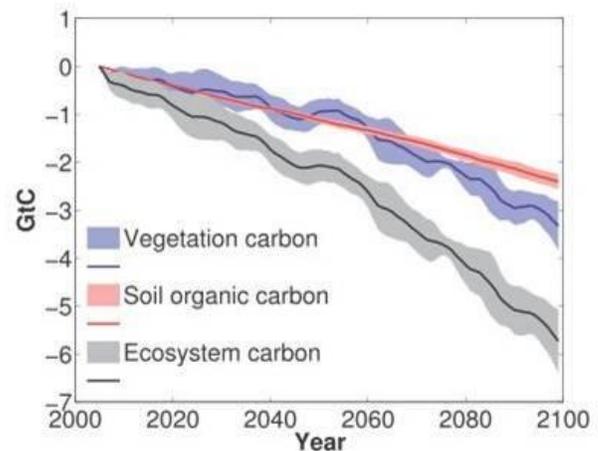


Figure 28. Time series of projected changes in vegetation carbon, soil organic carbon, and ecosystem carbon (vegetation and soil organic carbon) stocks for the period of 2005-99 over western North America. Changes are relative to year 2005 values. Shaded area represents the ensemble range of eight CESM runs. *Source: Reproduced from Jiang et al. (2013, Figure 10, p. 3683) by authors of this report.*

¹⁰⁸⁰ Verbatim from Anderson-Teixeira et al. (2013, p. 5)

¹⁰⁸¹ Verbatim from Jiang et al. (2013, p. 3681). *Projected future changes in vegetation in western North America in the Twenty-First Century.* Jiang et al. cite Pacala et al. (2001) for this information.

¹⁰⁸² Nearly verbatim from Jiang et al. (2013, p. 3683). *Projected future changes in vegetation in western North America in the Twenty-First Century.*

¹⁰⁸³ Nearly verbatim from Jiang et al. (2013, p. 3671)

¹⁰⁸⁴ Verbatim from Jiang et al. (2013, p. 3681). *Projected future changes in vegetation in western North America in the Twenty-First Century.*

¹⁰⁸⁵ Verbatim from Jiang et al. (2013, p. 3682). Jian et al. cite Friedlingstein et al. (2010) for this information.

¹⁰⁸⁶ Verbatim from Jiang et al. (2013, p. 3681). *Projected future changes in vegetation in western North America in the Twenty-First Century.*

¹⁰⁸⁷ Verbatim from Jiang et al. (2013, p. 3682)

In a similar modeling study of the effects of fire suppression and CO₂ emissions on carbon stocks and vegetation, in the West (i.e., west of the eastern border of Colorado) the response to increases in precipitation and relatively small increases in temperature was a 5% increase in total carbon stocks (2070-2099 vs. 1971-2000; Canadian CGCM2, UK HADCM3, and Australian CSIRO Mk2 simulated by MC1 DGVM and run with A2 and B2).¹⁰⁸⁸ As in the results for vegetation type, the unsuppressed *vs.* suppressed fire treatment had a significant effect on the response of total carbon to future climate.¹⁰⁸⁹ But unlike vegetation type, total carbon was also responsive to the CO₂ effect and emission treatments, and to their interactions.¹⁰⁹⁰ Specific overall results, as well as results for suppressed and unsuppressed fire, include:

- **Overall:** In the western region, there was a 5.3% increase in the total carbon pool averaged across all treatments.¹⁰⁹¹
- **Suppressed fire** (i.e., after 1950 at the historical level): With suppressed fire, carbon gains under all treatments averaged 10.3%, with the greatest gains simulated in response to the high CO₂ effect, especially in combination with the high A2 emission rate.¹⁰⁹²
- **Unsuppressed fire:** With unsuppressed fire, carbon gain in the West was negligible (0.4%) when averaged across a 3.5% loss and 4.3% gain under the low and high CO₂ response (i.e., lower net primary productivity, NPP, and higher NPP), respectively.¹⁰⁹³ Carbon gain with unsuppressed fire and the high CO₂ response was significantly greater in conjunction with the high A2 CO₂ emission rate.¹⁰⁹⁴

Global temperature increases pose a potential threat to Canada's boreal forests via eruptive beetle populations moving further north and east of their current range.¹⁰⁹⁵ An expanding disturbance footprint could further threaten forest carbon sinks in North America, which in turn could provide positive feedback to the global climate system.¹⁰⁹⁶ For example, bark beetle outbreaks have increased forest carbon loss and are likely to continue to do so in the next 30 years, probably negating the increased productivity from warming temperatures and elevated CO₂.¹⁰⁹⁷ Experimental soil-warming studies confirm that nitrogen mineralization will increase in response to higher temperatures, with an average

¹⁰⁸⁸ Nearly verbatim from Lenihan et al. (2008b, p. 16). *Simulated response of conterminous United States ecosystems to climate change at different levels of fire suppression, CO₂ emission rate, and growth response to CO₂.*

¹⁰⁸⁹ Verbatim from Lenihan et al. (2008b, p. 22). Lenihan et al. refer the reader to Figure 6 vs. 7 in the cited article for this information.

¹⁰⁹⁰ Verbatim from Lenihan et al. (2008b, p. 22)

¹⁰⁹¹ Verbatim from Lenihan et al. (2008b, p. 22). Lenihan et al. refer the reader to Table 1 in the cited article for this information.

¹⁰⁹² Verbatim from Lenihan et al. (2008b, p. 22). In the cited article, Lenihan et al. refer the reader to Table 1 for information on carbon gains under all treatments and to Figure 8B for information on the greatest gains.

¹⁰⁹³ Verbatim from Lenihan et al. (2008b, p. 22)

¹⁰⁹⁴ Verbatim from Lenihan et al. (2008b, p. 22). Lenihan et al. refer the reader to Figure 8A in the cited article for this information.

¹⁰⁹⁵ Verbatim from Sambaraju et al. (2012, p. 222)

¹⁰⁹⁶ Verbatim from Sambaraju et al. (2012, p. 222). Sambaraju et al. cite Safranyik et al. (2010) for information on the expanding disturbance footprint, and Kurz et al. (2008) for information on positive feedback to the global climate system.

¹⁰⁹⁷ Nearly verbatim from Ryan et al. (2012, p. 46). Ryan et al. refer the reader to Figure 2.17 in the cited article for this information.

increase in net nitrogen mineralization of about 50% (2-9 years of experimental warming in the range 0.5-11 °F, 0.3-6.0 °C).¹⁰⁹⁸

Southcentral and Southeast Alaska

Changes in growing season length may affect annual productivity, and increased nitrogen and CO₂ inputs strongly influence forest productivity if other factors (water, temperature, radiation) are less limiting.¹⁰⁹⁹

Carbon stored in soils may be lost in gaseous forms through oxidation of soil organic matter and by way of associated increases in dissolved organic carbon in surface water.¹¹⁰⁰ The potential to transfer soil carbon to the atmosphere by these means is high in southeastern Alaska where temperatures are mild and precipitation is abundant.¹¹⁰¹ Increasing temperature leads to increased oxidation of soil organic matter, and increased rainfall increases the export to streams of dissolved material including carbon.¹¹⁰²

In a modeling study using the dynamic global vegetation model MC1 state-wide, information on carbon losses from fire, carbon gains, and net change in carbon is provided:

- **Carbon losses from fire:** The model simulates an average loss of 17-19 Teragrams of carbon per year (Tg C yr⁻¹; 1 Tg = 1,000,000,000,000) due to fire emissions between 2025 and 2099, which corresponds to a 24-33% increase above historical conditions (compared to 1922-1996 under two climate change scenarios, CGCM1 and HADCM2SUL).¹¹⁰³
- **Carbon gains:** The carbon gain between 2025 and 2099 is projected at 0.5 Petagrams of carbon (Pg C; 1 Pg = 1,000,000,000,000,000) under the warmer CGCM1 climate change scenario and 3.2 Pg C under HADCM2SUL.¹¹⁰⁴
- **Net change in carbon:** The loss to fires under CGCM1 is thus greater than the carbon gained in those 75 years, while under HADCM2SUL it represents only about 40% of the carbon gained.¹¹⁰⁵ However, during the last decade of the 21st century, Alaska becomes a large carbon source (19–72 Tg C) under both scenarios.¹¹⁰⁶

Projections of net carbon flux in the Tongass National Forest (southeast Alaska) range from 0.33 Teragrams of carbon (Tg C) annual sequestration to 2.3 Tg C annual emissions for the period 1995-2095 (spatially explicit model comprised of GIS and forestry inventory data, then used with accretion data from permanent plots to examine five future management regimes).¹¹⁰⁷

¹⁰⁹⁸ Nearly verbatim from Ryan et al. (2012, p. 46). Ryan et al. cite Melillo et al. (2011) for information on increasing nitrogen mineralization in response to higher temperatures and Rustad et al. (2001) for information on the average increase of 50%.

¹⁰⁹⁹ Verbatim from Jezierski et al. (2010, p. 8). Jezierski et al. cite Ryan et al. (2008) for this information.

¹¹⁰⁰ Verbatim from Kelly et al. (2007, p. 50)

¹¹⁰¹ Verbatim from Kelly et al. (2007, p. 50)

¹¹⁰² Verbatim from Kelly et al. (2007, p. 50)

¹¹⁰³ Nearly verbatim from Bachelet et al. (2005, p. 2252). *Note: Scenarios were based on greenhouse gas experiments with sulfate aerosols from the Canadian Climate Center (CGCM1) and the Hadley Centre (HADCM2SUL).*

¹¹⁰⁴ Verbatim from Bachelet et al. (2005, p. 2245)

¹¹⁰⁵ Verbatim from Bachelet et al. (2005, p. 2245)

¹¹⁰⁶ Verbatim from Bachelet et al. (2005, p. 2254). Bachelet et al. refer the reader to Figure 9 in the cited report.

¹¹⁰⁷ Nearly verbatim from Leighty et al. (2006, p. 1051)

Western British Columbia

If stand-replacing disturbances are rare, as they are in wet coastal forests, many wet subalpine forests, and some interior wet-belt forests, older forests will occupy the majority of the landscape and they will continue to be net carbon sinks.¹¹⁰⁸

The future magnitude and direction of peatlands' influence on climate are uncertain.¹¹⁰⁹ In particular, it is unclear how long northern peatlands can continue to function as net carbon sinks, given their sensitivity to drought, water table drawdown, melting permafrost, and especially surface disturbance from oil and gas exploration and development, and the resultant emissions of CO₂ and methane (CH₄).¹¹¹⁰

Pacific Northwest

The 21st century carbon budget of the Pacific Northwest will likely be a balance between competing processes, such as increased spring precipitation and CO₂ fertilization versus summer drought and intensified fire regimes.¹¹¹¹ The maritime forests west of the Cascades appear vulnerable to increases in summer drought and fire occurrence, and could possibly lose up to 1.2 petagrams of carbon under the Hadley GCM (Pg C; 1 Pg = 1,000,000,000,000,000) by the end of the 21st century (2070-2099 vs. 1971-2000; CSIRO Mk3, MIROC 3.2 medres, and Hadley CM3 GCMs under A2 emissions scenario) (Table 23, Figure 29).¹¹¹² To put this in context, 1 Pg C is approximately one-eighth of our current global annual fossil fuel emissions and 23 times the size of Oregon and Washington's current combined annual emissions.¹¹¹³ Simulated fire suppression was unable to curtail this large fire-induced carbon source.¹¹¹⁴

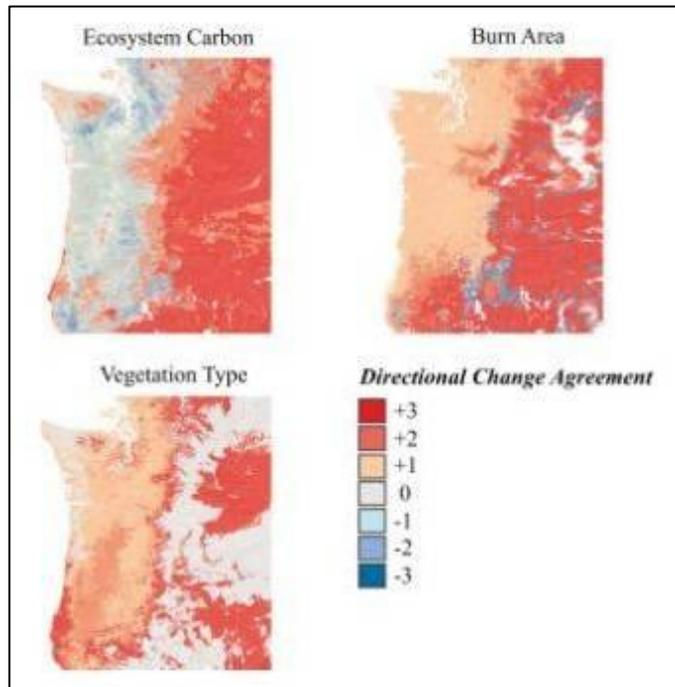


Figure 29. Number of future scenarios that agree on a change from the historical baseline. Changes in the positive and negative direction are given by positive and negative numbers for carbon and burn area. Changes of less than 5% (carbon) and 10% (burn area) from historical on a grid-cell basis were deemed insignificant. *Source: Reproduced from Rogers et al. (2011, Figure 8, p. 10) by authors of this report.*

¹¹⁰⁸ Verbatim from Pojar (2010, p. 62). Pojar cites Parish & Antos (2006) for information on wet coastal forests, Hallet et al. (2003) for information on wet subalpine forests, and Daniels & Gray (2006) for information on older forests continuing to occupy the majority of the landscape.

¹¹⁰⁹ Nearly verbatim from Pojar (2010, p. 54). Pojar cites Kelman et al. (2008) for this information.

¹¹¹⁰ Nearly verbatim from Pojar (2010, p. 54)

¹¹¹¹ Verbatim from Rogers et al. (2011, p. 2)

¹¹¹² Nearly verbatim from Rogers et al. (2011, p. 11)

¹¹¹³ Verbatim from Rogers et al. (2011, p. 6). Rogers et al. cite Le Quéré et al. (2009) for information on global annual fossil fuel emissions. For Washington and Oregon emissions, Rogers et al. cite Oregon Department of Energy (2010) and Waterman-Hoey & Nothstein (2006).

Woody expansion in the western United States may continue under future warming because of natural climate variability, ongoing increases in atmospheric CO₂, and continuing grazing restrictions and fire suppression.¹¹¹⁵ This expansion would allow for greater carbon sequestration (Table 24).¹¹¹⁶ However, it would also allow for an increase in coarse fuels likely to carry catastrophic fires if droughts were to occur more frequently in the future.¹¹¹⁷ On the other hand, future droughts may also limit tree growth, thus ultimately reducing fuel production and allowing for more open forests with lower fire danger.¹¹¹⁸

Table 23. Historical (1971-2000 Means) and Future (2070-2099 Means) Changes to Fire Regimes and Carbon Stocks in the Pacific Northwest Domain and Western Forests Sub-Domain.

Region	Variable	Historical	Percent Changes		
			CSIRO (cool-wet)	MIROC (hot-wet)	Hadley (hot-dry)
Pacific Northwest Domain	Burn area	0.326 ^a	+76.3	+95.0	+310.1
	Biomass consumed	8.95 ^b	+127.9	+165.3	+477.6
	Ecosystem carbon	29.4 ^c	+12.2	+9.9	-13.4
Western Forests Sub-Domain	Burn area	0.143 ^a	+161.5	+159.6	+1177.4
	Biomass consumed	5.74 ^b	+153.2	+182.1	+1313.4
	Ecosystem carbon	44.4 ^c	+2.5	+1.7	-23.9

a: % area burned per year; b: grams carbon m⁻² yr⁻¹; c: kg carbon m⁻²
Source: Modified from Rogers et al. (2011, Table 2, p. 9 by authors of this report.
Note: Eastern Forests and Columbia Plateau Sub-Domains are outside the NPLCC region. Results are not shown.

Table 24. Impacts of future climate change on carbon (C) sequestration in Oregon and Washington.

	Years	Oregon	California
Live vegetation carbon	1901-2000	2.43 Pg C	1.8 Pg C
	2001-2100	-0.08	-0.18
	2031-2060	+0.68	-0.23
	2071-2090	-0.14	-0.12
Soil carbon	1901-2000	6.20 Pg C	6.8 Pg C
	2001-2100	-0.04	-0.07
	2031-2060	-0.05	-0.07
	2071-2090	-0.04	-0.08

Source: Modified from Bachelet et al. (2007, Table 3, p. 15) by authors of this report.
Note: Impacts of future climate change on fire and carbon sequestration simulated by vegetation model MCI (Lenihan et al., 2003; Bachelet et al., 2001). Reported are average annual carbon stocks in Pg (billion tons) C, averaged over the historical period, and future fractional changes for the 21st century (2001–2100) and the middle (2031–2060) and late (2071–2090) 21st century in the CGCM2 climate model and the SRES A2 emissions scenario.

¹¹¹⁴ Verbatim from Rogers et al. (2011, p. 11)

¹¹¹⁵ Verbatim from Bachelet et al. (2007, p. 16-17)

¹¹¹⁶ Verbatim from Bachelet et al. (2007, p. 17)

¹¹¹⁷ Verbatim from Bachelet et al. (2007, p. 17)

¹¹¹⁸ Verbatim from Bachelet et al. (2007, p. 17)

Northwest California

A model sensitivity analysis was conducted by Lenihan et al. (2008) to assess the contribution of the direct effects of CO₂ (i.e., enhanced plant production and water use efficiency) on simulated net primary productivity trends in the state of California.¹¹¹⁹ Results indicated that direct CO₂ effects enhanced net primary productivity by approximately 6% at 500 ppm (concentration at the end of century under the B1 emission scenario) and by approximately 18% at 800 ppm (concentration at end of century under the A2 emission scenario).¹¹²⁰

In the same study, results for simulated trends in cumulative net biological production (i.e., NBP, the balance between carbon gained via primary productivity and carbon lost via decomposition and consumption by fire) varied by the model and scenario used (comparing 2070-2099 vs. 1961-1990 run using the GFDL-A2, GFDL-B1, and PCM-A2 scenarios):

- **PCM-A2 scenario** (cooler and less dry): The simulated trend in NBP showed a steady increase over the course of the future period, resulting in the accumulation of 321 Teragrams (Tg) of new ecosystem carbon in California by the end of the century (a 5.5% increase over the total carbon stocks simulated for the historical period).¹¹²¹ The majority of simulated new ecosystem carbon came from new soil and litter:
 - New soil/litter carbon accounted for over 80% of the new carbon sink under the PCM-A2 scenario.¹¹²²
 - The remaining 20% accumulated as live vegetation carbon, 80% of which was new grass carbon.¹¹²³
- **GFDL-B1 and GFDL-A2** (warmer and drier scenarios): The simulated trends in NBP showed a steady decrease over the course of the future period, resulting in the loss of 76 and 129 Tg (83.8 and 142.2 million tons) of total ecosystem carbon by the end of the century under the B1 and A2 emissions scenarios, respectively.¹¹²⁴ These losses represent a decline in total carbon stocks of 1.3% (B1) and 2.2% (A2) relative to simulated historical levels.¹¹²⁵ The source of simulated ecosystem carbon losses varied by emissions scenario:
 - Losses of live vegetation carbon accounted for 80% (B1) and 67% (A2) of the declines in total ecosystem carbon.¹¹²⁶

¹¹¹⁹ Nearly verbatim from Lenihan et al. (2008a, p. S223)

¹¹²⁰ Nearly verbatim from Lenihan et al. (2008a, p. S223)

¹¹²¹ Nearly verbatim from Lenihan et al. (2008a, p. S223). Lenihan et al. refer the reader to Figure 5b in the cited article for information on the simulated increase under the PCM-A2 scenario. Lenihan et al. also refer the reader to Table 2 in the cited article for information on the simulated percent increase in total carbon stocks compared to the historical period.

¹¹²² Verbatim from Lenihan et al. (2008a, p. S223). Lenihan et al. refer the reader to Figure 6a in the cited article for this information.

¹¹²³ Verbatim from Lenihan et al. (2008a, p. S223). Lenihan et al. refer the reader to Figure 6c in the cited article for this information.

¹¹²⁴ Nearly verbatim from Lenihan et al. (2008a, p. S223). Lenihan et al. refer the reader to Figure 5b in the cited article for information on the simulated trends in NBP. Lenihan et al. also refer the reader to Table 2 in the cited article for this information.

¹¹²⁵ Verbatim from Lenihan et al. (2008a, p. S223)

¹¹²⁶ Verbatim from Lenihan et al. (2008a, p. S223)

- Relative to simulated historical levels, total woody carbon declined by 29% while total grass carbon increased by 22% by the end of the century under the B1 emission scenario.¹¹²⁷
- Under the A2 scenario, woody carbon declined by 36% while grass carbon increased by 20%.¹¹²⁸

Regarding these results, Lenihan et al. (2008a) note the direct effect of increasing atmospheric CO₂ concentration on vegetation productivity and water-use efficiency is another source of uncertainty in Dynamic General Vegetation Model formulation.¹¹²⁹ They further note the uncertainty due to differences among future climate scenarios and to unrepresented or poorly understood processes preclude the use of these simulations as unflinching predictions of the future.¹¹³⁰

Information Gaps

Ryan et al. (2012) list four key information needs for nutrient cycling in forest ecosystems:

- More and longer term elevated CO₂ experiments in forests, especially in mature forests.¹¹³¹
- More forest-scale warming experiments.¹¹³²
- More information on multifactor interactions and species changes, processes leading to tree mortality and species migration, and the cause and potential saturation of the current carbon sink in the United States.¹¹³³
- Analyses of long-term stream chemistry data to provide an integrated measure of nutrient cycling responses to climate variability, including more analyses across a wider range of ecosystems to understand variation in controls and response patterns.¹¹³⁴

In southeastern Alaska forested watersheds, further measurements of organic soils need to be linked with transport studies to enhance understanding of carbon export.¹¹³⁵

¹¹²⁷ Verbatim from Lenihan et al. (2008a, p. S224)

¹¹²⁸ Verbatim from Lenihan et al. (2008a, p. S224)

¹¹²⁹ Nearly verbatim from Lenihan et al. (2008a, p. S228)

¹¹³⁰ Nearly verbatim from Lenihan et al. (2008a, p. S228)

¹¹³¹ Verbatim from Ryan et al. (2012, p. 47)

¹¹³² Verbatim from Ryan et al. (2012, p. 47)

¹¹³³ Verbatim from Ryan et al. (2012, p. 47)

¹¹³⁴ Verbatim from Ryan et al. (2012, p. 47)

¹¹³⁵ Nearly verbatim from Kelly et al. (2007, p. 50)

2. Altered soil attributes

Soil is the foundation upon which forest and range ecosystems develop.¹¹³⁶ Soil holds much of the nutrients and biological mass of forest and range lands.¹¹³⁷ It consists of inorganic material, decaying organic matter, air, water, and many microbial and larger organisms.¹¹³⁸ Soil provides a wide range of important functions including sustaining plant growth; absorbing, storing, filtering, and moving water; modifying the atmosphere; providing habitat for beneficial soil micro-organisms; and providing a medium upon which engineering structures (e.g., roads) can be constructed.¹¹³⁹ Soil attributes include soil temperature, moisture, composition, and respiration.

Climate change-induced perturbations in nutrient cycling and precipitation is very likely to impact the ability of soil to sequester and store carbon.¹¹⁴⁰ Soil water storage depends on vegetation type and cover, soil surface and subsurface characteristics (e.g., infiltration rate, slope, texture, depth, impermeable layers), and losses to deep drainage, lateral flow, and evaporation.¹¹⁴¹ Therefore, soils hold important clues about shifts in hydrology and vegetation across the landscape because, in terrestrial systems, soil characteristics govern the reception, storage and redistribution of precipitation.¹¹⁴² This, in turn, determines the supply of plant-available water and, indirectly, the nutrients necessary for plant establishment and growth.¹¹⁴³ Because soils with more water are less sensitive to warming, changes in soil moisture result in changes in soil heat capacity and conductivity, which, in turn, affect infiltration and water transport in the soil profile.¹¹⁴⁴ Soil response to changes in precipitation has implications for vegetation water needs, fire risk, pest outbreaks, infiltration rates, and groundwater recharge.¹¹⁴⁵ More specifically, because they hold or release moisture based on their texture, depth and chemistry, soils can either mitigate or exacerbate climate change impacts to plants, affecting ecosystem vulnerability to heat waves, wildfires, and pest outbreaks.¹¹⁴⁶

Key Terms in this Section

Hydric: *soils formed under saturated conditions long enough during the growing season to develop anaerobic conditions in the upper part of the saturated area*

Mesic: *a soil temperature class with mean annual temperature of 46-59 °F (8-15 °C)*

Xeric: *dry soils in which the limited amount of water available is not present at optimum periods for plant growth; found in Mediterranean climates*

Source: Soil Science Society of America (2013)

¹¹³⁶ Verbatim from B.C. Ministry of Forests, Mines, and Lands (2010, p. 92)

¹¹³⁷ Verbatim from B.C. Ministry of Forests, Mines, and Lands (2010, p. 92)

¹¹³⁸ Verbatim from B.C. Ministry of Forests, Mines, and Lands (2010, p. 92)

¹¹³⁹ Verbatim from B.C. Ministry of Forests, Mines, and Lands (2010, p. 92)

¹¹⁴⁰ Verbatim from Kareiva et al. (2012, p. 4-12)

¹¹⁴¹ Verbatim from Knapp et al. (2008, p. 3). *Consequences of more extreme precipitation regimes for terrestrial ecosystems*. Knapp et al. cite Brady & Weil (2002) for this information.

¹¹⁴² Verbatim from Peterman & Bachelet (2012, p. 160)

¹¹⁴³ Verbatim from Peterman & Bachelet (2012, p. 160)

¹¹⁴⁴ Verbatim from Peterman & Bachelet (2012, p. 160). Peterman & Bachelet cite Cherkauer & Lettenmaier (1999) and Iwata et al. (2008) for this information.

¹¹⁴⁵ Nearly verbatim from Peterman & Bachelet (2012, p. 160). Peterman & Bachelet cite USGCRP (2009) for this information.

¹¹⁴⁶ Verbatim from Peterman & Bachelet (2012, p. 173)

The soil CO₂ flux (i.e., from the land to the atmosphere) is normally low under dry conditions due to low root and microbial activities, and generally increases with soil water content, but can show decreases under waterlogged conditions.¹¹⁴⁷ Furthermore, while some snow manipulation experiments have produced marked increases in nutrient leaching losses and nitrous oxide flux, others have shown more muted effects.¹¹⁴⁸ Much of the variation in response appears to be linked to dissolved organic carbon, which sometimes increases in response to soil frost, dampening the nitrogen response, but sometimes does not.¹¹⁴⁹

Many of the key ecosystem effects of winter climate change are driven by changes in snow cover, which affects soil freezing and patterns of seasonal runoff.¹¹⁵⁰ Snow is an effective insulator for soils, and it buffers soil temperatures at the threshold between freezing and thawed conditions.¹¹⁵¹ A lack of snow can produce the somewhat surprising phenomenon of colder/frozen soils in a warmer world.¹¹⁵² However, it is not clear how the cooling effects of loss of snow insulation will play out against warming air temperatures and decreased albedo to ultimately determine the nature and extent of soil frost.¹¹⁵³

Soil temperature has marked effects on root characteristics (growth, morphology, longevity, respiration, and membrane fluidity), which influence plant nutrient acquisition efficiency.¹¹⁵⁴ Soil CO₂ flux (i.e., from land to the atmosphere) also increases with increasing temperature, and this relationship is usually described using an exponential (Arrhenius) equation.¹¹⁵⁵ Furthermore, soil warming in northern forests results in faster decomposition and microbial processing of soil carbon and nitrogen, which directly releases more CO₂ to the atmosphere because of enhanced soil respiration.¹¹⁵⁶ By increasing nitrogen mineralization rates, soil warming can have an indirect nitrogen fertilization effect, which generally increases above-ground production and lowers carbon allocation to fine root biomass.¹¹⁵⁷ The net ecosystem carbon balance in response to warming depends largely on the counteracting effects of carbon release through increased soil respiration and carbon sequestration through increased biomass growth.¹¹⁵⁸

¹¹⁴⁷ Nearly verbatim from Peng et al. (2008, p. 94). *Forest management and soil respiration: implications for carbon sequestration*. Peng et al. cite Londo et al. (1999) for this information.

¹¹⁴⁸ Nearly verbatim from Grimm et al. (2012, p. 3-16). Grimm et al. cite Austnes & Vestgarden (2008), Hentschel & others (2008), and Hentschel & others (2009) for this information.

¹¹⁴⁹ Verbatim from Grimm et al. (2012, p. 3-16). Grimm et al. cite Groffman & others (2011) and Haei & others (2010) for this information.

¹¹⁵⁰ Verbatim from Grimm et al. (2012, p. 3-16). Grimm et al. cite Brooks & others (2011) for this information.

¹¹⁵¹ Verbatim from Hennon et al. (2012, p. 151)

¹¹⁵² Nearly verbatim from Grimm et al. (2012, p. 3-16)

¹¹⁵³ Verbatim from Grimm et al. (2012, p. 3-16). Grimm et al. cite Venalainen & others (2001), Decker & others (2003), Henry (2008), and Campbell & others (2010) for this information.

¹¹⁵⁴ Verbatim from Lynch & St. Clair (2004, p. 108). *Mineral stress: the missing link in understanding how global climate change will affect plants in real world soils*. Lynch & St. Clair cite BassiriRad (2000) for this information.

¹¹⁵⁵ Nearly verbatim from Peng et al. (2008, p. 94). Peng et al. cite Lloyd & Taylor (1994) for this information.

¹¹⁵⁶ Verbatim from Anderson-Teixeira et al. (2013, p. 7). Anderson-Teixeira et al. refer the reader to Table S2 in the cited article for this information. Anderson-Teixeira et al. also cite Rustad et al. (2001) and Melillo et al. (2002, 2011) for this information.

¹¹⁵⁷ Verbatim from Anderson-Teixeira et al. (2013, p. 7). Anderson-Teixeira et al. refer the reader to Figure 3 in the cited article for this information. Anderson-Teixeira et al. also cite Zhou et al. (2011) for this information.

¹¹⁵⁸ Verbatim from Anderson-Teixeira et al. (2013, p. 7). Anderson-Teixeira et al. refer the reader to Figure 3 in the cited article for this information.

Observed Trends

Global

Soil is a major source of atmospheric CO₂ and an integral part of the global carbon cycle.¹¹⁵⁹ The evolution of CO₂ from the soils is the second largest flux in the carbon budget of forest ecosystems and is therefore one of the key components in the carbon cycle at regional and global scales.¹¹⁶⁰ It amounts to 60-90% of total ecosystem respiration and is a major portion of the global carbon cycle.¹¹⁶¹ Soil organic carbon pools may store as much as 90% of the carbon in terrestrial ecosystems but can also vary widely in response to woody plant encroachment (from -6,200 grams of carbon per square meter, g C m⁻², to +2700 g C m⁻²).¹¹⁶² Therefore, even a small impact on soil, the soil CO₂ flux (i.e., from land to atmosphere) could have profound effects on changes in atmospheric CO₂ concentration.¹¹⁶³

Southcentral and Southeast Alaska

In Alaska, higher temperatures over the last century have led to changes in the length of the growing season for terrestrial ecosystems, and increased evapotranspiration in response to warming is also leading to an overall decline in spring soil moisture.¹¹⁶⁴

Western British Columbia

Across B.C. as temperature and radiation increase in spring, the demand for water increases while monthly precipitation decreases, resulting in soil water deficits in many zones.¹¹⁶⁵ As precipitation increases in late September and October, most soils are replenished, although the driest sites do not fully recharge until late November.¹¹⁶⁶

¹¹⁵⁹ Verbatim from Peng et al. (2008, p. 94). Peng et al. cite Elberling (2007) for information on soil as a source of atmospheric CO₂ and Schlesinger & Andrews (2000) for information on soil as a part of the global carbon cycle.

¹¹⁶⁰ Verbatim from Peng et al. (2008, p. 96). Peng et al. cite Gower et al. (1996) for information on the evolution of CO₂ from soil being the second largest flux in the carbon budget of forest ecosystems. Peng et al. cite Raich & Schlesinger (1992) and Gower et al. (1996) for information on soil CO₂ as a component of the carbon cycle.

¹¹⁶¹ Verbatim from Peng et al. (2008, p. 96). Peng et al. cite Goulden et al. (1996), Schlesinger & Andrews (2000), and Davidson et al. (2006) for information on total ecosystem respiration. Peng et al. cite Raich & Schlesinger (1992), Schlesinger (1997), and Marland et al. (2001) for information on soil CO₂ as a major portion of the global carbon cycle.

¹¹⁶² Nearly verbatim from Peterman & Bachelet (2012, p. 168). Peterman & Bachelet cite Schlesinger (1997) for information on soil organic carbon holding up to 90% of carbon in terrestrial ecosystems. Peterman & Bachelet cite Barger et al. (2011), Bragg & Hulbert (1976), Archer et al. (1988), Lane et al. (1998), Ansley & Castellano (2006), Briggs et al. (2002), Goslee et al. (2003), Jackson et al. (2000), Jackson et al. (2002), and Wessman et al. (2004) for information on the variability in soil organic carbon pools in response to woody plant encroachment.

¹¹⁶³ Verbatim from Peng et al. (2008, p. 96). Peng et al. cite Andrews et al. (1999) for this information.

¹¹⁶⁴ Verbatim from Peterman & Bachelet (2012, p. 167). Peterman & Bachelet cite Kimball et al. (2006) for information on the length of the growing season and Meehl & Stocker (2007) for information on spring soil moisture.

¹¹⁶⁵ Verbatim from Coops et al. (2010, p. 519)

¹¹⁶⁶ Verbatim from Coops et al. (2010, p. 519)

Pacific Northwest

Alpine soils generally are drier than subalpine soils because they contain less organic matter and are less mature.¹¹⁶⁷ Soil parent material generally is coarse-textured in mountain provinces, although fine-grained soil accumulates in and near small tarns, ridgetops, flat benches, and cirque basins from deposition of loess (i.e., wind-deposited sediment) and volcanic ashes.¹¹⁶⁸ In all regional mountain ranges, there are wetter west-slope and drier east-slope conditions.¹¹⁶⁹ Dry periods can lead to difficult moisture conditions late in growing seasons on south-facing slopes.¹¹⁷⁰ Soil temperature regimes found in the alpine and subalpine zones are quite cold and are classified as cryic, meaning a range of approximately 32-46 °F (0-8 °C).¹¹⁷¹

At five mature, closed-canopy forest stands dominated by Douglas-fir in western Oregon, soil temperature typically reached 9 °F (~ -13 °C) at the mid-elevation sites in May and at the high elevation sites in June.¹¹⁷² Soil temperature at the Coast site was consistently > 9 °F (>-13 °C) throughout the year.¹¹⁷³ Growth was assumed not to occur when the average soil temperature was < 9 °F (>-13 °C).¹¹⁷⁴

In the Oregon Cascades, “red” soil conditions caused by severe soil heating alter soil nutrients and microbial community structure compared to less severely burned black soils.¹¹⁷⁵ Hebel et al.’s (2009) study revealed that red soils were highly nutrient-limited and exhibited reduced microbial abundance, arbuscular mycorrhizal (AM) fungal propagules, and plant growth.¹¹⁷⁶ Specific results for nutrient limitation and microbial abundance include:

- **Nutrient-limitation:** Net mineralizable nitrogen and available soil phosphorus were substantially reduced in red soil by 73% and 71%, respectively.¹¹⁷⁷ The severe loss of organic matter in red soil resulted in 71% less soil carbon than black soil, strongly contributing to the microbial community differences between red and black soil.¹¹⁷⁸ Overall, the severely burned red soil examined by Hebel et al. (2009) contained 71%, 69%, and 71% less total soil carbon and nitrogen, and less plant available phosphorus, respectively, than the less severely burned black soil.¹¹⁷⁹

¹¹⁶⁷ Verbatim from Rochefort et al. (2006, p. 244)

¹¹⁶⁸ Nearly verbatim from Rochefort et al. (2006, p. 245)

¹¹⁶⁹ Verbatim from Rochefort et al. (2006, p. 245)

¹¹⁷⁰ Verbatim from Rochefort et al. (2006, p. 245)

¹¹⁷¹ Nearly verbatim from Rochefort et al. (2006, p. 246)

¹¹⁷² Nearly verbatim from Beedlow et al. (2013, p. 175). *The importance of seasonal temperature and moisture patterns on growth of Douglas-fir in western Oregon, USA.*

¹¹⁷³ Verbatim from Beedlow et al. (2013, p. 175)

¹¹⁷⁴ Verbatim from Beedlow et al. (2013, p. 175)

¹¹⁷⁵ Nearly verbatim from Hebel et al. (2009, p. 158). *Invasive plant species and soil microbial response to wildfire burn severity in the Cascade Range of Oregon.*

¹¹⁷⁶ Verbatim from Hebel et al. (2009, p. 158)

¹¹⁷⁷ Verbatim from Hebel et al. (2009, p. 158). Hebel et al. refer the reader to Table 5 in the cited article for this information.

¹¹⁷⁸ Verbatim from Hebel et al. (2009, p. 153)

¹¹⁷⁹ Nearly verbatim from Hebel et al. (2009, p. 157)

- **Reduced microbial abundance:** In the freshly collected soil, total microbial biomass, as represented by phospholipid fatty acid analysis, was 60.9% lower in the red soil compared to black soil.¹¹⁸⁰

Northwest California

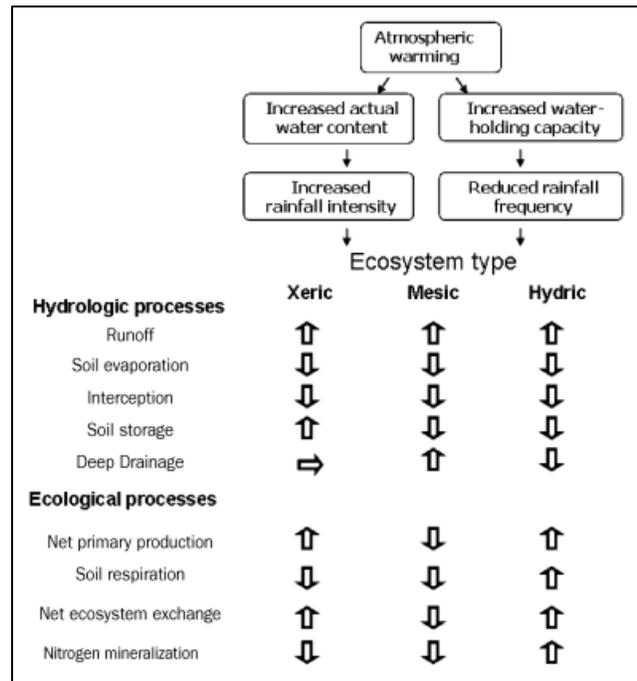
Information needed.

Future Projections

Global

Climate change is predicted to reduce the amount of carbon stores in soils world-wide.¹¹⁸¹ Modifications to the overall water balance and soil water dynamics of ecosystems are anticipated to affect most major ecosystem processes (Figure 30).¹¹⁸²

Figure 30. Hypothesized responses of mesic, xeric, and hydric ecosystems to extreme rainfall patterns characterized by fewer, but larger, individual events. We anticipate that extreme rainfall patterns will uniquely modify hydrological and ecological processes contingent on the ambient rainfall regimes of these systems. More extreme rainfall regimes are hypothesized to reduce soil water in mesic systems by increasing runoff and deep drainage, but increase it in xeric systems by increasing percolation depth and decreasing evaporative losses. The responses of hydric systems are predicted to be more similar to those of xeric ecosystems, because stress (anoxic) conditions will be alleviated more frequently. Increased (upward-pointing arrow), decreased (downward-pointing arrow), or neutral (right-pointing arrow) responses relative to ambient rainfall regimes represent hypotheses, because few empirical studies have focused on this aspect of climate change.
Source: Reproduced from Knapp et al. (2008, Figure 6, p. 8) by authors of this report.



Studies generally suggest that soil warming enhances nutrient uptake.¹¹⁸³ Although results from 32 individual sites showed considerable variation in response to warming, results from the meta-analysis showed that, across all sites and years, 2–9 years of experimental warming in the range of 0.5-11 °F (0.3-6.0 °C) significantly increased soil respiration rates by 20%, net nitrogen mineralization rates by 46%,

¹¹⁸⁰ Verbatim from Hebel et al. (2009, p. 153). Hebel et al. refer the reader to Table 3 in the cited article for this information.

¹¹⁸¹ Verbatim from Kareiva et al. (2012, Table 4.1). Kareiva et al. cite Parton & others (1995) for this information.

¹¹⁸² Verbatim from Knapp et al. (2008, p. 1). Knapp et al. refer the reader to Figure 6 in the cited article for this information.

¹¹⁸³ Verbatim from Lynch & St. Clair (2004, p. 108). Lynch & St. Clair cite BassiriRad (2000) for this information.

and plant productivity by 19%.¹¹⁸⁴ The response of soil respiration to warming was generally larger in forested ecosystems compared to low tundra and grassland ecosystems, and the response of plant productivity was generally larger in low tundra ecosystems than in forest and grassland ecosystems.¹¹⁸⁵ With the exception of aboveground plant productivity, which showed a greater positive response to warming in colder ecosystems, the magnitude of the response of these three processes to experimental warming was not generally significantly related to the geographic, climatic, or environmental variables evaluated in the analysis.¹¹⁸⁶

Potential interactions of global change with mineral stress in soils have also been evaluated. Affected soil processes include:

- **Transpiration-driven mass flow:** Global change variables that affect transpiration (e.g., CO₂, relative humidity, precipitation, light, temperature) should also affect the acquisition of these nutrients (i.e., nitrate, sulfate, calcium, magnesium, silicon).¹¹⁸⁷ Effects of global change variables on silicon transport to leaves are unknown but could have important ecological consequences.¹¹⁸⁸
- **Root growth and architecture:** Elevated atmospheric CO₂ generally increases plant carbon allocation to belowground processes, including root growth, respiration, and exudation.¹¹⁸⁹ Belowground effects of elevated CO₂ could have positive or negative feedbacks on plant productivity depending on nutrient availability and other belowground processes, including sequestration of carbon into soil pools.¹¹⁹⁰ Further, Knapp et al. (2008) predict that an increase in large rainfall events would favor the growth of more deeply rooted species in both mesic and xeric ecosystems, but for different reasons.¹¹⁹¹ In xeric ecosystems, greater soil water storage at depths where evaporation is less likely would promote deeper rooting strategies, whereas in mesic ecosystems, frequent drying of upper soil layers would negatively affect shallow-rooted herbaceous species that currently depend on a greater frequency of smaller rainfall events.¹¹⁹²
- **Mycorrhizal symbioses:** The effects of elevated CO₂ and temperature on arbuscular mycorrhizas appears to be mainly indirect, i.e., mediated by plant growth responses, rather than direct.¹¹⁹³ Numerous studies show increased resource allocation to mycorrhizal roots in plants exposed to

¹¹⁸⁴ Nearly verbatim from Rustad et al. (2001, p. 543-544). *A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. Note: Rustad et al. reported 95% confidence intervals for these results: 18% to 22% for soil respiration, 30% to 64% for net nitrogen mineralization, and 15% to 23% for plant productivity.*

¹¹⁸⁵ Verbatim from Rustad et al. (2001, p. 544)

¹¹⁸⁶ Nearly verbatim from Rustad et al. (2001, p. 544)

¹¹⁸⁷ Nearly verbatim from Lynch & St. Clair (2004, p. 105)

¹¹⁸⁸ Verbatim from Lynch & St. Clair (2004, p. 105)

¹¹⁸⁹ Verbatim from Lynch & St. Clair (2004, p. 105). Lynch & St. Clair cite Gorissen (1996), Gregory et al. (1996), and Rogers et al. (1996) for this information.

¹¹⁹⁰ Verbatim from Lynch & St. Clair (2004, p. 105). Lynch & St. Clair cite Zak et al. (1993) and Berntson & Bazzaz (1996) for information on the belowground effects of elevated CO₂ on plant productivity.

¹¹⁹¹ Nearly verbatim from Knapp et al. (2008, p. 9). Knapp et al. cite Schenk & Jackson (2002) for information on broadscale rooting patterns.

¹¹⁹² Verbatim from Knapp et al. (2008, p. 9). Knapp et al. cite Schwinning & Ehleringer (2001) and Huxman et al. (2004a) for this information.

¹¹⁹³ Verbatim from Lynch & St. Clair (2004, p. 106). Lynch & St. Clair cite Staddon et al. (2002) for this information.

elevated CO₂.¹¹⁹⁴ This may reflect the relative importance of edaphic constraints to plant growth in most ecosystems.¹¹⁹⁵

- **Root exudates** (i.e., compounds that leak from roots during the growth and expansion of root sections or from broken cells at the exit points of lateral roots): In some studies, elevated CO₂ caused no effect on root exudates, while in others it decreased root exudates but altered exudates composition.¹¹⁹⁶ Elevated CO₂ increases rhizosphere respiration, but it is not clear whether this is due to increased exudates per unit root surface area or simply increased root growth.¹¹⁹⁷
- **Biological nitrogen fixation:** Plant taxa capable of symbiotic nitrogen fixation are more responsive to elevated CO₂ than nonfixing taxa because they can directly utilize additional photosynthate to alleviate nitrogen limitation.¹¹⁹⁸ More severe drought intervals interspersed between infrequent, large rainfall events may produce pulses in soil nutrient availability, because available soil nitrogen increases during drought periods, when plant absorption is suppressed to a greater extent than nitrogen mineralization.¹¹⁹⁹ Consequently, the availability of soil water will coincide with high nitrogen levels during subsequent rainfall events, resulting in altered patterns of resource availability, with plant access determined by the species that can recover most rapidly from drought.¹²⁰⁰ The ability to adjust to these potential modifications in spatial and temporal patterns of resource availability may vary among species, potentially altering competitive interactions and the conditions that determine recruitment, plant establishment, and invasion.¹²⁰¹
- **Tissue dilution:** Elevated CO₂ can increase carbon gain in C3 plants, which can dilute tissue nutrient concentration.¹²⁰² For plants grown at double the current CO₂ concentration, the C:N ratio increases on average about 15%.¹²⁰³ Dilution effects for phosphorus are uncertain due to a small number of observations and variable results.¹²⁰⁴
- **Metal photochemistry:** Plants suffering sub-optimal availability of magnesium and transition metals because of high soil pH, base imbalances, aluminum toxicity, and manganese toxicity may be more sensitive to global change than healthy plants.¹²⁰⁵ Further, a number of global change

¹¹⁹⁴ Nearly verbatim from Lynch & St. Clair (2004, p. 106)

¹¹⁹⁵ Nearly verbatim from Lynch & St. Clair (2004, p. 106)

¹¹⁹⁶ Nearly verbatim from Lynch & St. Clair (2004, p. 106-107). Lynch & St. Clair cite Norby et al. (1987), Hodge (1996), and Uselman (2000) for information on elevated CO₂ having no effect on root exudates. Lynch & St. Clair cite Hodge & Millard (1998) and Hodge et al. (1998) for information on elevated CO₂ decreasing or altering the composition of root exudates.

¹¹⁹⁷ Verbatim from Lynch & St. Clair (2004, p. 107). Lynch & St. Clair cite Zak et al. (2000) and Nguyen (2003) for this information.

¹¹⁹⁸ Verbatim from Lynch & St. Clair (2004, p. 107)

¹¹⁹⁹ Verbatim from Knapp et al. (2008, p. 9). Knapp et al. cite Seastedt & Knapp (1993), Augustine & McNaughton (2006), and Yahdjian et al. (2006) for this information.

¹²⁰⁰ Verbatim from Knapp et al. (2008, p. 9). Knapp et al. cite Gebauer & Ehleringer (2000) for this information.

¹²⁰¹ Verbatim from Knapp et al. (2008, p. 9). Knapp et al. cite Lloret et al. (2004) and Peñuelas et al. (2004) for this information.

¹²⁰² Verbatim from Lynch & St. Clair (2004, p. 107)

¹²⁰³ Verbatim from Lynch & St. Clair (2004, p. 107). Lynch & St. Clair cite Gifford et al. (2000) for this information.

¹²⁰⁴ Verbatim from Lynch & St. Clair (2004, p. 107). Lynch & St. Clair cite Gifford et al. (2000) for this information.

¹²⁰⁵ Verbatim from Lynch & St. Clair (2004, p. 107)

variables can increase the formation of reactive oxygen species, including ozone, high light, UV radiation, temperature extremes, and drought.¹²⁰⁶

Southcentral and Southeast Alaska

Future changes in snow and ice will have cascading effects on the competition and soil nutrient cycling of coastal temperate forests.¹²⁰⁷

Western British Columbia

Very little is known about impacts of climate change on soils in B.C.¹²⁰⁸ Soils are living systems, with far greater species diversity than aboveground, and soil biology will likely present an important limitation to plant migration.¹²⁰⁹ There is growing evidence that changes in soil biology can cause ecosystems to collapse to an alternative regime that will hinder migration of species (other than weeds).¹²¹⁰

Regarding soil water, the trajectory of soil water stress across B.C.'s biogeoclimatic zones by the last three decades of the century shows an abrupt increase in water stress in May and June compared with current conditions in most biogeoclimatic zones (vs. 1961-1990; CGCM2 under A2x, an ensemble average of the three A2 runs).¹²¹¹ Still, soils are expected to recharge fully during the winter, but in late spring, reductions in precipitation toward the end of the century are likely to cause major limitations in available soil water in July and in subsequent months for some interior biogeoclimatic zones.¹²¹²

Pacific Northwest

Simulations for 6000 calendar years Before Present (cal yr BP) and A.D. 2050-2059 show similar patterns of soil moisture, particularly in the mountains of the northwestern U.S. (Figure 31).¹²¹³ The similar patterns of simulated summer soil moisture anomalies for 6000 cal yr BP and A.D. 2050-2059 suggest that future climate changes could create soil moisture conditions similar to those that occurred during times in the Holocene when fire frequencies were higher.¹²¹⁴

Northwest California

Information needed.

Information Gaps

Additional information is needed on observed trends and future projections throughout the NPLCC region, as few studies have been completed to date. A significant challenge is that soils have not been

¹²⁰⁶ Verbatim from Lynch & St. Clair (2004, p. 107). Lynch & St. Clair cite Foyer et al. (1994) for this information.

¹²⁰⁷ Verbatim from Wolken et al. (2011, p. 25)

¹²⁰⁸ Verbatim from Pojar (2010, p. 20)

¹²⁰⁹ Verbatim from Pojar (2010, p. 20)

¹²¹⁰ Verbatim from Pojar (2010, p. 20). Pojar cites Perry (1995) for this information.

¹²¹¹ Nearly verbatim from Coops et al. (2010, p. 519)

¹²¹² Nearly verbatim from Coops et al. (2010, p. 519)

¹²¹³ Verbatim from Whitlock et al. (2003, p. 14). Whitlock et al. refer the reader to Figure 3 in the cited article for this information.

¹²¹⁴ Verbatim from Whitlock et al. (2003, p. 15)

mapped in many subalpine and alpine areas of the Northwest.¹²¹⁵ To fill knowledge gaps in the understanding of ecological responses to more extreme rainfall regimes, Knapp et al. (2008) suggest that research programs focus on the need for (a) enhanced documentation and projection of intra-annual precipitation patterns at local, regional, and global scales; (b) greater insight into the direct effects of these modified rainfall delivery patterns on ecosystem structure and function, as well as interactions with other global change drivers; and (c) greater understanding of how modifying the dynamics of the ecosystem water balance may influence various biotic groups, with special emphasis on their responses to increased variability in soil water availability and stress levels.¹²¹⁶ There is a clear need for field experimentation combined with systems modeling to address this understudied component of climate change.¹²¹⁷

In addition, feedbacks from ecosystem processes to climate change, primarily via the enhanced production of greenhouse gases, need further study.¹²¹⁸ Key variables appear to be soil moisture and its correlates (water-holding capacity, water-filled pore space) and redox, which are influenced by soil water in terrestrial ecosystems but subject to feedbacks from productivity in aquatic ecosystems.¹²¹⁹

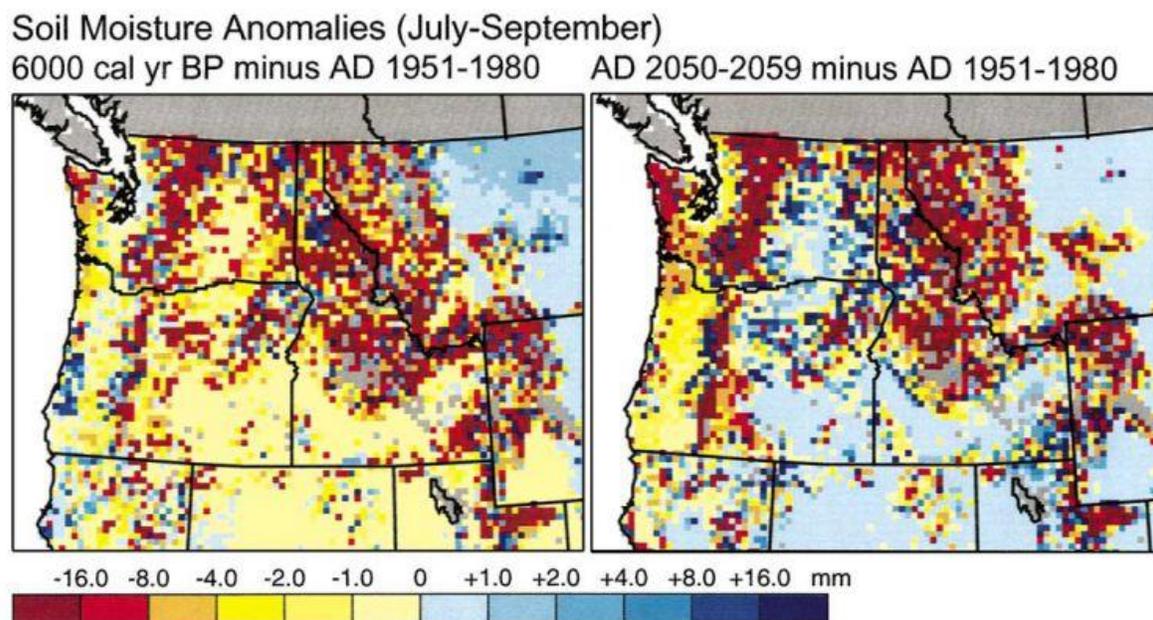


Figure 31. Mean summer (July–September) soil moisture anomalies (mm) for 6000 cal year BP (left) and A.D. 2050–2059 (10-year mean) (right) compared to present (A.D. 1951–1980, 30-year mean) in the northwestern US. The Olympic Mountains, Cascade Range, and Rocky Mountains display similar patterns of negative summer soil moisture anomalies for both time periods, indicating slightly drier soils in summer in these regions as compared with present conditions. Climate data: A.D. 1951–1980 (Thompson et al., 1999); 6000 cal year BP, CCM3 (Bonan, 1996); A.D. 2050–2059, HADCM2 HCGSa (Mitchell and Johns, 1997). Soil data: CONUS-Soil (Miller and White, 1998). Source: Reproduced from Whitlock et al. (2003, Figure 3, p.14) by authors of this report.

¹²¹⁵ Verbatim from Rochefort et al. (2006, p. 245)

¹²¹⁶ Nearly verbatim from Knapp et al. (2008, p. 9)

¹²¹⁷ Verbatim from Knapp et al. (2008, p. 9). Knapp et al. cite Weltzin et al. (2003) and Jentsch et al. (2007) for this information.

¹²¹⁸ Verbatim from Grimm et al. (2012, p. 3-37)

¹²¹⁹ Verbatim from Grimm et al. (2012, p. 3-37)

Discussion. Yellow-cedar, Yellow-cedar Decline, & Competition with Western Redcedar

Yellow-cedar and redcedar are abundant in the coastal temperate rainforest of the Pacific Northwest.¹²²⁰ Redcedar also has a substantial inland distribution in the Rocky Mountains in eastern British Columbia, and further south in Idaho and Montana.¹²²¹ Yellow-cedar is limited to high elevations throughout most of its range, especially in the southern portion, which extends to the California–Oregon border.¹²²² To the north, especially in Alaska, yellow-cedar grows from sea level to near timberline.¹²²³ Yellow-cedar and redcedar populations extend north into southeast Alaska, but redcedar reaches the northern limit of its range at about 57° north latitude (near Sitka).¹²²⁴

Locally, the yellow-cedar niche is strongly controlled by an affinity for wet soils.¹²²⁵ It is in these northern locales that the extensive mortality known as yellow-cedar decline occurs.¹²²⁶ The cumulative knowledge of yellow-cedar decline suggests that many interacting site and stand structure factors contribute to exposure freezing injury and possible tree death (Figure 32).¹²²⁷ Overall, the cause of yellow-cedar decline is influenced by climate that encouraged shallow rooting that was historically protected by snowpack, that more recently produced frequent warming in the winter that favored limited cold hardening,

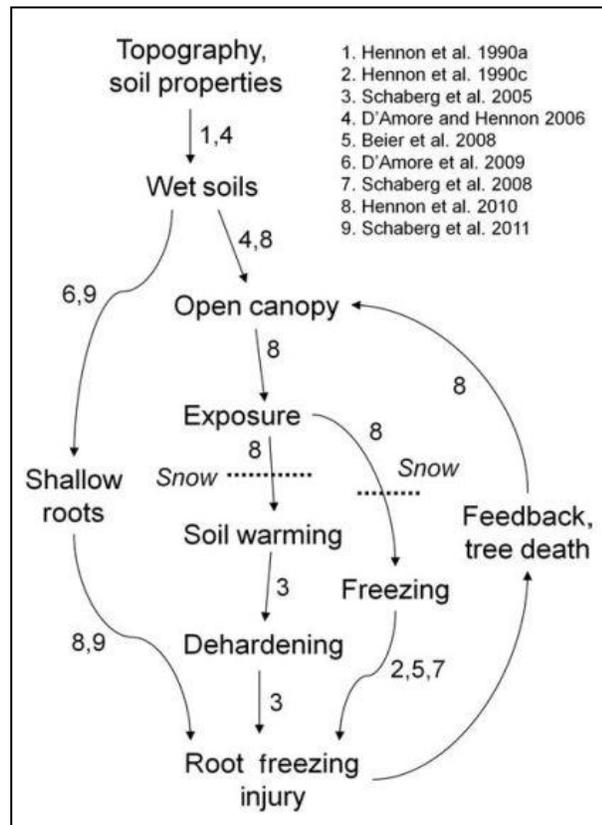


Figure 32. Cascading factors that contribute to yellow-cedar decline, culminating in fine-root mortality and tree death. The mitigating role of snow cover is shown. Tree death is a feedback that can expose adjacent trees to greater fluctuation in microclimate, thereby creating conditions for local spread of this forest decline. Numbers refer to studies on interacting factors.

Source: Reproduced from Hennon et al. (2012, Figure 3, p. 150) by authors of this report.

¹²²⁰ Verbatim from D'Amore et al. (2009, p. 2262). *Adaptation to exploit nitrate in surface soils predisposes yellow-cedar to climate-induced decline while enhancing the survival of western redcedar: A new hypothesis.*

¹²²¹ Verbatim from D'Amore et al. (2009, p. 2262). D'Amore et al. cite Minore (1983) for this information.

¹²²² Verbatim from Hennon et al. (2012, p. 148). *Shifting climate, altered niche, and a dynamic conservation strategy for yellow-cedar in the North Pacific coastal rainforest.*

¹²²³ Verbatim from Hennon et al. (2012, p. 148). Hennon et al. cite Harris (1990) for this information.

¹²²⁴ Verbatim from D'Amore et al. (2009, p. 2262). D'Amore et al. cite USDA Forest Service (1953) for this information.

¹²²⁵ Nearly verbatim from Hennon et al. (2012, p. 148). Hennon et al. cite Krajina (1969) and Neiland (1971) for this information.

¹²²⁶ Verbatim from Hennon et al. (2012, p. 148)

¹²²⁷ Verbatim from Hennon et al. (2010, p. 74). Hennon et al. refer the reader to Figure 2 in the cited article for this information.

and that reduced the protection of roots by snow.¹²²⁸ Shorter-term climate decadal oscillations exacerbate these latter two effects, which leads to pulses of mortality, such as that in the 1970s and 1980s.¹²²⁹

Competitive adaptations (i.e., of yellow-cedar and western redcedar) come at the risk of freezing injury to shallow roots, which was hidden as long as snow protected fine-roots from injury.¹²³⁰ Yellow-cedar expresses this injury as mortality, while redcedar may show only limited injury.¹²³¹

Observed Trends

Yellow-cedar is an ecologically, economically, and culturally important tree species that has experienced dramatic mortality in Southeast Alaska and nearby British Columbia for about 100 years.¹²³² The initiation of yellow-cedar decline in about 1900 approximately coincides with warming in the late 1800s that marked the end of the Little Ice Age (1400s-1800s).¹²³³ The ages of live and dead yellow-cedar trees in declining forests indicate that most regenerated during this snowy period of the Little Ice Age, conceivably becoming abundant in the low elevation areas where they are now dying.¹²³⁴ Yellow-cedar decline occurs in several thousand locations of concentrated mortality, totaling approximately 494,211 acres (200,000 hectares, ha) in southeast Alaska.¹²³⁵ Another 123,533 acres (50,000 ha) extend into adjacent British Columbia (Figure 33).¹²³⁶ Ground-based plots reveal the intensity of tree death; approximately 70% of the mature yellow-cedar trees are dead in these declining forests, but some areas experience nearly complete mortality.¹²³⁷ Decline at southern latitudes in British Columbia occurs considerably higher in elevation (i.e., 656-2297 feet; 200–700 meters).¹²³⁸ Along northern latitudes, decline is found at lower elevations, until finally, at the northern extent, 57.6 degrees north (°N) in Alaska, tree death is expressed in a narrow, low-elevation band from sea level to only 492 feet (150 meters).¹²³⁹ Most of the tree death is on wet soils where, paradoxically, yellow-cedar was previously well

¹²²⁸ Verbatim from Hennon et al. (2012, p. 153)

¹²²⁹ Verbatim from Hennon et al. (2012, p. 153)

¹²³⁰ Nearly verbatim from D'Amore et al. (2009, p. 2266)

¹²³¹ Verbatim from D'Amore et al. (2009, p. 2266)

¹²³² Verbatim from Schaberg et al. (2008, p. 1). *Influence of simulated snow cover on the cold tolerance and freezing injury of yellow-cedar seedlings*. Schaberg et al. cite Hennon & Shaw (1997) and Hennon et al. (2005) for this information.

¹²³³ Verbatim from D'Amore & Hennon (2006, p. 542). *Evaluation of soil saturation, soil chemistry, and early spring soil and air temperatures as risk factors in yellow-cedar decline*. D'Amore & Hennon cite Hennon et al. (1990c) for information on the initiation of yellow-cedar decline, Heusser (1952) for information on warming in the late 1800s, and Hebda (1995) for information on the length of the Little Ice Age.

¹²³⁴ Verbatim from Hennon et al. (2010, p. 85). *Influence of forest canopy and snow on microclimate in a declining yellow-cedar forest of southeast Alaska*. Hennon et al. cite Viens (2001) for information on yellow-cedar regeneration during the snowy period and Hennon & Shaw (1994) for information on the Little Ice Age.

¹²³⁵ Verbatim from Hennon et al. (2012, p. 148). Hennon et al. refer the reader to Figure 2, inset map, in the cited article for this information.

¹²³⁶ Verbatim from Hennon et al. (2012, p. 148). Hennon et al. cite Hennon et al. (2005) and Westfall & Ebata (2009) for this information.

¹²³⁷ Verbatim from Hennon et al. (2012, p. 148). Hennon et al. cite Hennon et al. (1990a) and D'Amore & Hennon (2006) for information on the intensity of tree death and refer the reader to Figure 1 in the cited article for information on near complete mortality in some areas.

¹²³⁸ Verbatim from Hennon et al. (2012, p. 152). Hennon et al. cite Hennon et al. (2005), Westfall & Ebata (2009), and Wootton & Klinkenberg (2011) for this information.

¹²³⁹ Verbatim from Hennon et al. (2012, p. 152)

adapted and competitive.¹²⁴⁰ Affected stands are typically composed of long-dead, recently dead, dying, and some surviving trees, which suggests that mortality is long term and continuing.¹²⁴¹

Research suggests adaptation to exploit nitrate in surface soils predisposes yellow-cedar to climate-induced decline while enhancing the survival of western redcedar.¹²⁴² If redcedar harbors fewer fine-roots in upper soil horizons and more roots in deeper mineral soil strata where calcium is less abundant, then redcedar may be somewhat less vulnerable to root injury associated with superficial freeze-thaw events.¹²⁴³ There is some evidence that redcedar is not uniformly shallow rooted.¹²⁴⁴ However, it is possible that redcedar is injured, but the damage is less severe and expressed differently than seen in yellow-cedar.¹²⁴⁵

Future Projections

A map of the 9.84-inch (250 mm) threshold of annual precipitation as snow (an indicator of yellow-cedar presence, based on detailed snow-accumulation models) indicates the changing snow conditions on Mount Edgecumbe (near Sitka, Alaska) and a future forecast in which snow accumulation adequate to protect superficial roots from freezing injury occurs only near the top of the mountain by the year 2080 (2020, 2050, and 2080 vs. 1961-1990; CGCM2 run with B2).¹²⁴⁶ Further, individual cold-weather periods in the spring with the potential to cause proximal injury (i.e., to yellow-cedar) continue to be frequent events, even in a warming climate.¹²⁴⁷

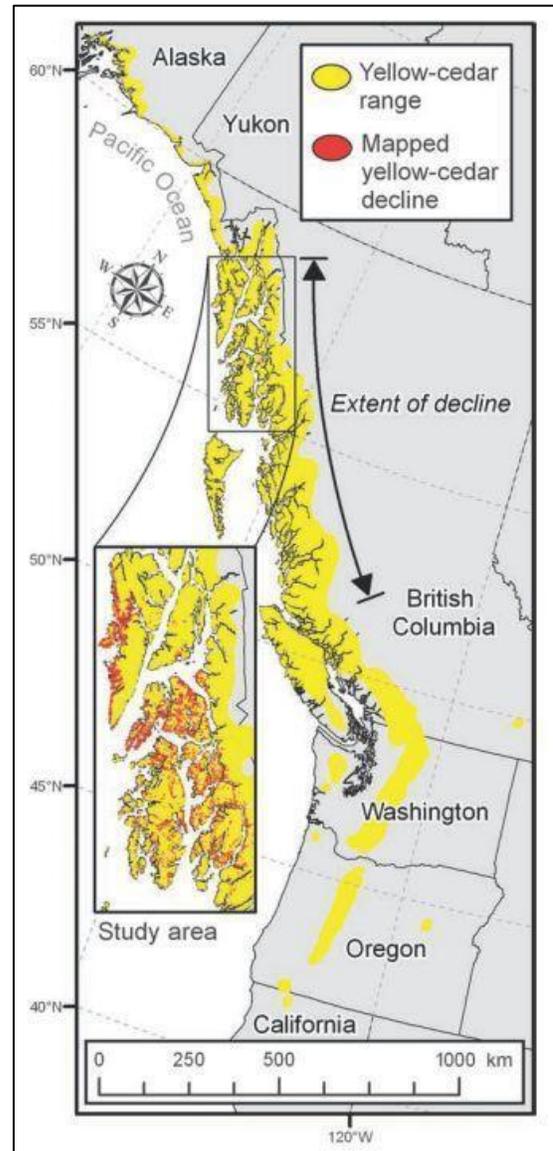


Figure 33. Natural distribution of yellow-cedar (Little 1971), latitudinal extent of decline covering approximately 1000 kilometers (km), and decline on 200,000 hectares in southeast Alaska (inset), mapped by aerial survey.

Source: Reproduced from Hennon et al. (2012, Figure 2, p. 149) by authors of this report.

¹²⁴⁰ Verbatim from Hennon et al. (2012, p. 148). Hennon et al. cite Johnson & Wilcock (2002) for information on tree death on wet soils and Neiland (1971) and Hennon et al. (1990a) for information on yellow-cedar being well-adapted and competitive previously on wet soils.

¹²⁴¹ Verbatim from Hennon et al. (2012, p. 148)

¹²⁴² Nearly verbatim from D'Amore et al. (2009, p. 2261)

¹²⁴³ Verbatim from D'Amore et al. (2009, p. 2265)

¹²⁴⁴ Verbatim from D'Amore et al. (2009, p. 2265). D'Amore et al. cite Bennett et al. (2002) for this information.

¹²⁴⁵ Nearly verbatim from D'Amore et al. (2009, p. 2265)

¹²⁴⁶ Nearly verbatim from Hennon et al. (2012, p. 152). Note: Hennon et al. are summarizing results from Wang et al. (2005).

¹²⁴⁷ Verbatim from Hennon et al. (2012, p. 153)

Hennon et al. (2012) nested soil drainage within favorable climate envelopes, with an emphasis on adequate snow-cover levels, to define habitat suitability as the foundation for a conservation and management strategy for yellow-cedar.¹²⁴⁸ They identified maladapted, persistent, and migration zones:

- **Maladaptation zone:** One species that might substitute for yellow-cedar in its maladapted zone is western redcedar, which grows in some of the declining yellow-cedar forests at lower elevations in Alaska and British Columbia, south of latitude 57 °N.¹²⁴⁹ The northern range extent and elevational limit of western redcedar suggest future warmer climate conditions will favor this tree in Alaska, which also appears to be the case in coastal British Columbia.¹²⁵⁰ In southern southeast Alaska, D'Amore et al. (2009) have observed abundant vigorous-appearing redcedar growing under the large dead yellow-cedars.¹²⁵¹ The mixed yellow-cedar and redcedar stands maintain forest conditions, and observation suggests the redcedars may replace yellow-cedars where they coexist.¹²⁵² Monitoring changes in tree species is under way to evaluate any response in the regeneration and growth of western hemlock, mountain hemlock, and shore pine.¹²⁵³
- **Persistence zone:** At a more landscape scale, yellow-cedar appears healthy on well-drained soils, where it mixes with other species, even in areas of little snow accumulation, where adjacent dead cedar forests exist on wet soils.¹²⁵⁴ It is on these productive sites that yellow-cedar roots more deeply and reaches its greatest stature but not its greatest competitive status.¹²⁵⁵ Western hemlock and Sitka spruce can outcompete yellow-cedar through greater rates of reproduction and faster growth, but active forest management can favor yellow-cedar.¹²⁵⁶
- **Migration zone:** When favorable climate develops beyond its existing range, yellow-cedar may be particularly slow to migrate because of its low reproductive capacity.¹²⁵⁷ Yellow-cedar is absent from much of the wide-spread forested wetland in these areas (i.e., toward the northeast), even though the conditions appear to be favorable for yellow-cedar and may have been so for thousands of years.¹²⁵⁸ As a cautious step, Hennon et al. (2012) conducted a trial planting of yellow-cedar near Yakutat, Alaska, (an area of discontinuous occurrence for yellow-cedar but still within its range limits) to test the survival and growth of yellow-cedar where it did not previously grow.¹²⁵⁹ The first-year survival rate was over 90%, which suggests that the targeted expansion of yellow-cedar is possible.¹²⁶⁰ *For additional information on assisted migration, please see Chapter IX.1.*

¹²⁴⁸ Nearly verbatim from Hennon et al. (2012, p. 154)

¹²⁴⁹ Verbatim from Hennon et al. (2012, p. 155)

¹²⁵⁰ Nearly verbatim from Hennon et al. (2012, p. 155). Hennon et al. cite Hamann & Wang (2006) for this information.

¹²⁵¹ Verbatim from D'Amore et al. (2009, p. 2266)

¹²⁵² Verbatim from D'Amore et al. (2009, p. 2266)

¹²⁵³ Verbatim from Hennon et al. (2012, p. 155)

¹²⁵⁴ Verbatim from Hennon et al. (2012, p. 156)

¹²⁵⁵ Verbatim from Hennon et al. (2012, p. 156). Hennon et al. cites Harris (1990) for this information.

¹²⁵⁶ Verbatim from Hennon et al. (2012, p. 156)

¹²⁵⁷ Verbatim from Hennon et al. (2012, p. 156). Hennon et al. cites Harris (1990) for this information.

¹²⁵⁸ Nearly verbatim from Hennon et al. (2012, p. 156)

¹²⁵⁹ Verbatim from Hennon et al. (2012, p. 156). Hennon et al. cite Hennon & Trummer (2001) for information on range limits for yellow-cedar.

¹²⁶⁰ Verbatim from Hennon et al. (2012, p. 156)

VI. Implications for Habitats

Habitat loss, degradation, and fragmentation is a leading cause of terrestrial biodiversity loss and the impairment of ecosystem functioning, resulting in a loss of ecosystem services.¹²⁶¹ Climate change is likely to interact with land cover change in ways that impact biodiversity, ecosystems, and ecosystem services, often in a way that exacerbates the detrimental effects of land cover change.¹²⁶² For example, habitat fragmentation may limit the pathways and increase the distance that species would need to disperse in response to climate change.¹²⁶³

Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations, the following implications of climate change for terrestrial habitats in the NPLCC region have been identified:

1. Changes in the growth and productivity of low- to mid-elevation forests
2. Changes in the range, distribution, and composition of low- to mid-elevation forests
3. Changes in the status, distribution, and connectivity of oak woodlands, savannas, prairies, and grasslands
4. Changes in the status, abundance, and distribution of alpine and subalpine habitats

Anthropogenic elevation of atmospheric CO₂ levels will affect global and regional vegetation distribution through the combined effects of the direct physiological effects of CO₂ and the indirect effects of CO₂-induced climate change, with topographically diverse regions expected to be particularly vulnerable.¹²⁶⁴

Alpine and subalpine ecosystems, dry grasslands, and wetlands are very different habitat types, but they have much in common: limited, patchy distributions; a high degree of fragmentation or isolation between occurrences; and very high biodiversity, including many species of plants and animals not adapted to other habitats.¹²⁶⁵ All three habitats also are especially susceptible to invasion by non-native plants, insects, and other animals.¹²⁶⁶ This combination of factors makes each of these habitats particularly vulnerable to disturbances resulting from climate change.¹²⁶⁷

The following structure will be used to present information on the implications of climate change for the NPLCC region's terrestrial habitats:

- **Observed Trends** – observed changes for southcentral and southeast Alaska, western British Columbia, the Pacific Northwest, western Washington, the Klamath Mountains, western Oregon, and northwest California. For context, summary information on observed changes globally or for western North America is also provided.

¹²⁶¹ Verbatim from Staudt et al. (2012, p. 5-5). Staudt et al. cite IPCC (2007), Fahrig (2003), Krauss & others (2010), and La Sorte (2006) for this information.

¹²⁶² Verbatim from Staudt et al. (2012, p. 5-5)

¹²⁶³ Verbatim from Staudt et al. (2012, p. 5-5). Staudt et al. cite Cristine & Kerr (2011) for this information.

¹²⁶⁴ Verbatim from Diffenbaugh et al. (2003, p. 13). *Vegetation sensitivity to global anthropogenic carbon dioxide emissions in a topographically complex region.*

¹²⁶⁵ Verbatim from Aubry et al. (2011, p. 7)

¹²⁶⁶ Verbatim from Aubry et al. (2011, p. 7)

¹²⁶⁷ Verbatim from Aubry et al. (2011, p. 7)

- **Future Projections** – projected direction and/or magnitude of change for southcentral and southeast Alaska, western British Columbia, Pacific Northwest, western Washington, western Oregon, and northwest California. For context, summary information on future projections globally or for western North America is also provided.
- **Information Gaps** – information and research needs identified by literature searches, as well as our summary of the sections missing information in this chapter.

1. Changes in the growth and development of low- to mid-elevation forests

Temperature, atmospheric CO₂ concentration, ecosystem water balance, and nitrogen cycling all interact to alter photosynthesis and growth.¹²⁶⁸ The critical issue is the balance among these factors affecting growth.¹²⁶⁹ For example, higher temperatures can benefit growth, but the most benefit would come with adequate nutrition and a positive water balance.¹²⁷⁰ Drought, for instance, can directly stress a tree's physiology, but also increases the vulnerability of trees to insect attacks and increases the probability for fire.¹²⁷¹ In addition, tree species have a wide range of susceptibility to tropospheric ozone, which also varies regionally, and damage caused by ozone is not completely offset by elevated CO₂.¹²⁷² At high concentrations, ozone reduces uptake of CO₂ by plants, and may predispose them to greater exposure to ultraviolet radiation, nutrient deficiency, water shortage, and attack by pathogens.¹²⁷³

Four developmental stages are conceptually recognized in temperate forests and widely cited in ecological literature.¹²⁷⁴ Oliver and Larson (1996) refer to these stages as stand initiation, stem exclusion, understory reinitiation, and old growth (Figure 34).¹²⁷⁵

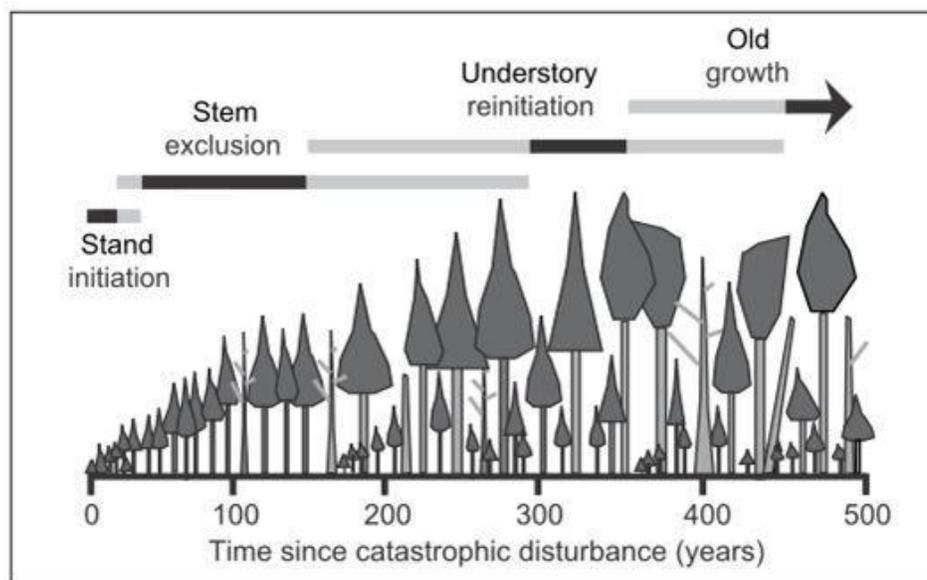


Figure 34. A conceptual timeline portraying developmental stages for temperate rainforests of southeast Alaska. Shaded bars represent temporal overlap among developmental stages.

Source: Reproduced from Nowacki & Kramer (1998, Figure 2, p. 2) by authors of this report.

¹²⁶⁸ Verbatim from Ryan et al. (2012, p. 43)

¹²⁶⁹ Verbatim from Ryan et al. (2012, p. 43)

¹²⁷⁰ Verbatim from Ryan et al. (2012, p. 43)

¹²⁷¹ Verbatim from Shafer et al. (2010, Case Study 2, p. 186). Shafer et al. refer the reader to Figure 5.5 in the cited report for this information.

¹²⁷² Verbatim from Ryan et al. (2012, p. 44). Ryan et al. cite Karnosky et al. (2005) for this information.

¹²⁷³ Verbatim from deVos, Jr. & McKinney (2007, p. 8). deVos, Jr. & McKinney cite Schulze et al. (2002) for this information.

¹²⁷⁴ Verbatim from Nowacki & Kramer (1998, p. 2). Nowacki & Kramer cite Alaback (1982), Bormann & Likens (1979), and Oliver & Larson (1996) for information on the four developmental stages in temperate forests.

¹²⁷⁵ Nearly verbatim from Nowacki & Kramer (1998, p. 2)

Observed Trends

Western North America

Forest growth appears to be slowly accelerating (less than 1% per decade) in regions where tree growth is limited by low temperatures and short growing seasons that are gradually being alleviated.¹²⁷⁶ Low-temperature limited geographic ranges show evidence of change resulting from warmer temperatures.¹²⁷⁷ For example, the northern range limit of lodgepole pine is advancing competitively against the more cold-tolerant black spruce in the Yukon.¹²⁷⁸

In a study of forest mortality, the evidence is consistent with contributions from exogenous causes, with regional warming and consequent drought stress being the most likely drivers.¹²⁷⁹ Analyses of longitudinal data from unmanaged old forests in the western United States showed that background (noncatastrophic) mortality rates have increased rapidly in recent decades (i.e., from 1955-2007, in forests ~450 years old

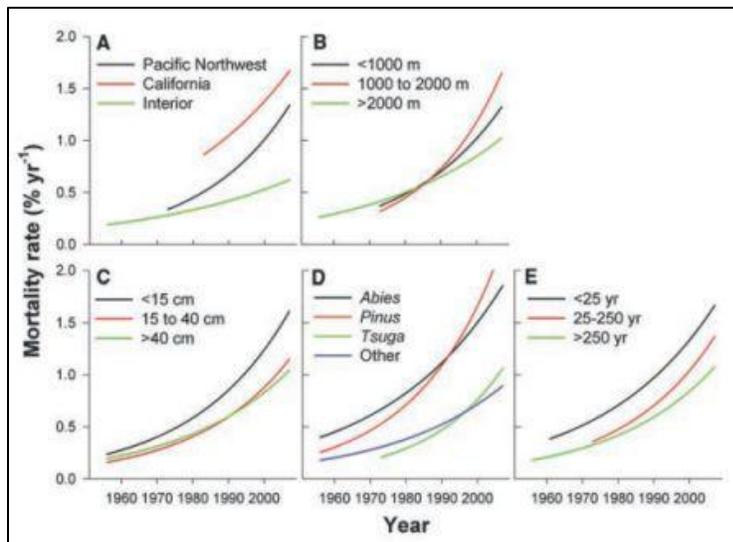


Figure 35. Modeled trends in tree mortality rates for (A) regions, (B), elevational class, (C) stem diameter class, (D) genus, and (E) historical fire return interval class.

Source: Reproduced from van Mantgem et al. (2009, Figure 2, p. 522) by authors of this report.

on average, and some plots exceeding 1000 years old), with doubling periods ranging from 17 to 29 years among regions (i.e., 17 years in the Pacific Northwest).¹²⁸⁰ Increases were also pervasive across elevations, tree sizes, dominant genera, and past fire histories (Figure 35).¹²⁸¹ Specific results for mortality and recruitment include:

- **Increased overall mortality:** Models showed that mortality rates increased in 87% of plots (Figure 36).¹²⁸²
- **Increased mortality across all tree genera:** The three most abundant tree genera in van Mantgem et al.'s (2009) plots (comprising 77% of trees) are dominated by different life history traits (hemlock, late

¹²⁷⁶ Verbatim from Running & Mills (2009, p. 9). Running & Mills cite Boisvenue & Running (2006), McKenzie et al. (2001), Joos et al. (2002), and Casperson (2000) for this information.

¹²⁷⁷ Verbatim from Running & Mills (2009, p. 9)

¹²⁷⁸ Nearly verbatim from Running & Mills (2009, p. 9). Running & Mills cite Johnstone & Chapin (2003) for this information.

¹²⁷⁹ Verbatim from van Mantgem et al. (2009, p. 523)

¹²⁸⁰ Nearly verbatim from van Mantgem et al. (2009, p. 521). *Widespread increase of tree mortality rates in the western United States.*

¹²⁸¹ Verbatim from van Mantgem et al. (2009, p. 521)

¹²⁸² Verbatim from van Mantgem et al. (2009, p. 522). van Mantgem et al. refer the reader to Figure 1 in the cited article for this information. van Mantgem et al. report the following statistics for this information: $P < 0.0001$, two-tailed binomial test.

successional; pine, generally shade-intolerant; fir, generally shade-tolerant); all three showed increasing mortality rates.¹²⁸³ Trees belonging to the remaining 16 genera (23% of all trees) collectively showed increasing mortality rates.¹²⁸⁴

- **No detectable trend in recruitment:** In contrast to mortality rates, recruitment rates increased in only 52% of plots – a proportion indistinguishable from random.¹²⁸⁵ There was no detectable trend in recruitment for all plots combined, nor when regions were analyzed separately.¹²⁸⁶

Southcentral and Southeast Alaska

The areal extent of sites undergoing primary succession in the coastal temperate forest region of Alaska has changed with the accelerated rate of glacier recession observed since the mid-19th century following advance during the Little Ice Age.¹²⁸⁷ Radial growth of white spruce in Alaska has decreased over the past 90 years because of increased drought stress on the dry southern aspects they occupy.¹²⁸⁸

Results from Kramer et al. (2001) suggest that while gap-scale disturbances may operate in both mature and old-growth forests, stand-replacement events control many of the age and size characteristics in coastal temperate rain forests, especially those most prone to catastrophic storm damage.¹²⁸⁹ Based on photo-interpretation, 20% (65,700 acres, 26,588 hectares) of the forest on Kuiu Island

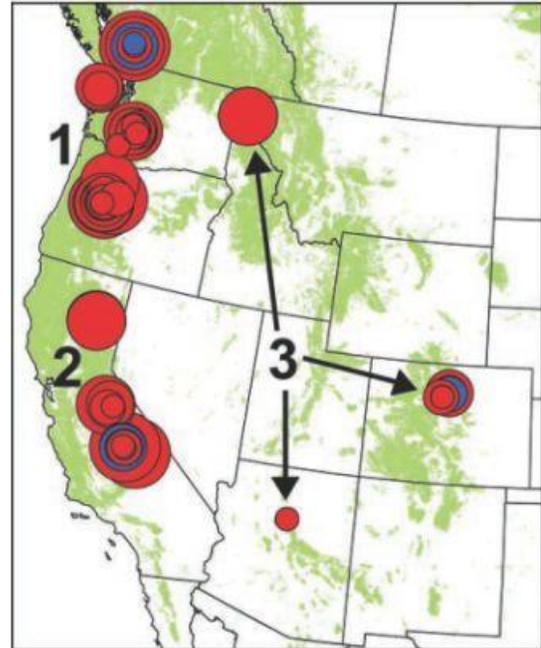


Figure 36. Locations of the 76 plots in the western United States and southwest British Columbia. Red and blue symbols indicate, respectively, plots with increasing or decreasing mortality rates. Symbol size corresponds to annual fractional change in mortality rate (smallest symbol, $<0.025 \text{ year}^{-1}$; largest symbol, $>0.100 \text{ year}^{-1}$; the three intermediate symbol sizes are scaled in increments of 0.025 year^{-1}). Numerals indicate groups of plots used in analyses by region: (1) Pacific Northwest, (2) California, and (3) interior. Forest cover is shown in green.

Source: Reproduced from van Mantgem et al. (2009, Figure 1, p.522) by authors of this report.

¹²⁸³ Verbatim from van Mantgem et al. (2009, p. 522). van Mantgem et al. refer the reader to Figure 2 and Table 1 in the cited article for this information.

¹²⁸⁴ Verbatim from van Mantgem et al. (2009, p. 522). van Mantgem et al. refer the reader to Figure 2 and Table 1 in the cited article for this information.

¹²⁸⁵ Verbatim from van Mantgem et al. (2009, p. 522). van Mantgem et al. report the following statistics for this information: $P = 0.80$, two-tailed binomial test.

¹²⁸⁶ Verbatim from van Mantgem et al. (2009, p. 522). van Mantgem et al. report the following statistics for this information: $P \geq 0.20$, Generalized Nonlinear Mixed Model. van Mantgem et al. also refer the reader to Table S2 in the cited article for this information.

¹²⁸⁷ Nearly verbatim from Wolken et al. (2011, p. 17)

¹²⁸⁸ Verbatim from Running & Mills (2009, p. 9). Running & Mills cite Barber et al. (2000) for this information.

¹²⁸⁹ Nearly verbatim from Kramer et al. (2001, p. 2760)

(southeast Alaska) was identified as even-aged stands which originated from windthrow.¹²⁹⁰ Of this 20%, stand origination and forest age varied:

- **Stand origination:** Stands that originated from a storm event that occurred approximately 110 years ago comprised 40% of plots.¹²⁹¹ The remaining even-aged patches originated from at least four other major storms that occurred anywhere from 50 to 400 years ago.¹²⁹²
- **Forest age:** Ground-truthing the remotely sensed data set resulted in 46% of the even-aged forests being classified as younger (< 150-year-old) confirmed windthrow, with an additional 48% identified as older (> 150-year-old) probable windthrow.¹²⁹³ No forests more than 150 years old (mature forests) could be confirmed as windthrown because decomposition made identification of dead and downed stems difficult.¹²⁹⁴

Western British Columbia

Forests cover 135 million acres (55 million hectares, ha), or about 60% of B.C.'s 235 million acres (95 million ha).¹²⁹⁵ From the south coast of British Columbia north through southeast Alaska, forests are dominated by cedars, hemlocks, true firs, and Sitka spruce.¹²⁹⁶ Older forests provide specialized habitats not found in younger forests.¹²⁹⁷ The wetter ecosystems in the Coast region and along the Interior mountain ranges have fewer wildfires and higher proportions of older forests (Figure 37).¹²⁹⁸ In addition, along the coast, frost is less restrictive, and across Vancouver and the Queen Charlotte Islands, its impact on growth is negligible.¹²⁹⁹

Landscapes are dominated by old-growth forests and major disturbances are infrequent enough that the ages of dominant trees, often used to indicate the time since last fire in a stand, bear little relation to stand age.¹³⁰⁰ Thus, even though individual trees may be very long-lived (e.g., 500 to >1000 years, depending on species), the age of such stands (i.e., those without a history of human intervention) essentially cannot

¹²⁹⁰ Nearly verbatim from Kramer et al. (2001, p. 2757). Kramer et al. refer the reader to Figure 2 in the cited article for this information.

¹²⁹¹ Verbatim from Kramer et al. (2001, p. 2757). Kramer et al. refer the reader to Figure 4a in the cited article for this information.

¹²⁹² Verbatim from Kramer et al. (2001, p. 2757). Kramer et al. refer the reader to Figure 4a in the cited article for this information.

¹²⁹³ Verbatim from Kramer et al. (2001, p. 2757)

¹²⁹⁴ Verbatim from Kramer et al. (2001, p. 2757)

¹²⁹⁵ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 36)

¹²⁹⁶ Nearly verbatim from Lertzman et al. (2002, p. 5). Lertzman et al. cite Veblen & Alaback (1996) and Meidinger & Pojar (1991) for this information.

¹²⁹⁷ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 42)

¹²⁹⁸ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 42)

¹²⁹⁹ Verbatim from Coops et al. (2010, p. 519). Coops et al. refer the reader to Figures 4A and 4B in the cited article for this information.

¹³⁰⁰ Verbatim from Lertzman et al. (2002, p. 5-6). Lertzman et al. cite the Scientific Panel for Sustainable Forest Practices in Clayoquot Sound (1995) and Lertzman et al. (1996) for information on old-growth forests. Lertzman et al. cite Johnson & Gutsell (1994) for information on using the ages of dominant trees to indicate time since the most recent fire.

be determined by standard methods and is often likely to be far greater than that of the oldest tree.¹³⁰¹ However, specific forest ages in B.C. are available and include:

- Forests over 80 years old amount to 72% (39.6 million hectares; ~153,000 mi²) of the province's forests (72% in the Interior and 73% on the Coast).¹³⁰²
- Forests over 140 years old exist in all 16 biogeoclimatic zones and cover 22.6 million hectares (~87,100 mi²; 24% of B.C. land; 43% of forests).¹³⁰³
 - Of this area, forests over 250 years old cover 7.1 million hectares (~27,000 mi²; 7.5% of B.C. land; 31% of old forests; 13% of B.C.'s total forests).¹³⁰⁴
- Only 4% (2.2 million hectares; ~8,500 mi²) of the forests are less than 20 years old.¹³⁰⁵

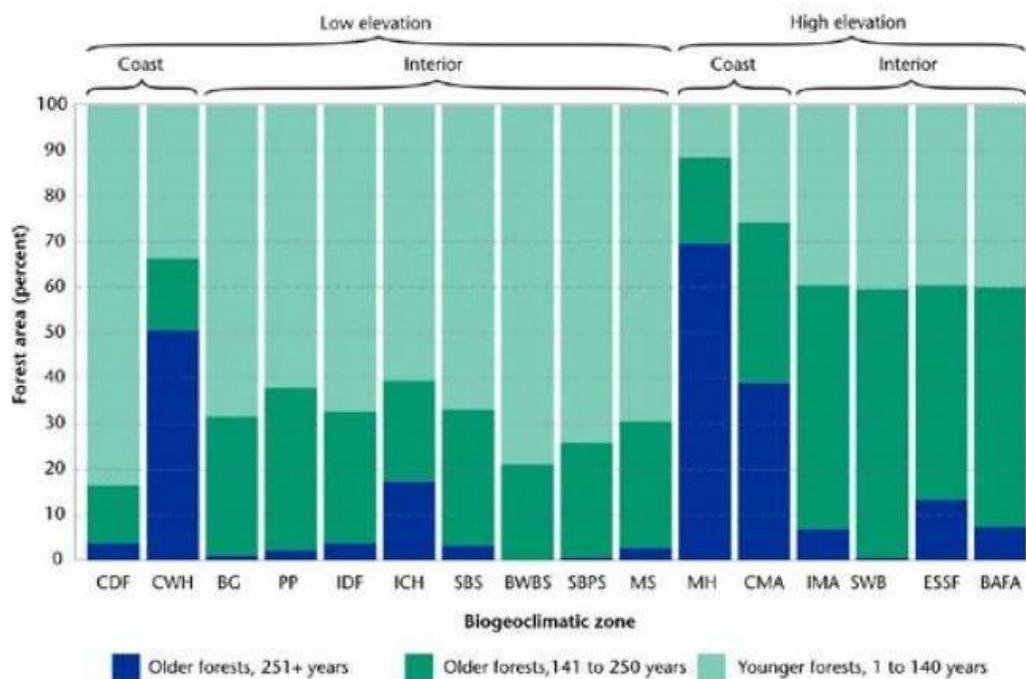


Figure 37. In each biogeoclimatic zone, percent of forest area by age class, 2008.

Source: Reproduced from B.C. Ministry of Forests, Mines, and Lands. (2010, Figure 1-4, p. 42) by authors of this report.

Note: Biogeoclimatic zones in the NPLCC region include Coastal Douglas-fir (CDF), Coastal Western Hemlock (CWH), Sub-boreal Spruce (SBS), Mountain Hemlock (MH), Coastal Mountain-heather Alpine (CMA), Engelmann Spruce-Subalpine Fir (ESSF), and Alpine Tundra (AT; not shown).

¹³⁰¹Verbatim from Lertzman et al. (2002, p. 6). Lertzman et al. cite the Pojar & MacKinnon (1994) for information on the age of individual trees, e.g., 500 to > 1000 years depending on species.

¹³⁰²Nearly verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 41)

¹³⁰³Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 36)

¹³⁰⁴Nearly verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 36)

¹³⁰⁵Nearly verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 39)

Pacific Northwest

Low elevation, late successional forests support the greatest biodiversity and biomass accumulation in the Pacific Northwest.¹³⁰⁶ Accelerated biomass accumulation has been observed in temperate deciduous forests in the eastern United States and in temperate-maritime forests in the Pacific Northwest.¹³⁰⁷ Likely explanations of these increases in secondary forest biomass accumulation rates include increased atmospheric CO₂, increased temperature, increased moisture, and increased growing season length.¹³⁰⁸ Thus, climate change appears to be increasing the rate of forest regrowth in some temperate forests; however, parallel studies have yet to be conducted in other regions.¹³⁰⁹

Douglas-fir growth in the Pacific Northwest was highly variable in space and time during the 20th century, and this variability was generally associated with water limitation (e.g., positively correlated with summer precipitation and actual evapotranspiration but negatively correlated with summer maximum temperature and potential evapotranspiration).¹³¹⁰ The strength of the correlation between water deficit and tree growth depends on the location of the stand along a gradient of mean summer water deficit – the most water-limited stands had the greatest sensitivity.¹³¹¹ However, radial growth in Douglas-fir can be limited by low temperature at the highest, snowiest elevations, but growth is often limited by moisture in places that develop modest snowpack.¹³¹² At elevations below the seasonal snowpack, growth is negatively related to summer and annual temperature.¹³¹³ The negative temperature effect is thought to result from increasing water deficit in trees as soil moisture is depleted during summer drought.¹³¹⁴ For the coastal variety of Douglas-fir, Chen et al. (2010) found positive correlations of tree ring width with summer precipitation and temperature of the preceding winter (i.e., November temperature), indicating that growth of coastal populations was limited by summer dryness and that photosynthesis in winter contributed to growth (time period: 1901-1980).¹³¹⁵ However, Chen et al. (2010) could not find a regional-level climate index that shows consistent positive or negative impacts of climate change on the observed chronology samples.¹³¹⁶ *For additional information on future projections for Douglas-fir, please see the Future Projections section of this chapter.*

¹³⁰⁶ Verbatim from North Cascades Conservation Council (2010, p. 20). North Cascades Conservation Council cite Ruggiero (1991) and Johnson & O'Neil (2001) for this information.

¹³⁰⁷ Verbatim from Anderson-Teixeira et al. (2013, p. 9). Anderson-Teixeira et al. cite McMahon et al. (2010a), Foster et al. (2010), and McMahon et al. (2010b) for information on the eastern U.S. temperate deciduous forests and Hember et al. (2012) for information on temperate-maritime forests in the Pacific Northwest. Anderson-Teixeira et al. also refer the reader to Figure 4 in the cited article for information on the Pacific Northwest forests.

¹³⁰⁸ Verbatim from Anderson-Teixeira et al. (2013, p. 9). Anderson-Teixeira et al. cite McMahon et al. (2010a) and Hember et al. (2012) for this information

¹³⁰⁹ Verbatim from Anderson-Teixeira et al. (2013, p. 9)

¹³¹⁰ Verbatim from Littell et al. (2010, p. 138). Littell et al. cite Littell et al. (2008) for information on the spatial and temporal variability of Douglas-fir growth in the 20th century.

¹³¹¹ Verbatim from Littell et al. (2010, p. 138)

¹³¹² Nearly verbatim from Beedlow et al. (2013, p. 174). Beedlow et al. cite Case & Peterson (2005) and Littell et al. (2008) for this information.

¹³¹³ Verbatim from Beedlow et al. (2013, p. 174). Beedlow et al. cite Case & Peterson (2005) for this information.

¹³¹⁴ Verbatim from Beedlow et al. (2013, p. 174). Beedlow et al. cite Littell et al. (2008) for this information.

¹³¹⁵ Nearly verbatim from Chen et al. (2010, p. 3384)

¹³¹⁶ Verbatim from Chen et al. (2010, p. 3384). *Geographic variation in growth response of Douglas-fir to interannual climate variability and projected climate change.*

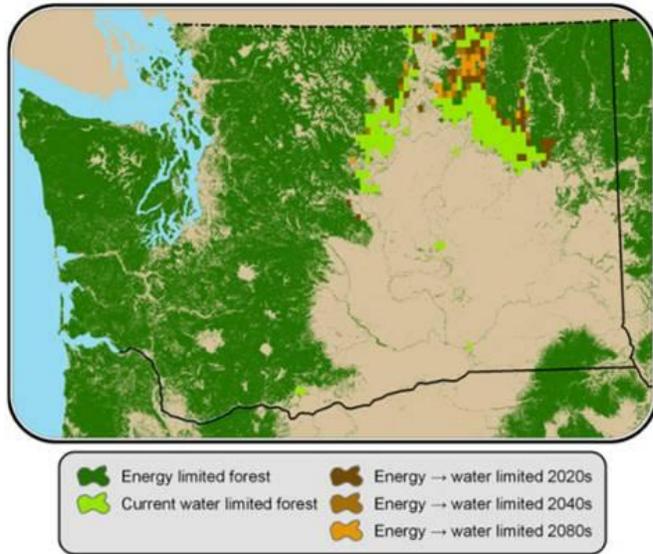


Figure 38. Locations of energy- and severely water-limited forests in Washington in the current climate as well as predicted changes to water limitation in the future. Energy-limited forests can be water-limited seasonally, but we focused on the chronic, long-term water limitation for forests where summer PET exceeds annual precipitation as the area most vulnerable to deficit related impacts. Climate projections indicate that areas within the Okanogan Highlands and the foothills of the northeastern Cascade Mountains will transition to severely water-limited forest by the 2080s. Forested area grid cells are smaller than the VIC cells (see Section 2.2) used to derive water balance variables for this map. Energy-limited forests can be either light- or thermally limited—we do not consider the former. Figure: Robert Norheim.

Source: Reproduced from Littell et al. (2010, Fig. 3, p. 139) by authors of this report.

In addition, the effect of chronic, profuse Swiss needle cast (i.e., a foliar disease of Douglas-fir) colonization of Douglas-fir foliage is to reduce growth rates of affected trees relative to competing species, such as spruce and hemlock.¹³¹⁷ Generally faster growing than western hemlock, Douglas-fir is an inferior competitor where Swiss needle cast disease pressure is high.¹³¹⁸

In the coastal lowlands and interior valleys of the western Coast Range, seasonal climatic conditions are the most favorable for Swiss needle cast growth and reproduction.¹³¹⁹ In these areas, a distinct natural forest type has historically been dominated by western hemlock and Sitka spruce, with Douglas-fir occurring only sporadically.¹³²⁰ Douglas-fir gradually becomes more abundant in natural forests at higher elevations and further inland, as the Sitka spruce zone gradually merges into the western hemlock vegetation zone, where Douglas-fir is a successional dominant and where climatic conditions are less favorable for Swiss needle cast growth.¹³²¹ This leads to the conclusion that the Sitka spruce vegetation zone occurs as a consequence not only of favorable habitat for Sitka spruce and western hemlock, but also because of the inhibition of their main competitor, Douglas-fir, as a result of Swiss needle cast disease.¹³²²

Western Washington

In Washington State, lodgepole pine is rarely found on sites with climatic water deficit greater than 9.84 inches (250 millimeters; occurred in two of 1,630 plots).¹³²³

¹³¹⁷ Nearly verbatim from Stone et al. (2008, p. 175)

¹³¹⁸ Verbatim from Stone et al. (2008, p. 175)

¹³¹⁹ Verbatim from Stone et al. (2008, p. 175)

¹³²⁰ Verbatim from Stone et al. (2008, p. 175)

¹³²¹ Verbatim from Stone et al. (2008, p. 175)

¹³²² Verbatim from Stone et al. (2008, p. 175)

¹³²³ Nearly verbatim from Littell et al. (2010, p. 144)

Western Oregon

At five mature, closed-canopy forest stands dominated by Douglas-fir and located along an elevation gradient from the Pacific coast to the west slope of the Cascade Mountains, maximum daily air temperature and plant available soil water were similar in relative importance to tree growth at four of the five sites.¹³²⁴ Plant available soil water was substantially more important at one site.¹³²⁵ Growth rate increased with maximum daily air temperature to an optimum (T_{opt}) and decreased with higher maximum daily air temperature.¹³²⁶ At the two drier sites (Moose Mountain and Toad Creek), maximum daily air temperature and plant available soil water affected growth interactively in that T_{opt} decreased with decreasing plant available soil water.¹³²⁷ More specifically:

- At Beedlow et al.'s (2013) sites, plant available soil water typically fell below 50% in July and maximum daily air temperature typically exceeded T_{opt} before plant available soil water fell below 50%.¹³²⁸
- At Moose Mountain, the T_{opt} dropped from 72.1 °F (22.3 °C) in May to 68.4 °F (20.2 °C) by July.¹³²⁹
- The decrease at Toad Creek was more dramatic, dropping from 87.3 °F (30.7 °C) in June to 54.9 °F (12.7 °C) in September.¹³³⁰

While Beedlow et al. (2013) were not able to precisely determine the level of plant available soil water at which T_{opt} began to decrease at Moose Mountain and Toad Creek, Granier et al. (1999) suggests that water stress begins when 40% of plant available water remains in the soil.¹³³¹ In Douglas-fir, sap flux begins to fall rapidly once approximately 50% of available water in the upper ~2 feet (0.6 meters) of soil is used.¹³³² Beedlow et al. (2013) conclude that both temperature and water are currently limiting growth in western Oregon, and that shifting T_{opt} is exacerbating temperature limitation at drier sites.¹³³³

¹³²⁴ Nearly verbatim from Beedlow et al. (2013, p. 174)

¹³²⁵ Verbatim from Beedlow et al. (2013, p. 174)

¹³²⁶ Verbatim from Beedlow et al. (2013, p. 174)

¹³²⁷ Nearly verbatim from Beedlow et al. (2013, p. 174)

¹³²⁸ Nearly verbatim from Beedlow et al. (2013, p. 182). Beedlow et al. refer the reader to Figure 5 in the cited article for this information.

¹³²⁹ Verbatim from Beedlow et al. (2013, p. 179)

¹³³⁰ Verbatim from Beedlow et al. (2013, p. 179)

¹³³¹ Nearly verbatim from Beedlow et al. (2013, p. 182)

¹³³² Nearly verbatim from Beedlow et al. (2013, p. 182). Beedlow et al. cite Warren et al. (2005) for this information.

¹³³³ Nearly verbatim from Beedlow et al. (2013, p. 183)

Northwest California

In northern California mixed-evergreen forest, late-successional forest structure is most likely to be found in lower slope positions and on north and east aspects.¹³³⁴

The coast redwood is the tallest living tree species and notably long-lived, with some individuals exceeding 2,000 yr in age.¹³³⁵ Redwoods are watered primarily by winter rains that residually drain through steep coastal watersheds during nearly rainless summer months.¹³³⁶ *For additional information on redwood forest hydrology, please see Chapter IV.1.*

Future Projections

Western North America

Western forests, particularly those that rely on snowmelt for their water, will probably show lower growth under drier conditions.¹³³⁷ The potential for enhancing carbon gain would be low in regions where nitrogen deposition is already high (e.g., the Northeast) and high in regions where nitrogen deposition is low (e.g., the Southwest).¹³³⁸ For western U.S. forests, climate-driven increased fire and bark beetle outbreaks are likely to substantially

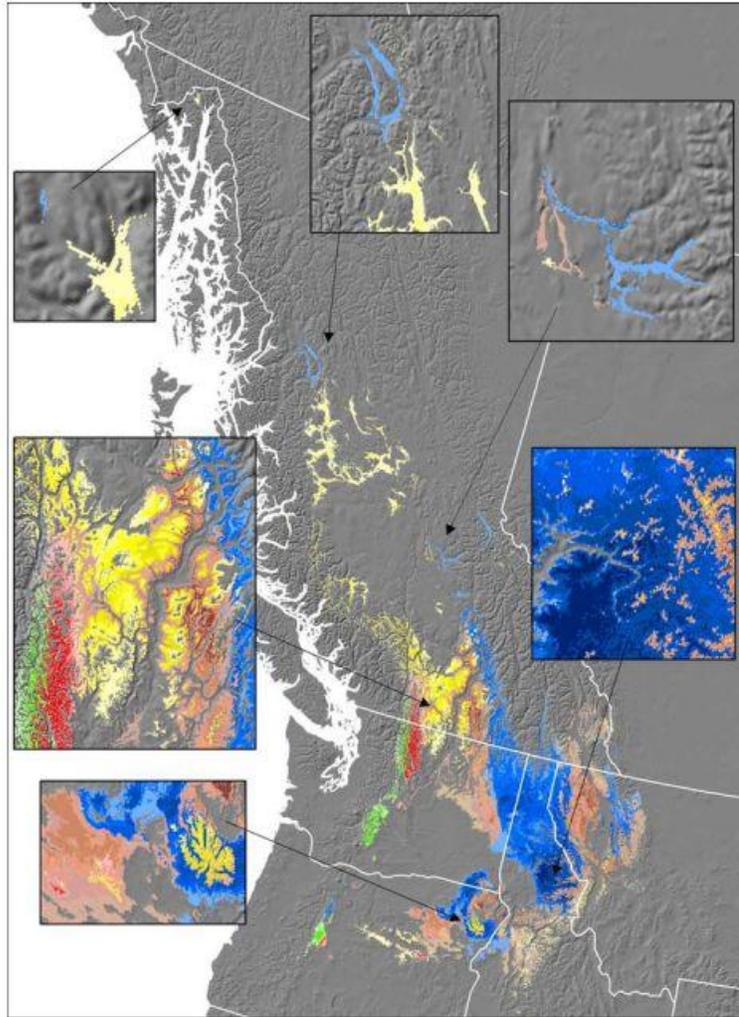


Figure 39. Concurrence among three GCMs and two scenarios for the 2030 location of five seed zones. Zones are coded by the color paths in Fig. 9 (in Rehfeldt & Barry, 2010), blue, yellow, brown, green and red, with the lightest shades denoting agreement among 3 projections and the darkest, agreement among 6 projections.

Source: Reproduced from Rehfeldt & Jaquish (2010, Figure 10, p. 301) by authors of this report.

¹³³⁴ Verbatim from Agee (1998). Agee cites Taylor & Skinner (*in review*) for this information.

¹³³⁵ Verbatim from Johnstone & Dawson (2010, p. 4533). Johnstone & Dawson cite Noss (2000) for this information.

¹³³⁶ Verbatim from Johnstone & Dawson (2010, p. 4533)

¹³³⁷ Verbatim from Ryan et al. (2012, p. 44). Ryan et al. cite Boisvenue & Running (2010) and Hu et al. (2010) for this information.

¹³³⁸ Verbatim from Ryan et al. (2012, p. 44)

reduce forest carbon storage and storage rate, jeopardizing the current U.S. forest sink.¹³³⁹ Further, tree regeneration is uncertain for western montane forests, where fire intensity exceeds historical patterns.¹³⁴⁰

Concurrence among projections (i.e., of the future distribution of western larch) was used to locate those sources of seed that should be best attuned genetically to future climates (Figure 39).¹³⁴¹ Consistent with patterns of genetic variation described by geographic variables, these five seed zones tend to be stratified by elevation.¹³⁴² Please see Chapter VI.2 for additional information on the projection of the future distribution of western larch.

Similar to Weiskittel et al. (2011) and Coops et al. (2010), Weiskittel et al.'s (2012) analysis suggests significant future changes in Douglas-fir productivity as measured by site index

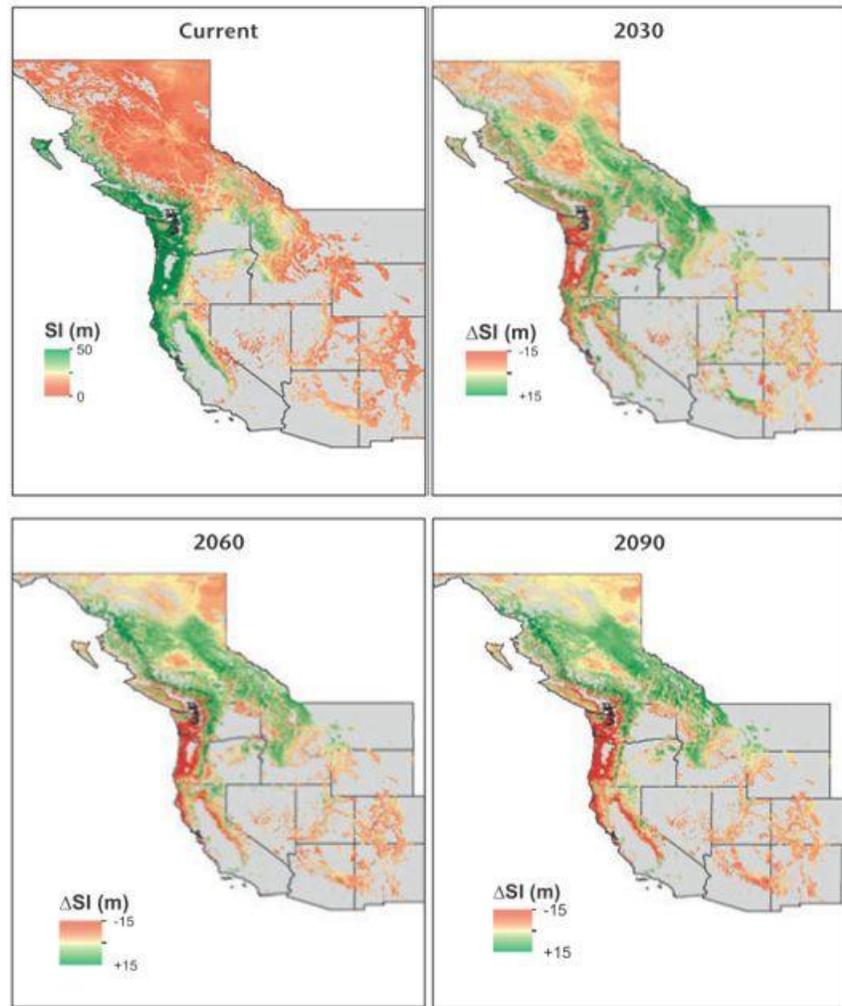


Figure 40. Predicted current and future changes in productivity of Douglas-fir in terms of base-age 50 years site index (m) based on the developed random forest model and the Canadian Center for Climate Modeling and Analysis general circulation model under the A2 emissions scenario.

Source: Reproduced from Weiskittel et al. (2012, Figure 2, p. 73) by authors of this report.

¹³³⁹ Verbatim from Ryan et al. (2012, p. 45). Ryan et al. cite Metsaranta et al. (2010) and Westerling et al. (2006, 2011) for information on reductions in forest carbon storage and storage rate.

¹³⁴⁰ Verbatim from Ryan et al. (2012, p. 45). Ryan et al. cite Bonnet et al. (2005) and Haire & McGargial (2010) for this information.

¹³⁴¹ Nearly verbatim from Rehfeldt & Jaquish (2010, p. 283). *Ecological impacts and management strategies for western larch in the face of climate-change*.

¹³⁴² Verbatim from Rehfeldt & Jaquish (2010, p. 300). Rehfeldt & Barry cite Rehfeldt (1982, 1995) for information on patterns of genetic variation described by geographic variables. Rehfeldt & Barry also refer the reader to Figure 9 (upper left panel) in the cited article for information on the five seed zones.

throughout its entire range (Figure 40).¹³⁴³ In general, the overall spatial pattern was that coastal areas showed the highest reductions in site index, while interior areas showed increased potential productivity.¹³⁴⁴ This parallels the findings presented for Douglas-fir habitat.¹³⁴⁵ This is likely because coastal areas will generally become warmer and drier than currently, while the growing season length will increase in interior areas.¹³⁴⁶ However, seed source and future climate would need to be matched in order to realize the expected increases in site index predicted in certain areas.¹³⁴⁷

Southcentral and Southeast Alaska

Trees and certain shrubs that use the C₃ pathway will benefit more from warming than will grasses and other shrubs that use the C₄ pathway.¹³⁴⁸ Longer growing seasons with warmer temperatures likely will result in faster growth.¹³⁴⁹

Although the frequency and intensity of windstorms are difficult to predict, wind-protected landscapes support old-growth stands with multi-aged structures where stem decays and other disease agents produce fine-scale disturbances involving the death of individual or small groups of trees.¹³⁵⁰ Projected increases in temperature and growing season length will increase growth rates of these fungi (i.e., stem-decay fungi), which combined with the susceptibility of decayed trees to wind-breakage, could increase the proportion of early-successional tree species.¹³⁵¹

Western British Columbia

With respect to tree species, the factors of rapid climate change and increased disturbances will ultimately lead to genetic erosion (reduced genetic diversity) and declining productivity of populations for several forest generations at least.¹³⁵² This decline probably will be greatest for genetically specialized species, for example, Douglas-fir and ponderosa pine.¹³⁵³ Further, projected effects of climate shifts on productivity vary among regions of British Columbia; they also vary according to the modelling approach used:¹³⁵⁴

- **Wetter coastal ecosystems** could benefit from a longer growing season.¹³⁵⁵
- **Drier ecosystems** in the southern interior and along the south coast are likely to experience increased drought and decreasing productivity.¹³⁵⁶
- *For information on BC's high-elevation ecosystems, please see Chapter VI.4.*

¹³⁴³ Nearly verbatim from Weiskittel et al. (2012, p. 77). *Projected future suitable habitat and productivity of Douglas-fir in western North America.*

¹³⁴⁴ Verbatim from Weiskittel et al. (2012, p. 77)

¹³⁴⁵ Verbatim from Weiskittel et al. (2012, p. 77)

¹³⁴⁶ Verbatim from Weiskittel et al. (2012, p. 77)

¹³⁴⁷ Nearly verbatim from Weiskittel et al. (2012, p. 77)

¹³⁴⁸ Verbatim from Kelly et al. (2007, p. 51). Kelly et al. cite Wheaton et al. (1987) for this information.

¹³⁴⁹ Verbatim from Kelly et al. (2007, p. 51)

¹³⁵⁰ Verbatim from Wolken et al. (2011, p. 17). Wolken et al. cite Hennon (1995) and Hennon & McClellan (2003) for this information.

¹³⁵¹ Nearly verbatim from Wolken et al. (2011, p. 17)

¹³⁵² Verbatim from Pojar (2010, p. 38)

¹³⁵³ Verbatim from Pojar (2010, p. 38)

¹³⁵⁴ Nearly verbatim from Pojar (2010, p. 24)

¹³⁵⁵ Verbatim from Pojar (2010, p. 24)

¹³⁵⁶ Verbatim from Pojar (2010, p. 24)

If climate change causes shifts in mean annual temperature of 5.4 – 9 °F (3–5 °C) over the generation time of Sitka spruce, then we would expect the optimum date of bud set to change by approximately 39–65 days, assuming populations are currently locally adapted.¹³⁵⁷ When Aitken et al. (2008) consider a mild scenario with a 5.4 °F (3 °C) change affecting the most variable populations, the change in temperature would require a change in mean phenotype of 1.56 phenotypic standard deviations.¹³⁵⁸ This is well above the critical threshold of ~0.4 phenotypic standard deviations derived by Aitken et al. (2008), suggesting that Sitka spruce could not tolerate prolonged change at this rate of climate change (~1 °C per generation would be the fastest rate of change tolerable over a long period of time).¹³⁵⁹ Of course, this crude approximation of risk ignores many biological details, especially density dependent effects, the fact that local adaptation and fitness are a function of many traits, and that analyses of multivariate traits may provide more realistic predictions.¹³⁶⁰

Toward the end of this century, warmer temperatures are predicted to reduce frost limitations on the growth of Douglas-fir throughout the province.¹³⁶¹ Using a process-based model to evaluate how climatic variation might alter growth of Douglas-fir across biogeoclimatic zones in British Columbia, site index (the height of dominant trees at 50 years) along the coast overall is predicted to increase to a maximum of 141 feet (43 meters, m) by 2080 (vs. 1961-1990 run with CGCM2 under A2x, an ensemble average of the three A2 runs).¹³⁶² Overall, relative changes show increases between 10% and 30% along the coast (except the Coastal Douglas-fir zone) and mean decreases in the interior of less than 10%.¹³⁶³ Results for specific biogeoclimatic zones are also available:

- **Coastal Western Hemlock zone:** In the case of the Coastal Western Hemlock zone, the mean site index is predicted to increase from 85 feet (26 m) to only 112 feet (34 m; a 31% increase).¹³⁶⁴
- **Mountain Hemlock zone:** Similarly, the mean of the Mountain Hemlock zone is predicted to increase from 72 feet (22 m) to 85 feet (26 m; an 18% increase).¹³⁶⁵
- **Coastal Douglas-fir zone:** In contrast, the Coastal Douglas-fir zone will exhibit a significant reduction in site index, declining from current levels of 105-85 feet (32-26 m).¹³⁶⁶

A reduction in the frequency of frost and more suitable temperatures during the growing season are likely to account for an increase in productivity within B.C.'s biogeoclimatic zones, whereas a depletion in the available soil water will likely be the main cause for any major reduction in future productivity.¹³⁶⁷

¹³⁵⁷ Verbatim from Aitken et al. (2008, p. 102)

¹³⁵⁸ Nearly verbatim from Aitken et al. (2008, p. 103). *Adaptation, migration or extirpation: climate change outcomes for tree populations.*

¹³⁵⁹ Nearly verbatim from Aitken et al. (2008, p. 103)

¹³⁶⁰ Nearly verbatim from Aitken et al. (2008, p. 103). Aitken et al. refer the reader to p. 102-103 in the cited article for information on density dependent effects.

¹³⁶¹ Verbatim from Coops et al. (2010, p. 519)

¹³⁶² Nearly verbatim from Coops et al. (2010, p. 511)

¹³⁶³ Nearly verbatim from Coops et al. (2010, p. 521)

¹³⁶⁴ Verbatim from Coops et al. (2010, p. 521)

¹³⁶⁵ Verbatim from Coops et al. (2010, p. 521)

¹³⁶⁶ Verbatim from Coops et al. (2010, p. 521)

¹³⁶⁷ Nearly verbatim from Coops et al. (2010, p. 521)

Pacific Northwest

Latta et al. (2010) projected the potential change in forest productivity in the Pacific Northwest at 5-year intervals through the 21st century (vs. 1971-2000 run with CCSM3, CGCM3, CSIRO MK3, and Hadley CM3 under A1B, A1, B1, and COMMIT; the latter holds global CO₂ emissions to year 2000 levels).¹³⁶⁸ Results indicate that climate scenarios with increase in future temperatures would lead to an overall increase in forest productivity in the Pacific Northwest.¹³⁶⁹ This increase will not be consistent across the region, with lower elevations experiencing declines while increase in higher elevation forests partially offset those declines (Figure 41).¹³⁷⁰ In addition, the eastern half of the region will see greater changes in productivity through the next century regardless of the scenario.¹³⁷¹ A second pattern across scenarios is that Washington will have greater changes in productivity than Oregon.¹³⁷² These patterns, however, are not as evident in the COMMIT scenario.¹³⁷³ For the west and east side of the Cascade Mountains, projected potential mean annual increment (i.e., a measurement of productivity) increases:¹³⁷⁴

- **West of the Cascade Mountains:** +2% to +8% (COMMIT and A2 scenarios, respectively), with a 5% increase projected under the B1 scenario and a 7% increase projected under the A1B scenario.¹³⁷⁵
- **East of the Cascade Mountains:** +5% to +23% (COMMIT and A2 scenarios, respectively), with a 15% increase under the B1 scenario and a 20% increase projected under the A1B scenario.¹³⁷⁶

These projections should be viewed as potential changes in productivity, since they do not reflect the mitigating effects of any shifts in management or public policy.¹³⁷⁷

Western Washington

Spatial patterns of forest productivity will change—state-wide productivity may initially increase due to warmer temperatures but will then decrease due to increased drought stress.¹³⁷⁸ Climatic variability will continue to mediate productivity.¹³⁷⁹

In both the B1 and A1B climate scenarios, the climatic water deficit of plots currently occupied by lodgepole pine increasingly extends beyond the envelope where lodgepole pine currently exists (historic period: 1980-2003; future climate projections after Mote & Salathé 2010).¹³⁸⁰ These projections of deficit suggest that areas with climatic conditions favorable for lodgepole pine will decrease considerably; 27%

¹³⁶⁸ Latta et al. (2010, p. 721). *Analysis of potential impacts of climate change on forests of the United States Pacific Northwest*.

¹³⁶⁹ Nearly verbatim from Latta et al. (2010, p. 727)

¹³⁷⁰ Verbatim from Latta et al. (2010, p. 727)

¹³⁷¹ Nearly verbatim from Latta et al. (2010, p. 725)

¹³⁷² Nearly verbatim from Latta et al. (2010, p. 725)

¹³⁷³ Verbatim from Latta et al. (2010, p. 725)

¹³⁷⁴ Nearly verbatim from Latta et al. (2010, p. 720)

¹³⁷⁵ Latta et al. (2010, p. 720)

¹³⁷⁶ Latta et al. (2010, p. 720)

¹³⁷⁷ Verbatim from Latta et al. (2010, p. 720)

¹³⁷⁸ Nearly verbatim from Littell et al. (2010, p. 154)

¹³⁷⁹ Verbatim from Littell et al. (2010, p. 154)

¹³⁸⁰ Verbatim from Littell et al. (2010, p. 144)

of plots will be subject to more water stress than those under the most stress today.¹³⁸¹ These projections of deficit suggest that areas with climatic conditions favorable for lodgepole pine will become increasingly rare because trees will be subject to significantly more water stress, with a correspondingly greater vapor pressure deficit.¹³⁸²

Douglas-fir productivity appears to vary with climate across the region and will potentially increase in energy-limited forests in the near term.¹³⁸³ However, by the end of the 2060s, independent species range modeling based on IPCC scenarios suggests that climate will be sufficiently different from the late twentieth century to put Douglas-fir at increasing risk at the edges of its current range in Washington (Figure 42).¹³⁸⁴ This is probably due to increases in temperature and decreases in growing season water availability in more arid environments (e.g., in the Columbia Basin) but could be due to other variables in less arid parts of the species' range.¹³⁸⁵

Specific projections for the 2060s (vs. 1960-1990; HadCM3 & CGCM2; IS92a scenario) include:

- About 32% of the area currently classified as appropriate climate for Douglas-fir will be outside the identified climatic envelope by the 2060s, and about 55% of the area will be in the 50%–75% range of marginal climatic agreement among models.¹³⁸⁶
- Only about 13% of the current area would be climatically suitable for Douglas-fir in > 75% of the statistical species models.¹³⁸⁷
- The decline in climatically suitable habitat for Douglas-fir is most widespread at lower elevations and particularly in the Okanogan Highlands, south Puget Sound and the southern Olympic Mountains.¹³⁸⁸

In the Olympic Mountains, biomass increases in the southwest and generally decreases in the northeast, depending on aspect and precipitation regime.¹³⁸⁹ For the northeast-north transects (i.e., the northern aspect of the northeast area sampled), the wetter scenario results in a smaller biomass decrease at middle to lower elevation plots, and tree establishment in meadows at the highest elevations leads to increased biomass in both precipitation scenarios.¹³⁹⁰ The northeast-south plots (i.e., the southern aspect of the northeast area sampled) maintain or increase biomass at most plots in the wetter scenario, while biomass decreases from present levels in the drier scenario for the lower elevation plots.¹³⁹¹ In the southwest region, there is a trend of increased biomass with warmer climate in both north and south transects in about three hundred years regardless of whether the climatic change is wetter or drier.¹³⁹²

¹³⁸¹ Verbatim from Littell et al. (2010, p. 144)

¹³⁸² Verbatim from Littell et al. (2010, p. 144)

¹³⁸³ Verbatim from Littell et al. (2010, p. 154)

¹³⁸⁴ Verbatim from Littell et al. (2010, p. 139). Littell et al. refer the reader to Figure 4 in the cited article for this information.

¹³⁸⁵ Verbatim from Littell et al. (2010, p. 139)

¹³⁸⁶ Verbatim from Littell et al. (2010, p. 139)

¹³⁸⁷ Verbatim from Littell et al. (2010, p. 139)

¹³⁸⁸ Verbatim from Littell et al. (2010, p. 139). Littell et al. refer the reader to Figure 4 in the cited article for this information.

¹³⁸⁹ Nearly verbatim from Zolbrod & Peterson (1999, p. 1966)

¹³⁹⁰ Nearly verbatim from Zolbrod & Peterson (1999, p. 1975)

¹³⁹¹ Nearly verbatim from Zolbrod & Peterson (1999, p. 1975)

¹³⁹² Verbatim from Zolbrod & Peterson (1999, p. 1975)

Western Oregon

Drought is an important disturbance agent in itself and, while most vegetation types in Oregon are well adapted to the state's dry summers, projected future changes in the hydrological regime have the potential to cause large-scale tree mortality.¹³⁹³ Projected increases in temperature will lengthen the growing season and increase evaporative demand, causing ecosystems to extract all available soil moisture before the end of the growing season.¹³⁹⁴

Northwest California

Information needed.

Information Gaps

Information gaps include:

- **Geographic distribution of genetic variability and climatic tolerances for tree species:** The geographic variability of sub-species genotypes and how those genotypes perform in different climatic conditions is poorly documented for most species.¹³⁹⁵ Planning for future resilience and responses to disturbance require well developed knowledge of genotypic variability and sub-species climatic tolerances so that seed stock well adapted to likely future conditions can be selected.¹³⁹⁶
- **Role of climate in tree establishment:** Because establishment is more sensitive than persistence of established trees, it is likely that important tree species will fail to establish after disturbance when the climate has shifted sufficiently.¹³⁹⁷ Most of the bioclimatic approaches to future vegetation response to climate change do not account for this potential sensitivity in early life-history stages and instead focus on climate relationships for established trees.¹³⁹⁸
- **Effects of silvicultural treatments on stand vigor and fire behavior:** Potential impacts identified by Littell et al. (2010) point to two silvicultural research needs: understanding the physiological response of mature trees to changing climate conditions to determine if silvicultural treatments could stem those impacts, and understanding how different silvicultural treatments can be used in anticipation of different projected climatic changes.¹³⁹⁹
- **Implications of climate change impacts for management strategies and institutional structure:** Research needs include not only the response of forest ecosystems to future climate, but also what those impacts mean for human systems that depend on and affect forests.¹⁴⁰⁰

¹³⁹³ Nearly verbatim from Shafer et al. (2010, p. 186). Shafer et al. refer the reader to Chapter 3 in the cited report for information on the hydrologic regime. Shafer et al. cite Neilson (1993), Bachelet et al. (2001), Bachelet et al. (2003), Mote et al. (2003), Whitlock et al. (2003) and Lenihan et al. (2008) for this information.

¹³⁹⁴ Verbatim from Shafer et al. (2010, p. 186)

¹³⁹⁵ Verbatim from Littell et al. (2010, p. 152)

¹³⁹⁶ Verbatim from Littell et al. (2010, p. 152)

¹³⁹⁷ Verbatim from Littell et al. (2010, p. 152-153)

¹³⁹⁸ Verbatim from Littell et al. (2010, p. 152)

¹³⁹⁹ Nearly verbatim from Littell et al. (2010, p. 153).

¹⁴⁰⁰ Nearly verbatim from Littell et al. (2010, p. 153). Littell et al. cite Millar et al. (2007) and Joyce et al. (2008) for this information.

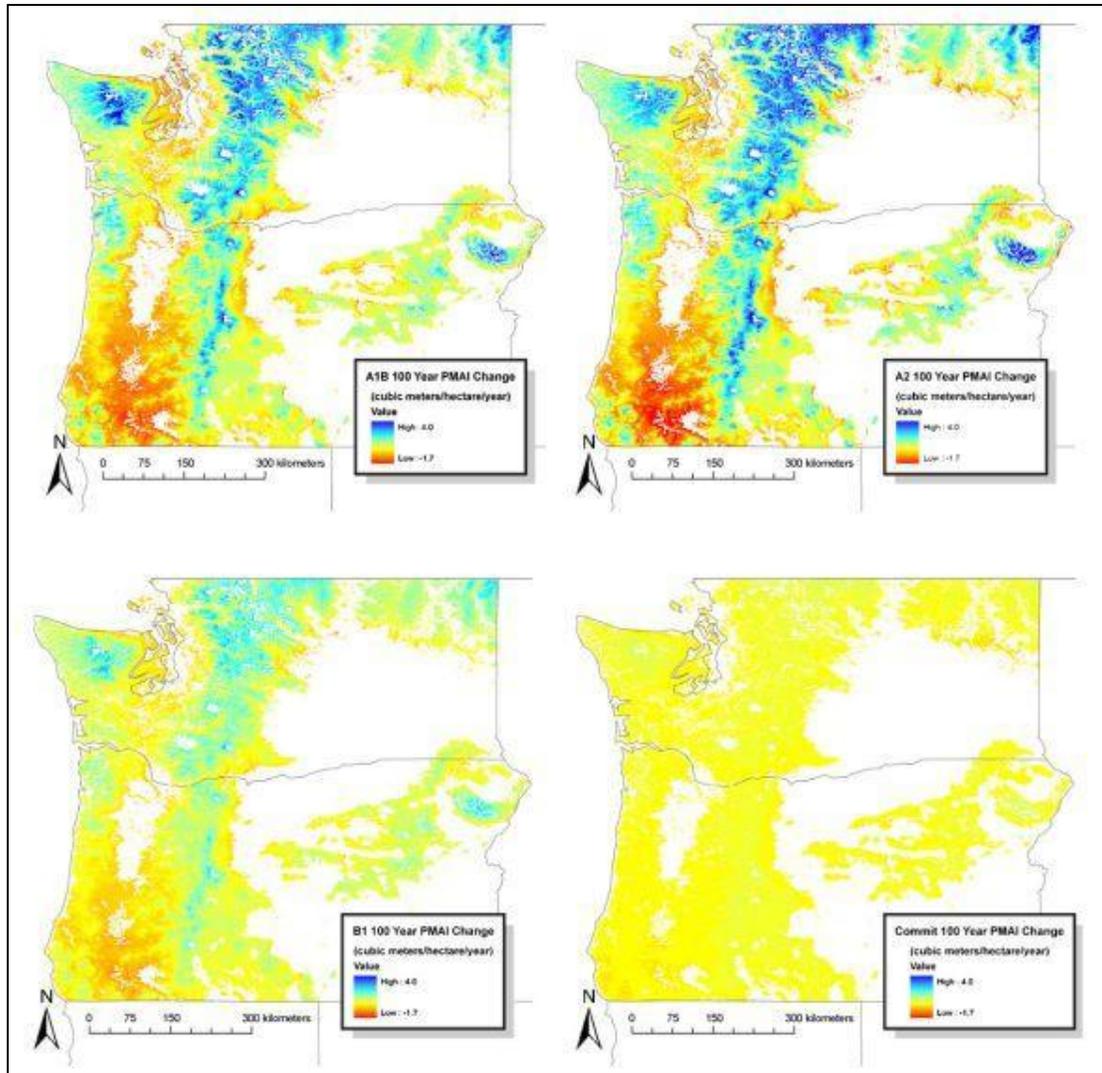


Figure 41. Change in Pacific Northwest potential mean annual increment over the next century by IPCC scenario. *Source: Reproduced from Latta et al. (2010, Figure 6, p. 727) by authors of this report.*

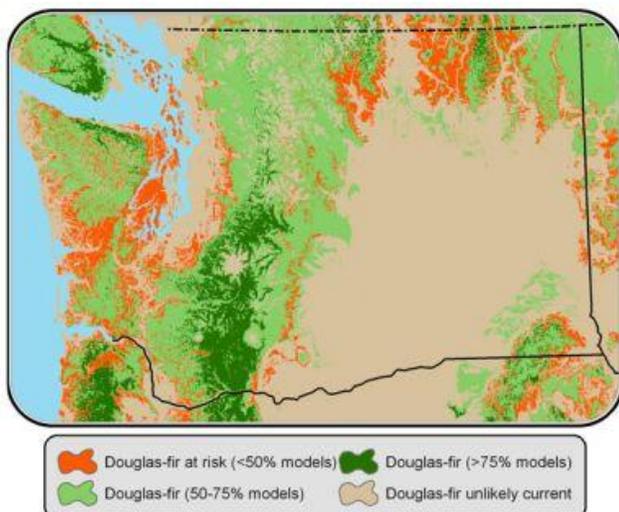


Figure 42. Change in area of climate suitable for Douglas-fir. *Tan* indicates areas where current climate is not suitable for Douglas-fir; *all other colors* indicate locations where current climate is suitable. *Orange* indicates area where fewer than 50% of the statistical models suggest climate appropriate for Douglas-fir presence in the 2060s and thus indicates locations where climate is likely to move from currently suitable to unsuitable. *Dark green* indicates areas where more than 75% of statistical models agree that climate is currently suitable for Douglas-fir and will remain so in the 2060s. *Light green* indicates an intermediate amount of model agreement, suggesting that these areas having current climate suitability may be at some risk due to interannual variability in climate or additional climate change beyond 2060. Data from Rehfeldt et al. (2006). Figure: Robert Norheim. *Source: Reproduced from Littell et al. (2010, Fig. 4, p. 140) by authors of this report.*

2. Changes in the range, distribution and composition of low- to mid-elevation forests

Many organisms are threatened by global climate change, but as sessile organisms, plants are particularly vulnerable.¹⁴⁰¹ Unable to individually move to areas with more suitable conditions as the climate changes, plants must instead rely on their seeds dispersing far and often in order to migrate fast enough to keep pace with the changing climate.¹⁴⁰² The fragmentation of natural landscapes by clearing for agricultural or urban development, or a species' requirement for particular soil types or topography, makes this migration even more problematic.¹⁴⁰³ The likelihood of a plant species persisting will thus depend on factors such as the rate of climate change, the degree of landscape fragmentation, and also the plant species' lifecycle, seed production, dispersal, and establishment.¹⁴⁰⁴

The western mountain ranges of the Pacific Northwest are noted for their high diversity of conifer species.¹⁴⁰⁵ These forests are also particularly sensitive to climate change.¹⁴⁰⁶

The paleoenvironmental record provides clear evidence that species respond individually to climate change and supports the current scientific consensus that the geographical distributions of plant species will change as climate changes.¹⁴⁰⁷ With rapidly changing environments, plant populations face three possibilities:

1. **Migration to new habitats in which they are adapted:** The persistence of plant populations by migration will depend upon the rate of migration via seed dispersal and establishment of new stands, and upon the rate of gene flow via pollination from distant stands.¹⁴⁰⁸
2. **Adaptation via natural selection as climate changes:** Responses to natural selection within populations depend upon phenotypic variation, genetic variation, and the heritability of traits important for survival and reproduction, as well as the intensity of selection.¹⁴⁰⁹
3. **Extinction:** Populations that may be most vulnerable to climate change include small, fragmented and disjunct populations, particularly those at the low elevation and southern latitude edges of species' range.¹⁴¹⁰ Although they may persist for awhile, long-lived species may be at a greater threat from climate change than short-lived species.¹⁴¹¹ Rare species and populations

¹⁴⁰¹ Verbatim from Renton et al. (2013, p. 50). *Plant migration and persistence under climate change in fragmented landscapes: Does it depend on the key point of vulnerability within the lifecycle?*

¹⁴⁰² Verbatim from Renton et al. (2013, p. 50)

¹⁴⁰³ Verbatim from Renton et al. (2013, p. 50)

¹⁴⁰⁴ Verbatim from Renton et al. (2013, p. 50)

¹⁴⁰⁵ Verbatim from Shafer et al. (2001, p. 211). Shafer et al. cite Ricketts and others (1999) for this information.

¹⁴⁰⁶ Verbatim from Shafer et al. (2001, p. 211)

¹⁴⁰⁷ Verbatim from Shafer et al. (2010, p. 178-179). Shafer et al. cite Huntley (1991), Pitelka (1997), Jackson & Overpeck (2000), Bachelet et al. (2001), Hansen et al. (2001), Shafer et al. (2001), Walther et al. (2002), Higgins et al. (2003), Sans-Elorza et al. (2003), McLachlan et al. (2005), Neilson et al. (2005b), Wang et al. (2006), Jurasinski (2007), McKenney et al. (2007), Xu et al. (2007), and Thuiller et al. (2008) for this information.

¹⁴⁰⁸ Verbatim from Shafer et al. (2010, p. 192)

¹⁴⁰⁹ Nearly verbatim from Shafer et al. (2010, p. 192)

¹⁴¹⁰ Verbatim from Shafer et al. (2010, p. 193)

¹⁴¹¹ Verbatim from Shafer et al. (2010, p. 193)

already threatened by other factors such as habitat loss, fire, disease, and insects may be at an even greater risk of loss given the added impact of climate change.¹⁴¹²

Observed Trends

Western North America

Although western North America supports a great diversity of habitat, the spatial extent of any particular habitat type may be relatively small and separated from other similar patches of habitat by large distances.¹⁴¹³ Migration rates for tree taxa during the Holocene were only on the order of ~3,281 feet per year (1,000 meters per year).¹⁴¹⁴ Further, past range shifts during the postglacial period of the Holocene, inferred from paleoecological studies, support the importance of small outlying populations during migration.¹⁴¹⁵ Small northern disjunct populations, which typically are ignored in regional paleoecological studies, appear to have provided crucial foci for colonization and to have spread northward during the Holocene.¹⁴¹⁶

Currently, classic old-growth forests are found west of the Cascade Mountains in Oregon, Washington, and California and west of the coastal mountains in British Columbia and Alaska.¹⁴¹⁷ The Level 1 ecoregion Marine West Coast Forests extends from Alaska in a progressively narrowing band to San Francisco.¹⁴¹⁸ Western hemlock and Sitka spruce are present throughout most of this fog-belt defined ecoregion, with Douglas-fir, coast redwood and western red cedar locally abundant.¹⁴¹⁹ For the Northwest Forested Mountains (i.e., another Level 1 ecoregion), Douglas-fir and western hemlock are frequently abundant in mixtures with many species of pine and true firs.¹⁴²⁰ At higher elevations and latitudes, lodgepole pine, mountain hemlock, subalpine fir, and Engelmann spruce are characteristic species.¹⁴²¹

Lodgepole pine is widely distributed in western North America.¹⁴²² Within the Pacific Northwest, the species, or one of its subspecies, occurs on sandy soils along the coast, and inland over much of the subalpine zone, which extends to east of the Rocky Mountains and north into the Yukon Territory.¹⁴²³

In a study of adaptational lags (i.e., the difference between a population's current habitat and the assumed optimal climate habitat) in 15 wide-ranging forest tree species, on average, populations already lag behind their optimal climate niche by approximately 80.8 miles (130 km) in latitude or 197 feet (60 meters) in elevation (1997-2006 vs. 1961-1990, representing an approximately 25-year climate change from

¹⁴¹² Verbatim from Shafer et al. (2010, p. 193)

¹⁴¹³ Verbatim from Shafer et al. (2001, p. 211)

¹⁴¹⁴ Nearly verbatim from Shafer et al. (2001, p. 211). Shafer et al. cite Pitelka and the Plant Migration Workshop (1997) for this information.

¹⁴¹⁵ Nearly verbatim from Pojar (2010, p. 30). Pojar cites Hebda (1995) for information on paleoecological studies.

¹⁴¹⁶ Verbatim from Pojar (2010, p. 30). Pojar cites McLachlan et al. (2005) for this information.

¹⁴¹⁷ Nearly verbatim from Franklin et al. (2006, p. 97)

¹⁴¹⁸ Nearly verbatim from Coops & Waring (2011b, p. 2120). *Estimating the vulnerability of fifteen tree species under changing climate in Northwest North America.*

¹⁴¹⁹ Verbatim from Coops & Waring (2011b, p. 2120)

¹⁴²⁰ Verbatim from Coops & Waring (2011b, p. 2120)

¹⁴²¹ Verbatim from Coops & Waring (2011b, p. 2120)

¹⁴²² Verbatim from Coops & Waring (2011a, p. 314). *A process-based approach to estimate lodgepole pine (Pinus contorta Dougl.) distribution in the Pacific Northwest.*

¹⁴²³ Verbatim from Coops & Waring (2011a, p. 314)

midpoint to midpoint).¹⁴²⁴ In a similar study of 15 tree species vulnerability to climate change, climatically driven decision-tree models predict on average that 30% of the 15 tree species' ranges have become vulnerable to climate change (vulnerable areas defined as those within a species' baseline range, 1950-1975, that have less than a 50% probability of species occurrence from 1976-2006).¹⁴²⁵ There is, however, considerable variation, with up to 50% of the range becoming vulnerable for ponderosa pine, noble fir, grand fir and western larch, and <10% for Pacific silver fir and western red cedar.¹⁴²⁶ Higher elevation sites appear to contain far more species characterized as "vulnerable" than do lower and mid-elevation sites.¹⁴²⁷

Specific results for the Marine West Coast Forests and Northwest Forested Mountains Level 1 ecoregions are also available:

- **Marine West Coast Forests:** Within the cool, moist, coastal ecoregion both noble fir and subalpine fir, although recorded infrequently on observations, are predicted to become highly vulnerable during the transitional period.¹⁴²⁸ Alaska yellow cedar is predicted to be vulnerable over 25% of its baseline-defined range.¹⁴²⁹
- **Northwest Forested Mountains:** Within the Northwest Forested Mountains, where all of the 15 species occur except Sitka spruce, most of the species have only moderate areas of their range classified as vulnerable (between 5 and 30%), with the exception of grand fir and ponderosa pine.¹⁴³⁰ Some species, such as whitebark pine remain well adapted within their predicted baseline range for the period 1976–2006.¹⁴³¹
- *Note: For a list of all 15 tree species studied, please see Figure 45 (p. 186).*

Southcentral and Southeast Alaska

Alaska's forests cover one-third of the state's 425 million acres (172 million hectares, ha) of land and are functionally significant, both regionally and globally.¹⁴³² Coastal temperate forests (i.e., those in the NPLCC region) comprise 10% of Alaska's forests (12 million acres, 5 million ha) and represent 19% of the world's coastal temperate forests.¹⁴³³ Ninety percent of the forests are classified as boreal 104 million

¹⁴²⁴ Nearly verbatim from Gray & Hamann (2013, p. 289). *Tracking suitable habitat for tree populations under climate change in western North America.*

¹⁴²⁵ Nearly verbatim from Coops & Waring (2011b, p. 2125). Coops & Waring refer the reader to Figure 4 in the cited article for this information.

¹⁴²⁶ Verbatim from Coops & Waring (2011b, p. 2125)

¹⁴²⁷ Verbatim from Coops & Waring (2011b, p. 2125)

¹⁴²⁸ Nearly verbatim from Coops & Waring (2011b, p. 2125)

¹⁴²⁹ Verbatim from Coops & Waring (2011b, p. 2125)

¹⁴³⁰ Verbatim from Coops & Waring (2011b, p. 2125)

¹⁴³¹ Verbatim from Coops & Waring (2011b, p. 2125)

¹⁴³² Verbatim from Wolken et al. (2011, p. 2). Wolken et al. refer the reader to Figure 1A for an image of the forested areas of Alaska. Wolken et al. cite Parson et al. (2001) for information on the area of Alaska's land covered by forest.

¹⁴³³ Verbatim from Wolken et al. (2011, p. 2). Wolken et al. cite NAST (2003) for this information.

acres (42 million ha), collectively representing 4% of the world's boreal forests; these occur throughout the Interior-, Southcentral-, and Kenai-boreal regions.¹⁴³⁴

On the Kenai Peninsula, wooded regions increased in area by 28% between 1950 and 1996, while open, wet, and watered areas decreased in size.¹⁴³⁵ Type shifts from wetlands to upland habitats were observed during the same time period.¹⁴³⁶

Western British Columbia

Forests cover 55 million hectares (~210,000 square miles, mi²), or about 60% of B.C.'s 95 million hectares.¹⁴³⁷ A further 3.7 million hectares are other wooded land with woody shrubs, stunted trees, or scattered tree cover.¹⁴³⁸ In the Coastal region, forests cover 18 million hectares (~69,000 mi²; 33% of all B.C. forests; 19% of all B.C. land) (Figure 43).¹⁴³⁹ About 3% of former forests have been converted to other land uses.¹⁴⁴⁰ The Coastal Douglas-fir (CDF) zone has been most affected, with 46% of its former forests now converted.¹⁴⁴¹

Based on a comparison of mapped predictions of ecosystem distributions for the 1970s and for 2001-2009 using the Random Forest model, geographic distributions of the suitable climate habitats for BC ecosystems have already shifted in 23% of British Columbia since the 1970s.¹⁴⁴² The magnitude of the shift (loss or gain) varied between 5 and 77% among ecosystems.¹⁴⁴³ The least affected were two coastal (Coastal Douglas-fir and Coastal Western Hemlock) and one boreal zone (Boreal White and Black Spruce).¹⁴⁴⁴

However, forty-five percent of the Coastal Douglas-fir biogeoclimatic zone has been converted to urban, rural residential and agricultural use.¹⁴⁴⁵ Of particular concern in the Coastal Douglas-fir zone is the loss of (nearly 90%) Garry oak woodlands, aesthetically pleasing ecosystems with high species richness and many at-risk species.¹⁴⁴⁶ For more information on Garry oak woodlands, please see Chapter VI.3. The remaining, mostly secondary forests and woodlands of the Coastal Douglas-fir zone are being infiltrated by non-native invasive plants, including spurge-laurel, English ivy, Himalayan blackberry, and numerous grasses, eliminating or reducing native species and changing ecosystem processes.¹⁴⁴⁷

¹⁴³⁴ Verbatim from Wolken et al. (2011, p. 2). Wolken et al. refer the reader to Figure 1B for an image of the forest regions in Alaska. Wolken et al. cite Shvidenko & Apps (2006) for information on the contribution of Alaska's boreal forests to the global total.

¹⁴³⁵ Verbatim from Jezierski et al. (2010, p. 8)

¹⁴³⁶ Verbatim from Jezierski et al. (2010, p. 8). Jezierski et al. cite Klein et al. (2005) for this information.

¹⁴³⁷ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 36)

¹⁴³⁸ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 39)

¹⁴³⁹ Nearly verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 36)

¹⁴⁴⁰ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 38)

¹⁴⁴¹ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 38)

¹⁴⁴² Nearly verbatim from Wang et al. (2012, p. 2). *Projecting future distributions of ecosystem climate niches: uncertainties and management applications.*

¹⁴⁴³ Verbatim from Wang et al. (2012, p. 9)

¹⁴⁴⁴ Verbatim from Wang et al. (2012, p. 9)

¹⁴⁴⁵ Nearly verbatim from Pojar (2010, p. 27)

¹⁴⁴⁶ Nearly verbatim from Pojar (2010, p. 27). Pojar cites Austin et al. (2008) for this information.

¹⁴⁴⁷ Verbatim from Pojar (2010, p. 27)

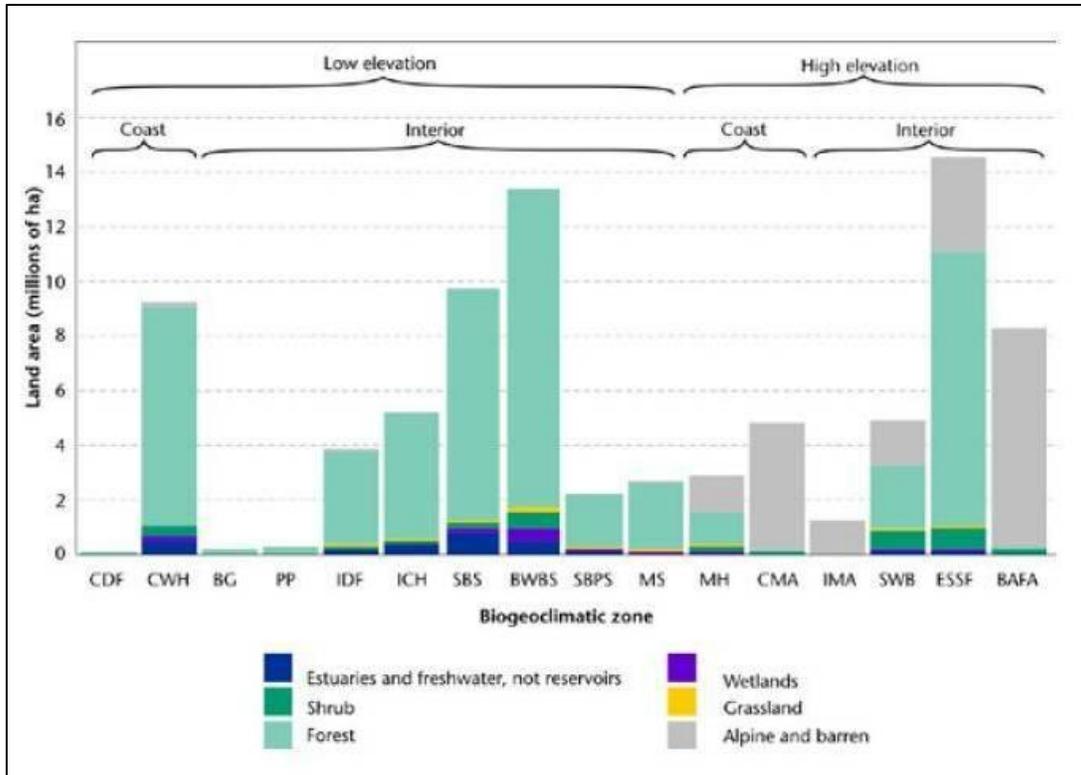


Figure 43. Area of province by ecosystem type and biogeoclimatic zone, 2008.

Source: Reproduced from B.C. Ministry of Forests, Lands, and Mines (2010, Figure 1-1, p. 37) by authors of this report.

Note: Biogeoclimatic zones in the NPLCC region include Coastal Douglas-fir (CDF), Coastal Western Hemlock (CWH), Sub-boreal Spruce (SBS), Mountain Hemlock (MH), Coastal Mountain-heather Alpine (CMA), Engelmann Spruce-Subalpine Fir (ESSF), and Alpine Tundra (AT; not shown).

Pacific Northwest

The composition, assemblages, and distribution of conifer-dominated forests west of the mountains are traced to about 5,000 years Before Present, when a cool, moist climate replaced a warmer and drier one over much of the region.¹⁴⁴⁸ Pollen evidence indicates that western hemlock and cedar were able to move from higher to lower elevations into what had been dry Douglas-fir woodlands.¹⁴⁴⁹

Since the time of Euro-American settlement of the Northwest, old-growth forests have been lost as a result of multiple factors, including conversion of forests to farms and towns, the geographic spread of timber harvest, and natural disturbances, such as a 1921 windstorm, multiple large fires in the early to mid-20th century, the 1980 eruption of Mt. St. Helens, and several very large recent fires in British Columbia, northern Washington, and southern Oregon.¹⁴⁵⁰ Currently, only about 10% of the forest in the lower U.S. part of the region is in old growth, most on federal lands.¹⁴⁵¹

¹⁴⁴⁸ Verbatim from Franklin et al. (2006, p. 98)

¹⁴⁴⁹ Verbatim from Franklin et al. (2006, p. 98)

¹⁴⁵⁰ Verbatim from Franklin et al. (2006, p. 98)

¹⁴⁵¹ Verbatim from Franklin et al. (2006, p. 98). Franklin et al. cite FEMAT (1993) for this information.

Western larch is most prominent in the upper Columbia River Basin of southeastern British Columbia and in northwestern Montana and adjacent Idaho but also occurs along the east slopes of the Cascade Range in Washington and Oregon.¹⁴⁵² The original extent of Northwest riparian woodlands is unknown.¹⁴⁵³

Western Washington

Currently, conifer species dominate forest ecosystems within Washington State, with hardwood species only in riparian areas that experience frequent flooding or other heavily disturbed areas such as avalanche chutes or recently logged sites.¹⁴⁵⁴ Forest composition varies with both elevation and position on a broad west-east (maritime-continental) gradient across the state.¹⁴⁵⁵ At a finer scale, orographic (i.e., influenced by mountains) effects on species composition are apparent on the leeward (i.e., sheltered from wind, downwind) versus windward (i.e., facing the wind) sides of both the Olympic Mountains and the Cascade Range, where complex topography produces steep gradients in the biophysical environment across relatively short distances.¹⁴⁵⁶ Specific information on forest composition at Panther Potholes and Mt. Constitution is available:

- **Panther Potholes(North Cascades):** The most recent arrival of tree species at the Panther Potholes was Alaska yellow-cedar at approximately 2000 cal yr BP.¹⁴⁵⁷ Mountain hemlock has never been abundant at the Panther Potholes, but its increase in the pollen record in the last 2000 years along with the increase in Alaska yellow-cedar macrofossils indicate that the last two millennia have been particularly cool and moist.¹⁴⁵⁸ Both species are typically found at high elevations on moist sites in the Pacific Northwest.¹⁴⁵⁹ The greater occurrence of Ericaceae pollen (i.e., pollen from the heath family) in the last millennium also suggests cooler, moister climatic conditions.¹⁴⁶⁰ The modern forest assemblage has the highest diversity of tree species of any time in the Holocene.¹⁴⁶¹
- **Mt. Constitution (Orcas Island):** The vegetation and fire regimes on Mt. Constitution 5300-7000 years ago were similar to those at present, suggesting that the climate was also similar.¹⁴⁶² After 2000 years BP, charcoal deposition increased at all three sites, and pine increased in the central and south-central sites, suggesting a return to drier conditions.¹⁴⁶³ Stands on different sites in close proximity responded individually to the same climate change, depending on local site conditions and the ecology of the dominant trees.¹⁴⁶⁴

¹⁴⁵² Nearly verbatim from Rehfeldt & Jaquish (2010, p. 284). Rehfeldt & Barry refer the reader to Figure 1 in the cited article for this information.

¹⁴⁵³ Verbatim from Apostol & Berg (2006, p. 130)

¹⁴⁵⁴ Nearly verbatim from Littell et al. (2010, p. 131)

¹⁴⁵⁵ Verbatim from Littell et al. (2010, p. 131)

¹⁴⁵⁶ Nearly verbatim from Littell et al. (2010, p. 131). Littell et al. cite Williams & Lillybridge (1983), Franklin & Dyrness (1988), Henderson et al. (1989, 1992), Williams et al. (1990), and Lillybridge et al. (1995) for this information.

¹⁴⁵⁷ Verbatim from Prichard et al. (2009, p. 65)

¹⁴⁵⁸ Verbatim from Prichard et al. (2009, p. 65)

¹⁴⁵⁹ Verbatim from Prichard et al. (2009, p. 65)

¹⁴⁶⁰ Verbatim from Prichard et al. (2009, p. 65)

¹⁴⁶¹ Verbatim from Prichard et al. (2009, p. 65)

¹⁴⁶² Nearly verbatim from Sugimura et al. (2008, p. 548-549)

¹⁴⁶³ Nearly verbatim from Sugimura et al. (2008, p. 539)

¹⁴⁶⁴ Nearly verbatim from Sugimura et al. (2008, p. 539)

Klamath Mountains

In the Klamath-Siskiyou region, elements of the Pacific Northwest, California and Great Basin floras intergrade with many endemic species, including Brewer spruce, Baker's cypress, and Sadler's oak.¹⁴⁶⁵ The region includes the southern distributional limit of Pacific silver fir, Alaska cedar and Engelmann spruce, as well as the northern limit for coast redwood, Jeffrey pine and Shasta red fir.¹⁴⁶⁶

Western Oregon

Oregon's vegetation is strongly influenced by climate and topography.¹⁴⁶⁷ Along the Oregon coast, the Pacific Ocean affects local climate conditions that support maritime species such as Sitka spruce and shore pine.¹⁴⁶⁸ Further inland, vegetation varies along the west slope of the Cascade Range from oak woodlands in the Willamette Valley to mixed conifer forests dominated by Douglas-fir at mid-elevations, to high elevation mountain hemlock and true fir stands (Figure 44).¹⁴⁶⁹ These natural patterns in the distribution of vegetation are modified by human activities, including urbanization, agriculture, road building, logging, grazing, and fire suppression.¹⁴⁷⁰

The state of Oregon estimates that 15% of the entire state land area is classified as riparian, or within 328 feet (100 meters) of perennial streams and rivers.¹⁴⁷¹ The Willamette River has lost 80% of the riparian vegetation that it had at the time of Euro-American settlement and one half of its stream channel complexity.¹⁴⁷² In the 500,000 acre (~200,000 hectares) Siuslaw watershed, 36% of the total riparian area (200 feet, or ~60 meters, on each side of streams) is classified as mature forest (more than 80 years old), 38% is either young conifer or hardwoods, and 26% is essentially treeless.¹⁴⁷³ In Johnson Creek watershed, the largest remaining open creek in the Portland area, only 5% of active stream segments have forested riparian vegetation that extends beyond the immediate stream channel edge.¹⁴⁷⁴ Thirty-two percent contain little or no riparian vegetation.¹⁴⁷⁵

Worona and Whitlock (1995) analyzed pollen from the sediments of Little Lake in the Oregon Coast Range (near Blachly, Oregon), which provide a record of vegetation change going back ~42,000 years.¹⁴⁷⁶ This pollen record indicates that the current Douglas-fir, western hemlock, and western red cedar forests of Oregon's Coast Range developed in the last ~5600 years, possibly in response to cooling climate

¹⁴⁶⁵ Nearly verbatim from Frost & Sweeney (2000, p. 3)

¹⁴⁶⁶ Verbatim from Frost & Sweeney (2000, p. 3)

¹⁴⁶⁷ Verbatim from Shafer et al. (2010, p.175)

¹⁴⁶⁸ Verbatim from Shafer et al. (2010, p.175)

¹⁴⁶⁹ Verbatim from Shafer et al. (2010, p.175)

¹⁴⁷⁰ Verbatim from Shafer et al. (2010, p.175)

¹⁴⁷¹ Nearly verbatim from Apostol & Berg (2006, p. 130)

¹⁴⁷² Verbatim from Apostol & Berg (2006, p. 130). Apostol & Berg cite Hulse et al. (2000) for this information.

Apostol & Berg also refer the reader to Figures 6.4 and 6.5 in the cited book chapter for this information.

¹⁴⁷³ Verbatim from Apostol & Berg (2006, p. 130). Apostol & Berg cite Ecotrust (2002) for this information.

¹⁴⁷⁴ Verbatim from Apostol & Berg (2006, p. 130)

¹⁴⁷⁵ Verbatim from Apostol & Berg (2006, p. 130). Apostol & Berg cite Portland-Multnomah Progress Board (2000) for this information.

¹⁴⁷⁶ Verbatim from Shafer et al. (2010, p.176). Note: Shafer et al. are the authors of Chapter 5 of the Oregon Climate Assessment Report, a compendium report from which this report draws. As explained in the Introduction to this report, we accept secondary literature in compendium reports as it is presented.

conditions during this time period.¹⁴⁷⁷ Charcoal from past fires found in the sediments of Little Lake and Taylor Lake (south of Warrenton, Oregon) indicate that fires in the region also became less frequent during this same time period, as would be expected under cooler climate conditions.¹⁴⁷⁸

Northwest California

Perhaps the most famous example of a cloud-connected coastal ecosystem is that of the iconic coast redwood, whose natural distribution is restricted to a narrow (~31 mile, 50 km) belt from approximately 42 °N to 36°N along the northeast Pacific Rim.¹⁴⁷⁹ The latitudinal limits of the coast redwood distribution correspond approximately to the 35% fog threshold at both northern and southern ecotones.¹⁴⁸⁰ This result supports the long-suspected relationship between coastal fog frequency and the modern coast redwood distribution.¹⁴⁸¹ Quaternary pollen evidence shows severe reductions in redwood populations during glacial periods when coastal upwelling may have been reduced.¹⁴⁸² Today, alluvial flats in west-draining canyons provide the prime habitat for the oldest and tallest redwood trees, and significant populations also occupy low-elevation coastal hillslopes and ridgetops.¹⁴⁸³

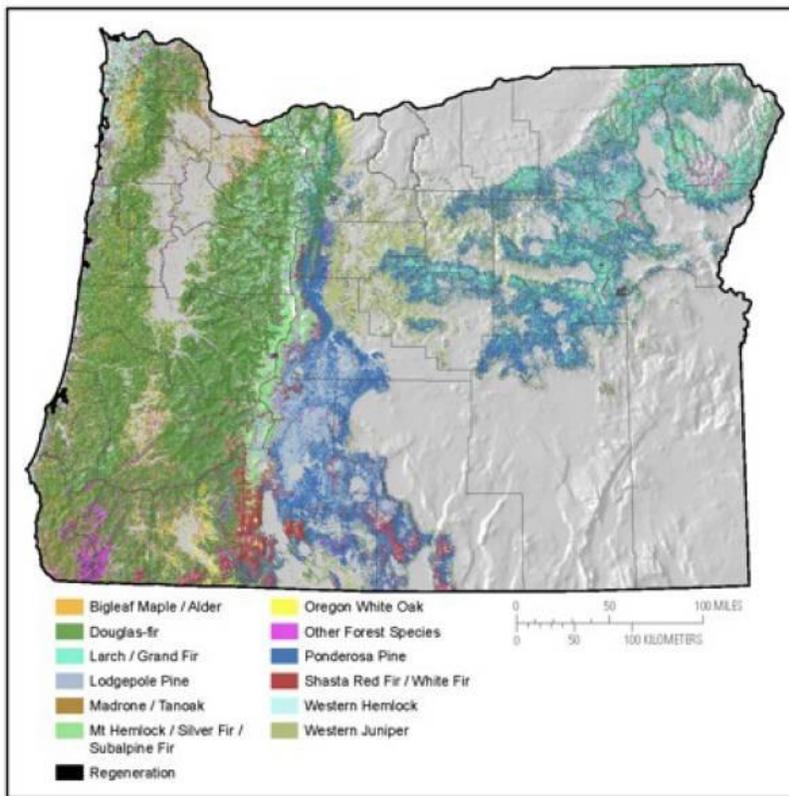


Figure 44. The distribution of dominant tree species in Oregon as modeled using the gradient nearest neighbor (GNN) method. Data: GNN Vegetation Imputations (LEMMA Laboratory, USFS PNW Research Station, Corvallis, Oregon); Ecological Systems (Oregon Institute for Natural Resources, Oregon State University); Development Zone Study (Resource Planning Program, Oregon Department of Forestry). (Figure: R. T. Pelltier, USGS) *Source: Reproduced from Shafer et al. (2010, Figure 5.2, p. 177) by authors of this report.*

¹⁴⁷⁷ Verbatim from Shafer et al. (2010, p.176)

¹⁴⁷⁸ Verbatim from Shafer et al. (2010, p.176-177). Shafer et al. cite Long et al. (1998) for information from Little Lake and Long & Whitlock (2002) for information from Taylor Lake.

¹⁴⁷⁹ Verbatim from Johnstone & Dawson (2010, p. 4533)

¹⁴⁸⁰ Verbatim from Johnstone & Dawson (2010, p. 4534)

¹⁴⁸¹ Verbatim from Johnstone & Dawson (2010, p. 4534)

¹⁴⁸² Verbatim from Johnstone & Dawson (2010, p. 4533). Johnstone & Dawson cite Barron et al. (2003) and Heusser (1998) for information on redwood populations during glacial periods and Herbert et al. (2001) and Ortiz & Mix (1997) for information on reduced coastal upwelling.

¹⁴⁸³ Verbatim from Johnstone & Dawson (2010, p. 4533)

Future Projections

Western North America

Gray & Hamann (2013) applied a bioclimate envelope model (Box 5) that tracks habitat of individual populations to estimate adaptational lags (i.e., the difference between a population's current habitat and the assumed optimal climate habitat) for 15 wide-ranging forest tree species in western North America (2020s, 2050s, and 2080s vs. 1961-1990 run with CGCM, CSIRO2, HADCM3, ECHAM4, and PCM under A1F1, A2, B1, and B2).¹⁴⁸⁴ Projected latitudinal or elevation shifts for western North America on average double for the 2020s, and double again for the 2050s compared to habitat shifts for the 1997-2006 observed climate:¹⁴⁸⁵

- **For the 2020s**, shifts are 193 miles (310 km) north and 459 feet (140 meters, m) in elevation.¹⁴⁸⁶ Average standard deviations across all populations for northward shifts are 76.4 miles (123 km) and for elevation shifts are 177 feet (54 m).¹⁴⁸⁷
- **For the 2050s**, shifts are 367 miles (590 km) north and 853 feet (260 m) in elevation.¹⁴⁸⁸ Average standard deviations across all populations for northward shifts are 155 miles (249 km) and for elevation shifts are 361 feet (110 m).¹⁴⁸⁹ Northern and coastal populations of tree species are projected to experience large geographic lags.¹⁴⁹⁰ For example, populations of yellow cedar, Sitka spruce, Pacific silver fir, western hemlock, and western redcedar would be affected (Table 25).¹⁴⁹¹

For the 2080s, Gray & Hamann (2013) do not report northward and elevation shifts across populations. Standard deviations for the 2080s are very large at the population level and even at the species level.¹⁴⁹²

Coops & Waring (2011b) also evaluated the extent that conditions have become more or less suitable for each of 15 tree species, first over a transitional interval from 1976 to 2006, and then at 30-year intervals (i.e., 2020s, 2050s, 2080s vs. 1950-1975) to the end of the 21st century based on projections for the A2 and B1 emission scenarios from the CGCM3 (Figure 45).¹⁴⁹³ Specific results include:

- Douglas-fir, western hemlock, whitebark pine, and western red cedar are all predicted to expand their individual ranges, potentially, beyond 308,882 square miles (800,000 km²) before the end of

¹⁴⁸⁴ Nearly verbatim from Gray & Hamann (2013, p. 289)

¹⁴⁸⁵ Nearly verbatim from Gray & Hamann (2013, p. 298). Gray & Hamann refer the reader to Figure 3 in the cited article for this information.

¹⁴⁸⁶ Gray & Hamann (2013, p. 298)

¹⁴⁸⁷ Nearly verbatim from Gray & Hamann (2013, p. 298)

¹⁴⁸⁸ Gray & Hamann (2013, p. 298)

¹⁴⁸⁹ Nearly verbatim from Gray & Hamann (2013, p. 298)

¹⁴⁹⁰ Nearly verbatim from Gray & Hamann (2013, p. 298)

¹⁴⁹¹ Verbatim from Gray & Hamann (2013, p. 298). Gray & Hamann refer the reader to Table 4 in the cited article for this information.

¹⁴⁹² Verbatim from Gray & Hamann (2013, p. 298). Gray & Hamann refer the reader to Figure 1 and Online Resources 1d-15d in the cited article for this information.

¹⁴⁹³ Nearly verbatim from Coops & Waring (2011b, p. 2122). Coops & Waring refer the reader to Table 1 in the cited article for a list of the 15 species.

the century.¹⁴⁹⁴ These widely distributed species, with the exception of whitebark pine, are projected to maintain most or all of their originally defined ranges.¹⁴⁹⁵

- Of the species investigated, only ponderosa pine and lodgepole pine are predicted to occupy smaller total areas near the end of the century than they now do.¹⁴⁹⁶

Box 5. Niche- and Process-based Modeling.

Niche- and process-based models are used to project the possible future range, distribution, abundance, and/or other characteristics of individuals, species, and/or populations based on existing data.

Niche-based models, also known as (bio)climatic envelope models or predictive habitat distribution models, statistically relate the geographic distribution of species or communities to their current environment. They establish statistical or theoretical relationships between environmental predictors, especially climate data, and observed species distributions. Examples of niche-based models or techniques include generalized linear and additive models, MaxEnt, and Random Forest.

Species-specific **process-based models**, on the other hand, model the response of an individual or population to environmental conditions by incorporating data on biological processes obtained from observational datasets on individuals in natural populations. Examples of process-based models include gap, landscape, or fitness-based models.

Where niche-based models are static and probabilistic, process-based models are dynamic and mechanistic. Each approach has strengths and limitations, which are discussed in the literature. See for example:

- Morin, X., and W. Thuiller. (2009). Comparing niche- and process-based models to reduce prediction uncertainty in species range shifts under climate change. *Ecology*. 90(5): 1301-1313.
- Guisan, A. and N. E. Zimmerman. (2000). Predictive habitat distribution models in ecology. *Ecological Modelling*. 135: 147-186.
- Price, K., and D. Daust. (n.d.). Forested Ecosystems. In: *A Climate Change Vulnerability Assessment for British Columbia's Managed Forests*. 11 pp.
- Robinson, D.C.E., Beukema, S.J., and L.A. Greig. (2008). *Vegetation models and climate change: workshop results*. Prepared by ESSA Technologies Ltd., for Western Wildlands Environmental Threat Assessment Center, USDA Forest Service, Prineville, OR. 50 pp.

Note: This report also presents results from dynamic global vegetation models (DGVMs), which simulate vegetation at a particular location by using submodels for photosynthesis, plant carbon balance, and other factors. Morin & Thuiller (2009) briefly discuss the strengths and limitations of DGVMs.

Sources: Guisan & Zimmerman (2000); Morin & Thuiller (2009); Price & Daust (n.d.); Robinson, Beukema & Greig (2008)

¹⁴⁹⁴ Verbatim from Coops & Waring (2011b, p. 2126)

¹⁴⁹⁵ Verbatim from Coops & Waring (2011b, p. 2126). Coops & Waring refer the reader to Figure 6b in the cited article for this information.

¹⁴⁹⁶ Verbatim from Coops & Waring (2011b, p. 2126)

Table 25. Northward and elevation shift of suitable habitat for 9 tree populations found in the NPLCC region relative to the 1961-1990 reference projection, averaged over 18 climate change scenarios. Elevation change is reported at constant latitude, and latitudinal change is reported at constant elevation. For seed transfer, these values represent maximum limits for a latitudinal or elevation transfer.

Species	Region*	1997-2006 shifts		2020s shifts		2050s shifts	
		North miles (km)	Elevation feet (m)	North miles (km)	Elevation feet (m)	North miles (km)	Elevation feet (m)
Douglas-fir	Mid Coast	87.6 (141)	203 (62)	150 (242)	348 (106)	332 (535)	771 (235)
	Mid Coast Mountains	55 (88)	128 (39)	102 (164)	236 (72)	259 (417)	600 (183)
	South Coast	47 (75)	108 (33)	236 (380)	548 (167)	338 (544)	784 (239)
Engelmann spruce	Mid Coast Mountains	19 (31)	46 (14)	121 (195)	282 (86)	248 (399)	577 (176)
Lodgepole pine	Mid Coast Mountains	70.2 (113)	164 (50)	162 (260)	374 (114)	355 (571)	823 (251)
Pacific silver fir	Mid Coast	109 (175)	253 (77)	166 (267)	387 (118)	338 (544)	784 (239)
	North Coast	134 (215)	312 (95)	201 (323)	466 (142)	459 (739)	1066 (325)
Sitka spruce	Mid Coast	47 (75)	108 (33)	59 (95)	138 (42)	167 (268)	387 (118)
	North Coast	97.6 (157)	226 (69)	220 (354)	512 (156)	518 (834)	1204 (367)
Western hemlock	Mid Coast	83.9 (135)	194 (59)	113 (182)	262 (80)	259 (417)	604 (184)
	North Coast	98.8 (159)	230 (70)	227 (366)	528 (161)	532 (856)	1237 (377)
Western redcedar	Mid Coast	96.3 (155)	223 (68)	158 (254)	367 (112)	353 (568)	820 (250)
	North Coast	79.5 (128)	184 (56)	204 (328)	476 (145)	468 (753)	1086 (331)
Western white pine	Mid Coast Mountains	7.5 (12)	16 (5)	91.3 (147)	213 (65)	244 (392)	564 (172)
Yellow cedar	Mid Coast	43 (70)	102 (31)	163 (262)	377 (115)	320 (515)	745 (227)
	North Coast	95.1 (153)	223 (68)	231 (371)	535 (163)	516 (830)	1198 (365)

***North Coast** refers to B.C.'s coastal western hemlock and mountain hemlock zone north of 51° latitude, and the U.S. Alaskan panhandle. **North Coast Mountains** refers to B.C.'s Engelmann spruce-subalpine fir and interior cedar-hemlock zones north of 51° latitude. **Mid Coast** refers to B.C.'s coastal western hemlock, coastal Douglas-fir, and mountain hemlock zones south of 51° latitude as well as the U.S.'s Coast Range and Puget Lowlands Level III natural regions. **Mid Coast Mountains** refers to B.C.'s Engelmann spruce-subalpine fir and interior cedar-hemlock zones south of 51° latitude as well as the U.S.'s Cascades and North Cascades Level III natural regions. **South Coast** refers to the southern and central California chaparral and oak woodlands Level III natural regions. **South Coast Mountains** refers to the U.S.'s Klamath Mountains, southern California mountains, and the Sierra Nevada Level III natural regions. Region descriptions are acquired from Table 3 in Gray & Hamann (2013, p. 297).
Source: Modified from Gray & Hamann (2013, Table 4, p. 299) by authors of this report.

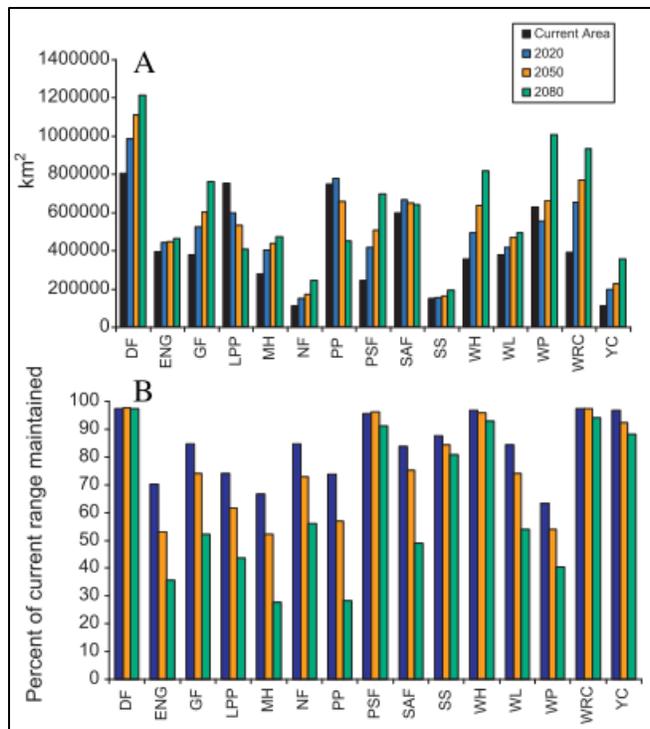


Figure 45. Predicted changes in species' ranges over the rest of the 21st century expressed in (a) area, and (b) as a percentage of the historical range maintained.

Note: Species codes are Douglas-fir (DF), Engelmann spruce (ENG), grand fir (GF), lodgepole pine (LPP), mountain hemlock (MH), noble fir (NF), ponderosa pine (PP), Pacific silver fir (PSF), subalpine fir (SAF), Sitka spruce (SS), western hemlock (WH), western larch (WL), whitebark pine (WP), western redcedar (WRC), and yellow-cedar (YC).

Source: Reproduced from Coops & Waring (2011b, Figure 7, p. 2127) by authors of this report.

needleleaf evergreen trees.¹⁵⁰⁰ More specifically, by the end of 2099 (vs. 2005), about 24 grid cells (or 30% of grid cells) are projected to exceed the heat stress mortality threshold in the simulations.¹⁵⁰¹ Correspondingly, about 20% (or 7 grid cells) of the needleleaf evergreen tree grid cells, which are defined when there is greater than or equal to 1% needleleaf evergreen tree coverage, are projected to experience a 20% or more loss of needleleaf evergreen trees.¹⁵⁰²

In a modeling study of projected future changes in vegetation across western North America (2070-2099 vs. 1961-1990; CESM run with its DGVM under A2), the findings suggest a potential for a widespread shift from tree-dominated landscapes to shrub- and grass-dominated landscapes because of future warming and consequent increases in water deficits.¹⁴⁹⁷ Specific projections include:

- **Western North America:** There is a broad consensus across the different climate trajectories simulated in the ensemble for a decrease (from an average of 25% in 2005 to an average of 11% in 2100) in needleleaf evergreen tree coverage and an increase (from an average of 11% in 2005 to an average of 25% in 2100) in shrubs and grasses beginning around the year 2030.¹⁴⁹⁸

- **Northwestern North America:** An analysis of changes in spatial coverage indicates that the area covered by the needleleaf evergreen tree plant functional type (i.e., temperate and boreal tree types with temperature of coldest month above -2.2 °F, -19 °C and growing degree days exceeding 1200) shrinks and is partially replaced by shrubs or grasses between 40° and 59 °N.¹⁴⁹⁹ The results indicate that heat stress mortality is responsible for about 70% of projected loss of

¹⁴⁹⁷ Nearly verbatim from Jiang et al. (2013, p. 3671)

¹⁴⁹⁸ Verbatim from Jiang et al. (2013, p. 3679)

¹⁴⁹⁹ Nearly verbatim from Jiang et al. (2013, p. 3678). Jiang et al. refer the reader to Figure 5b in the cited article for this information.

¹⁵⁰⁰ Nearly verbatim from Jiang et al. (2013, p. 3679)

¹⁵⁰¹ Nearly verbatim from Jiang et al. (2013, p. 3679)

¹⁵⁰² Nearly verbatim from Jiang et al. (2013, p. 3679). Jiang et al. refer the reader to Figure 5d in the cited article for this information.

The analysis of the climatic controls on vegetation growth in Jiang et al.'s (2013) model suggests that heat stress resulting from projected temperature increase is the dominant driver of the simulated decrease in needleleaf evergreen tree coverage over western North America.¹⁵⁰³ In addition, the indirect effects of increased evaporative demand (and associated stomatal closure) and the longer duration of snow-free periods as a result of earlier and faster snowmelt also appear to be associated with model projected vegetation changes.¹⁵⁰⁴

In a similar modeling study of the effects of fire suppression and CO₂ emissions on vegetation and carbon stocks, in the West (i.e., west of the eastern border of Colorado) there was widespread conversion of shrubland to woodland and woodland to forest with suppressed fire (2071-2100 vs. 1961-1990; Canadian CGCM2, UK HADCM3, and Australian CSIRO Mk2 simulated by MC1 DGVM and run with A2 and B2).¹⁵⁰⁵ As in the results for unsuppressed fire, there were only subtle differences in the simulated future vegetation type distributions due to the CO₂ emission level.¹⁵⁰⁶ The most prominent change in vegetation distribution under the future climate with unsuppressed fire was the widespread expansion of woodland/savanna both in the Southeast, where it replaced forest, and in the interior West, where it replaced shrubland.¹⁵⁰⁷ Other notable features were a near complete loss of alpine and subalpine forest vegetation to temperate forest types, a northward shift of forest-type boundaries in the East, and a consequent reduction in the extent of cool mixed forest in the Northeast.¹⁵⁰⁸

In an earlier modeling study, all but three biome types (barren, desert, and warm mixed forest) showed very high sensitivity to the experimental prescription (560 ppm vs. 280 ppm using the RegCM2.5 climate model and BIOME4 vegetation model), as changes created by elevated CO₂ levels were combined with the effects of CO₂-induced regional climate change.¹⁵⁰⁹ The very high overall sensitivity was due in large part to the expansion of temperate conifer forest, primarily at the expense of cool mixed forest, temperate xerophytic (i.e., adapted to a dry environment) shrubland, open conifer woodland, and temperate grassland.¹⁵¹⁰ Expansion of temperate conifer forest occurred primarily along the northern Pacific coast, as well as in central and southern Arizona.¹⁵¹¹ Temperate grassland was replaced almost entirely along the Pacific Coast, but expanded dramatically in the northeast quadrant of the domain (southern Idaho, northern Nevada and Utah).¹⁵¹²

¹⁵⁰³ Verbatim from Jiang et al. (2013, p. 3682)

¹⁵⁰⁴ Verbatim from Jiang et al. (2013, p. 3682)

¹⁵⁰⁵ Nearly verbatim from Lenihan et al. (2008b, p. 20)

¹⁵⁰⁶ Verbatim from Lenihan et al. (2008b, p. 21). Lenihan et al. refer the reader to Figures 4 B vs. C, and 5 in the cited article for this information.

¹⁵⁰⁷ Verbatim from Lenihan et al. (2008b, p. 19). Lenihan et al. refer the reader to Figures 3B,C and 5 in the cited article for this information.

¹⁵⁰⁸ Verbatim from Lenihan et al. (2008b, p. 19)

¹⁵⁰⁹ Nearly verbatim from Diffenbaugh et al. (2003, p. 8-9). Diffenbaugh et al. refer the reader to Table 5 in the cited article for this information.

¹⁵¹⁰ Nearly verbatim from Diffenbaugh et al. (2003, p. 9). Diffenbaugh et al. refer the reader to Table 5 in the cited article for this information.

¹⁵¹¹ Verbatim from Diffenbaugh et al. (2003, p. 9). Diffenbaugh et al. refer the reader to Figure 2d in the cited article for this information.

¹⁵¹² Nearly verbatim from Diffenbaugh et al. (2003, p. 9)

In an assessment of the potential impacts of a changing climate on western larch, projections of the contemporary climate profile into the climates of the future portray different impacts on western larch (i.e., 2030, 2060, and 2090 vs. 1961-1990 run with CCCMA CGCM3 under A2 and B1, UKMO Had CM3 under A2 and B2, and GFDL CM2.1 under A2 and B1).¹⁵¹³ However, the six projections that Rehfeldt & Jaquish et al. (2010) use agree that the 2030 climates suitable for western larch should be concentrated in four geographic regions, one of which (insert D in the B.C. Coast Mountains) is largely beyond the distribution of today (Figure 46).¹⁵¹⁴ By 2060, the concurrence would be greatly reduced, with the only areas of unanimity restricted to a few valley locations in the Coast Mountains.¹⁵¹⁵

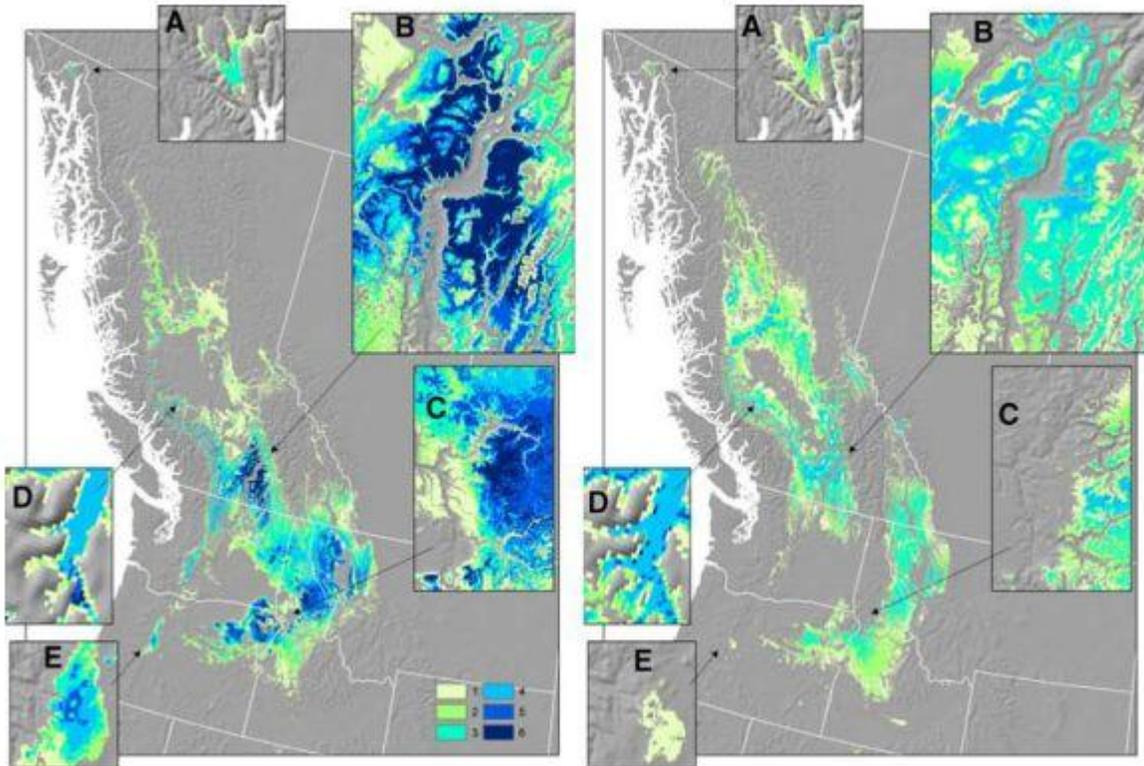


Figure 46. Mapped climate profile of western larch projected for the decade surrounding 2030 (*left*) and 2060 (*right*) superimposed for the three GCMs and two scenarios. Coloring codes the number of projections agreeing that the climate should be suitable.

Source: Reproduced from Rehfeldt & Jaquish (2010, Figure 5, p. 296) by authors of this report.

¹⁵¹³ Nearly verbatim from Rehfeldt & Jaquish (2010, p. 292). Rehfeldt & Barry refer the reader to Table 2 and Figure 4 in the cited article for this information.

¹⁵¹⁴ Nearly verbatim from Rehfeldt & Jaquish (2010, p. 292). Rehfeldt & Barry refer the reader to Figure 5 in the cited article for this information.

¹⁵¹⁵ Verbatim from Rehfeldt & Jaquish (2010, p. 292)

In a modeling study of potential future changes in Douglas-fir habitat and productivity, by 2090, the amount of potential Douglas-fir habitat is projected to change little in terms of area (-4%; 2030, 2060, and 2090 vs. 1961-1990 run with CGCM under A2).¹⁵¹⁶ However, the habitat is expected to shift from coastal areas of North America to the interior (Figure 47).¹⁵¹⁷ Specific results for 2030, 2060, and 2090 include:

- **2030 and 2060:** Based on CGCM projections, the total potential Douglas-fir habitat is expected to increase by 10% and 21% in the decade surrounding 2030 and 2060, respectively, when compared to the amount of current habitat.¹⁵¹⁸
- **2090:** However, the amount of total potential Douglas-fir habitat should decrease by 4% in 2090 when compared to the amount of current habitat.¹⁵¹⁹ Overall, only 40% of the potential Douglas-fir habitat in 2090 will overlap with current habitat.¹⁵²⁰

Southcentral and Southeast Alaska

Two common conifers in southeastern Alaska, Sitka spruce and western hemlock, are expected to move upslope as the climate warms.¹⁵²¹ Mountain hemlock, which grows at elevations above Sitka spruce and western hemlock but below tundra, also will move upslope, and may eventually disappear as predicted for British Columbia.¹⁵²² Mountain hemlock also occurs in wetlands and may persist there while being extirpated in other locations.¹⁵²³

In a modeling study using the dynamic global vegetation model MC1, the temperate and maritime coniferous forests found in southcentral and southeast Alaska are projected to expand by 2090-2100 (compared to 1922-1996 under two climate change scenarios, CGCM1 and HADCM2SUL):

- As both the minimum mean monthly temperature (MMT) and the continental index (maximum MMT – minimum MMT) increase, **temperate coniferous forests** greatly expand across the southern half of the state at the expense of the heat-limited tundra and the boreal forests, which are constrained by a minimum MMT of 3.2 °F (-16 °C), to cover 36% of the total area.¹⁵²⁴
- **Maritime coniferous forests** also expand in regions where the continental index remains below 59 °F (15 °C).¹⁵²⁵
- *Note: Scenarios were based on greenhouse gas experiments with sulfate aerosols from the Canadian Climate Center (CGCM1) and the Hadley Centre (HADCM2SUL).*¹⁵²⁶

¹⁵¹⁶ Nearly verbatim from Weiskittel et al. (2012, p. 70)

¹⁵¹⁷ Verbatim from Weiskittel et al. (2012, p. 70)

¹⁵¹⁸ Verbatim from Weiskittel et al. (2012, p. 73-74). Weiskittel et al. refer the reader to Table 2 in the cited article for this information.

¹⁵¹⁹ Verbatim from Weiskittel et al. (2012, p. 74)

¹⁵²⁰ Verbatim from Weiskittel et al. (2012, p. 74)

¹⁵²¹ Verbatim from Kelly et al. (2007, p. 52)

¹⁵²² Verbatim from Kelly et al. (2007, p. 52). Kelly et al. cite Hamann & Wang (2006) for this information.

¹⁵²³ Verbatim from Kelly et al. (2007, p. 52)

¹⁵²⁴ Verbatim from Bachelet et al. (2005, p. 2251). Bachelet et al. refer the reader to Figures 4 and 5 in the cited article for this information.

¹⁵²⁵ Verbatim from Bachelet et al. (2005, p. 2251)

¹⁵²⁶ Nearly verbatim from Bachelet et al. (2005, p. 2246). Bachelet et al. cite Mitchell et al. (1995) and Johns et al. (1997) for information on HADCM2SUL.

Those conditions (i.e., longer growing seasons with warmer temperatures) will favor more rapid decomposition and a transition of bog and forested wetlands to more productive forests with larger stature trees.¹⁵²⁷ New habitats will be colonized by plants as glaciers recede and inter-tidal areas are uplifted.¹⁵²⁸

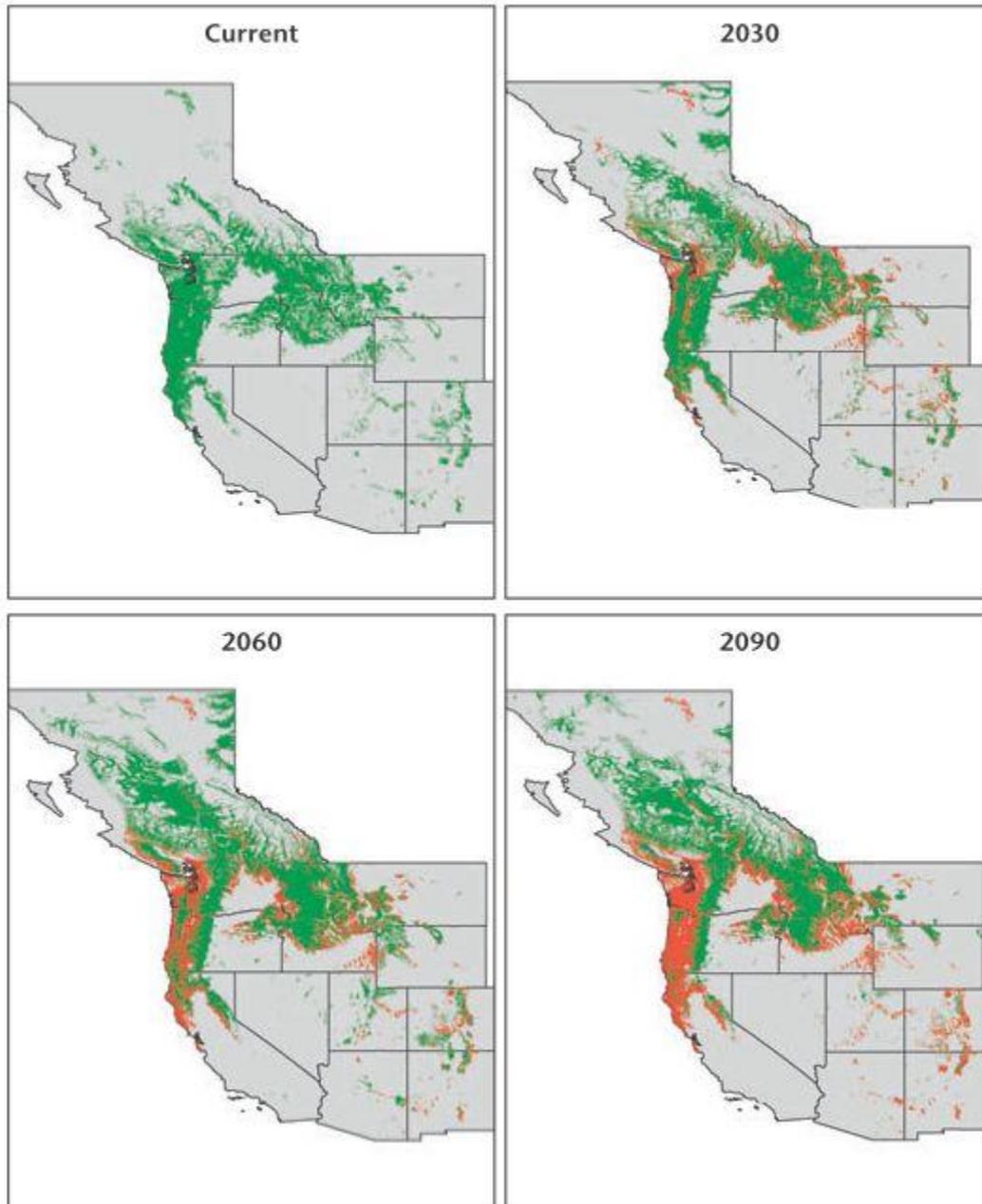


Figure 47. Predicted current and future distribution of Douglas-fir potential habitat based on the developed random forest model and the Canadian Center for Climate Modeling and Analysis general circulation model under the A2 emissions scenario. **Green:** current and predicted habitat, **red:** losses in habitat.

Source: Reproduced from Weiskittel et al. (2012, Figure 2, p. 73) by authors of this report.

¹⁵²⁷ Nearly verbatim from Kelly et al. (2007, p. 51)

¹⁵²⁸ Verbatim from Kelly et al. (2007, p. 51)

Murphy et al. (2010) projected spatial shift in potential biomes for three future periods: 2030-2039, 2060-2069, and 2090-2099.¹⁵²⁹ Climate data inputs were all based on the midrange (A1B) emissions scenario for the Scenarios Network for Alaska Planning (SNAP's) Composite GCM, and included mean monthly temperatures and precipitation for the months of June and December for the decades 2000-2009, 2030-2039, 2060-2069, and 2090-2099.¹⁵³⁰ Figure 48 shows results from 2090-2099.

By 2069, projections indicate marked northward shifts, almost complete change in western coastal regions, and some Canadian biomes moving in from the east.¹⁵³¹ It is important to note that these shifts represent **potential** rather than actual biome shift, since in many cases it is unconfirmed that seed dispersal, soil formation, and other functional changes could occur at the same rate as climate change (emphasis in original).¹⁵³² In addition, much of southeast Alaska may be in the process of shifting from North Pacific Maritime to Canadian Pacific Maritime—again, as constrained by functional barriers (Box 6).¹⁵³³

The model suggests that two-thirds of Alaska will experience a potential biome shift in climate this century, although shifts are occurring at temporally and spatially different rates across the landscape.¹⁵³⁴ The three most southern biomes (Boreal Transition, Aleutian Islands, and North Pacific Maritime) were the only biomes with climate envelopes that occur in greater distribution through the next century.¹⁵³⁵ Using Marxan, Murphy and colleagues find that, in general, the Boreal Transition, Aleutian, and Northern Pacific Maritime regions in the southeast portions of the state are more likely to be resilient to change (Figure 49).¹⁵³⁶

A similar and more recent study to identify potential ecological refugia and areas of greatest and least change has been conducted for Alaska. The study uses cliomes instead of biomes in the assessment; a cliome is a broadly defined region of temperature and precipitation patterns that reflect assemblages of species and vegetation communities (biomes) that occur or might be expected to occur based on linkages with climate conditions.¹⁵³⁷ However, these results are not included here because the authors of the study note the cliome covering southcentral and southeast Alaska (Cliome 17) is “effectively locked on the landscape...because our clustering region and clustering methodology did not offer an alternate cluster similar enough to capture the expected change.”¹⁵³⁸

¹⁵²⁹ Murphy et al. (August 2010, p. 14)

¹⁵³⁰ Nearly verbatim from Murphy et al. (August 2010, p. 14)

¹⁵³¹ Verbatim from Murphy et al. (August 2010, p. 21)

¹⁵³² Verbatim from Murphy et al. (August 2010, p. 21)

¹⁵³³ Verbatim from Murphy et al. (August 2010, p. 21)

¹⁵³⁴ Verbatim from Murphy et al. (August 2010, p. 21)

¹⁵³⁵ Nearly verbatim from Murphy et al. (August 2010, p. 21)

¹⁵³⁶ Nearly verbatim from Murphy et al. (August 2010, p. 29)

¹⁵³⁷ Nearly verbatim from SNAP & EWHALE Lab (2012, p. 8)

¹⁵³⁸ SNAP & EWHALE Lab (2012, p. 37)

Box 6. Vegetation in the North Pacific Maritime and Canadian Pacific Maritime regions.

Alaska's North Pacific Maritime biome extends along the north and east shores of the Gulf of Alaska. Old-growth forests of Sitka spruce, hemlock, and cedar are found in the Alexander Archipelago. Hemlock extends to the end of the Kenai Peninsula, while cedar extends to Prince William Sound. Wetlands are found throughout the region. As elevation increases, upper forests are replaced by a narrow subalpine zone of alder and herbaceous meadow. Alpine tundra and bedrock or ice are found at the highest elevations.

Canada's Pacific Maritime Ecozone includes the mainland Pacific coast and offshore islands of British Columbia. Mixtures of western red cedar, yellow cedar, western hemlock, Douglas-fir, amabilis fir, mountain hemlock, Sitka spruce, and alder comprise the region's temperate coastal forests. Amabilis fir is more common in the north, and Douglas-fir is found largely in the extreme southern portion of the ecozone. Ecosystems range from low-elevation coastal rainforest (mild, humid) to higher-elevation, cool boreal and alpine conditions. Mountain hemlock tends to populate higher elevations.

Source: Murphy et al. (2010, p. 65-66, 68-69)

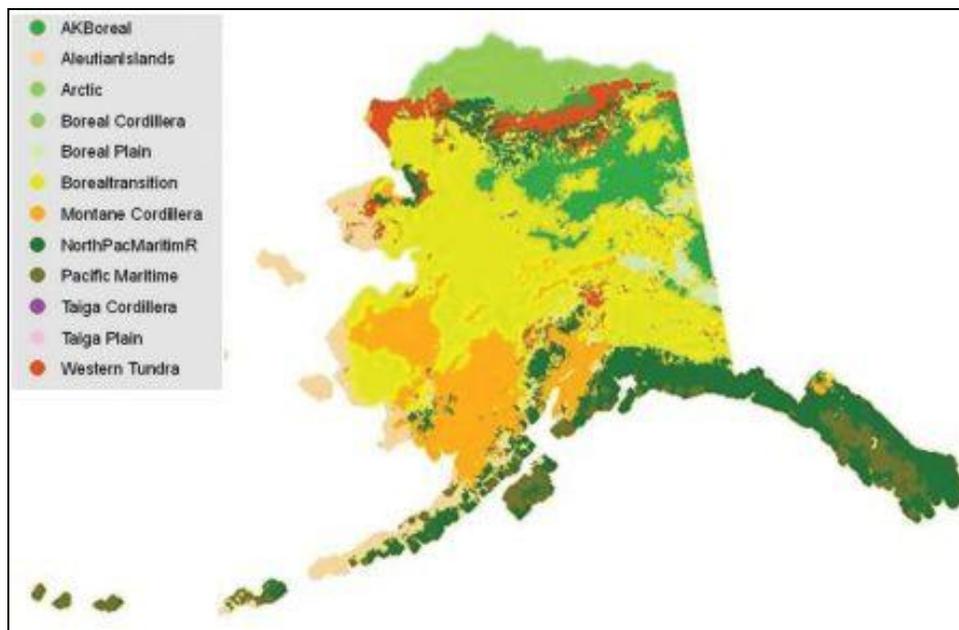


Figure 48. Projected potential biomes for 2090-2099. The Arctic, Alaska Boreal, and Western Tundra biomes are all greatly diminished, in favor of the Montane Cordillera and Boreal Transition. In addition, nearly half of southeast Alaska has shifted from North Pacific Maritime to the Canadian Pacific Maritime. *Source: Reproduced from Murphy et al. (2010, Fig. 7, p. 19) by authors of this report.*

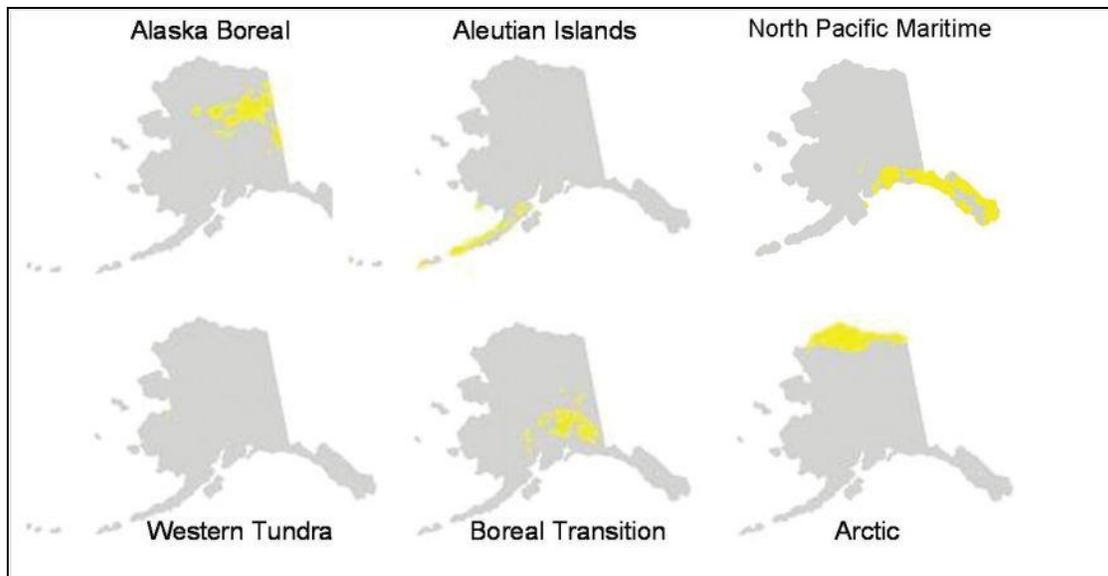


Figure 49. Biome refugia. Areas shaded in yellow are projected to see no change in potential biome by the end of the twenty-first century. Thus, these regions may be more ecologically resilient to climate change and may serve as refugia for species assemblages from each biome. *Source: Reproduced from Murphy et al. (2010, Fig. 11, p. 25) by authors of this report.*

Western British Columbia

Modelling of anticipated climate change suggests that B.C.'s forest types will change during this century, and that grasslands will expand considerably into areas that are currently forested.¹⁵³⁹ Climax species (i.e., late seral or late successional species, those species found in a biological community that has reached a steady state and will remain unchanged unless disturbed) that are not good colonizers, species with short-distance seed dispersal (for example, among B.C. trees, ponderosa pine, Douglas-fir, western white pine, and true fir species), and small local populations (subalpine larch, yellow-cedar, and limber pine) will probably be least successful at migration in the short term.¹⁵⁴⁰

In contrast, individuals of highly plastic species can tolerate a wide range of environments and may be less sensitive to climate change.¹⁵⁴¹ Western redcedar, B.C.'s provincial tree, could expand its range significantly in the Kootenays, the central interior, and on the north coast, but could also suffer widespread decline in south coastal B.C. generally.¹⁵⁴²

In a study projecting future ecosystem climate niches for three future time periods (2020s, 2050s, 2080s; vs. 1961-1990) using the Random Forests model, vulnerability to a changing climate was projected to differ substantially among ecosystems (multiple GCMs run with A1, A1B or B2) (Figure 50).¹⁵⁴³ High-elevation (Boreal Altai Fescue Alpine, Interior Mountain-heather Alpine, Montane Spruce) and sub-

¹⁵³⁹ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 32)

¹⁵⁴⁰ Nearly verbatim from Pojar (2010, p. 34)

¹⁵⁴¹ Verbatim from Pojar (2010, p. 34)

¹⁵⁴² Nearly verbatim from Pojar (2010, p. 29). Pojar cites Wilson & Hebda (2008) for this information.

¹⁵⁴³ Nearly verbatim from Wang et al. (2012, p. 9). Wang et al. refer the reader to Table 5 and Figure 4 in the cited article for this information.

boreal ecosystems (Sub-Boreal Pine – Spruce, Sub-Boreal Spruce, Spruce-Willow-Birch) were most vulnerable and over 80% of the area covered by their climate envelopes was projected to be lost by the end of the century.¹⁵⁴⁴ The extent of low elevation boreal (Boreal White and Black Spruce) and coastal (Coastal Western Hemlock and Coastal Douglas-fir) ecosystems was projected to remain relatively unchanged.¹⁵⁴⁵ Substantial expansion of the geographic area with suitable climate for Douglas-fir in future periods was projected.¹⁵⁴⁶ Such expansions were projected to occur throughout coastal and southern BC, resulting in doubling of the total area potentially suitable for this species at the end of the century (Figure 51).¹⁵⁴⁷

Confidence in these consensus projections about future ecosystem climate niche distribution varied over time and space.¹⁵⁴⁸ Consensus was moderate to strong in the 2020s, with agreement on projected ecosystem averaging 66% across all pixels.¹⁵⁴⁹ By the 2080s, projections became less certain with average consensus of projected ecosystem for a pixel declining to 51%.¹⁵⁵⁰ Future ecosystem climate niches were projected with greatest confidence in northeast BC and along parts of the coast.¹⁵⁵¹ Specific results for the NPLCC region are available for the projected shifts in climate habitat (Table 26) and elevation and northward shift (Table 27).

Worst-case scenarios are becoming the most likely (5.4 to 9 °F, 3 to 5°C in 70 to 100 years), forcing a shift of today's ecological zones (or rather, the climate envelopes for such zones) a predicted ~2952 to 4921 feet (900 to 1500 meters) up in elevation and ~280 to 466 miles (450 to 750 km) north.¹⁵⁵² The rate of projected climate envelope shifts is estimated to be at least ~25 miles per decade (40 km/decade).¹⁵⁵³ Suitable habitats will shift too fast for many species to keep up, or to compensate through dispersal and migration.¹⁵⁵⁴ General predicted changes in the zonal climate envelopes relevant for western British Columbia include the following (refer to Figure 43 for current biogeoclimatic zones):¹⁵⁵⁵

- A general shift of zones from the southern to the northern half of B.C.¹⁵⁵⁶
- A major expansion northward and upslope of dry non-forest (grasslands, shrub-steppe) and dry forest zones (especially in the interior but also on the south coast).¹⁵⁵⁷
- A massive expansion of moist coastal and interior conifer forest zones upslope and north at the expense of subalpine and sub-boreal spruce zones.¹⁵⁵⁸
- A near disappearance of northern subalpine/subarctic spruce-willow-birch bioclimates.¹⁵⁵⁹

¹⁵⁴⁴ Verbatim from Wang et al. (2012, p. 9-10)

¹⁵⁴⁵ Verbatim from Wang et al. (2012, p. 10)

¹⁵⁴⁶ Nearly verbatim from Wang et al. (2012, p. 10). Wang et al. refer the reader to Figure 9 in the cited article for this information.

¹⁵⁴⁷ Verbatim from Wang et al. (2012, p. 10)

¹⁵⁴⁸ Verbatim from Wang et al. (2012, p. 10). Wang et al. refer the reader to Figures 7a-7c in the cited article.

¹⁵⁴⁹ Verbatim from Wang et al. (2012, p. 10)

¹⁵⁵⁰ Verbatim from Wang et al. (2012, p. 10)

¹⁵⁵¹ Verbatim from Wang et al. (2012, p. 10)

¹⁵⁵² Nearly verbatim from Pojar (2010, p. 18)

¹⁵⁵³ Nearly verbatim from Pojar (2010, p. 18)

¹⁵⁵⁴ Verbatim from Pojar (2010, p. 18)

¹⁵⁵⁵ Nearly verbatim from Pojar (2010, p. 18)

¹⁵⁵⁶ Verbatim from Pojar (2010, p. 18)

¹⁵⁵⁷ Verbatim from Pojar (2010, p. 18)

¹⁵⁵⁸ Verbatim from Pojar (2010, p. 18)

- A shrinking of alpine tundra ecosystems and disappearance of alpine “islands” as woody ecosystems (subalpine forests and shrublands) shift up in elevation.¹⁵⁶⁰ Some of the worst-case scenarios project subalpine conditions into much of the province’s alpine environment.¹⁵⁶¹
- Large diebacks of trees, including further diebacks of aspen, paper birch, ponderosa pine, and whitebark pine, are expected due to drought and drought-facilitated insect, disease and fire damage.¹⁵⁶²

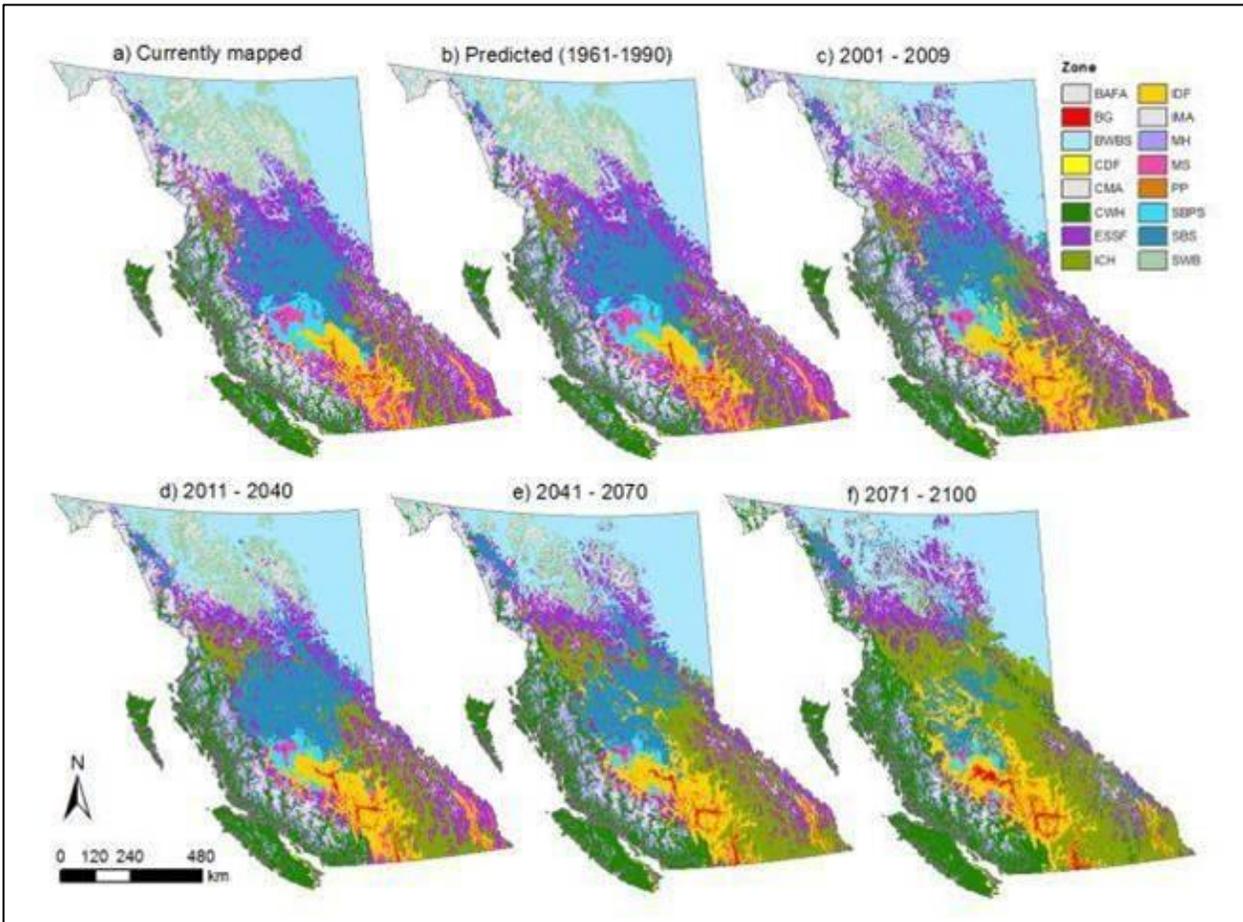


Figure 50. Geographic distributions of ecological zones currently mapped (a), predicted (1961-1990) (b), and their projected climate envelopes for current (2001-2009) (c), 2020s (d), 2050s (e), and 2080s (f) based on consensus predictions with the best-model agreement among 20 selected climate change scenarios.

Source: Reproduced from Wang et al. (2012, Figure 4) by authors of this report.

Note: Ecological zones in the NPLCC region include the Coastal Western Hemlock (CWH, dark green), Mountain Hemlock (MH, light purple), Engelmann Spruce – Subalpine Fir (ESSF, dark purple), Coastal Douglas-fir (CDF, yellow), Sub-Boreal Spruce (SBS, dark blue), and Coastal Mountain-heather Alpine (CMA, lightest gray).

¹⁵⁵⁹ Verbatim from Pojar (2010, p. 18)

¹⁵⁶⁰ Verbatim from Pojar (2010, p. 18)

¹⁵⁶¹ Verbatim from Pojar (2010, p. 18). Pojar cites Vyse & Simard (2009) for this information.

¹⁵⁶² Nearly verbatim from Pojar (2010, p. 18)

Table 26. Predicted shifts in climate envelopes for ecological zones for the current (2001-2009) and projected shifts based on the consensus among the 20 selected climate change scenarios and three future periods 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100) relative to the reference period (1961-1990).

Ecosystem Zone	Loss, gain, and change of climate habitat* (%)				
		Current	2020s	2050s	2080s
Coastal Western Hemlock (CWH)	Loss	-5	-2	0	-2
	Gain	+13	+24	+40	+71
	Change	+8	+22	+40	+69
Mountain Hemlock (MH)	Loss	-23	-33	-70	-74
	Gain	+30	+29	+63	+62
	Change	+7	-4	-7	-12
Engelmann Spruce – Subalpine Fir (ESSF)	Loss	-21	-34	-59	-74
	Gain	+27	+15	+38	+41
	Change	+6	-19	-21	-33
Coastal Douglas-fir (CDF)	Loss	-5	-15	-19	-22
	Gain	+24	+14	+16	+41
	Change	+19	-1	-3	+19
Coastal Mountain-heather Alpine (CMA)	Loss	-18	-29	-60	-60
	Gain	+29	+13	+15	+15
	Change	+11	-16	-45	-45
Sub-boreal Spruce (SBS)	Loss	-31	-19	-52	-80
	Gain	+21	+30	+37	+36
	Change	-10	+11	-15	-44

* Loss indicates the percent decrease in area of a mapped zone due to pixels that now have or are projected in the future to have climates outside of the climatic envelope of that zone. Gain indicates the percent increase in area of a zone due to pixels mapped in other zones that have climates that fall within the climatic envelope of the zone.

Source: Modified from Wang et al. (2012, Table 5, p. 24) by authors of this report.

Table 27. Predicted elevation and northward shifts in climate envelopes for ecological zones for the current (2001-2009) and projected shifts based on the consensus among the 20 selected climate change scenarios and three future periods 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100) relative to the reference period (1961-1990).

Ecosystem Zone	Elevation Shift <i>Feet (meters)</i>				Northward Shift <i>Miles (kilometers)</i>			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Coastal Western Hemlock (CWH)	161 (49)	344 (105)	627 (191)	1060 (323)	4 (7)	11 (18)	22 (36)	43 (69)
Mountain Hemlock (MH)	82 (25)	577 (176)	938 (286)	1493 (455)	34 (54)	17 (28)	34 (55)	47 (75)
Engelmann Spruce – Subalpine Fir (ESSF)	-49 (-15)	338 (103)	390 (119)	404 (123)	64.6 (104)	34 (54)	108 (174)	173 (278)
Coastal Douglas-fir (CDF)	30 (9)	52 (16)	79 (24)	420 (128)	3 (5)	2 (-3)	4 (-6)	6 (10)
Coastal Mountain-heather Alpine (CMA)	49 (15)	295 (90)	469 (143)	682 (208)	9.9 (16)	33 (53)	58 (94)	85.7 (138)
Sub-boreal Spruce (SBS)	69 (21)	154 (47)	331 (101)	505 (154)	17 (27)	11 (18)	39 (63)	90.1 (145)

Source: Modified from Wang et al. (2012, Table 5, p. 24) by authors of this report.

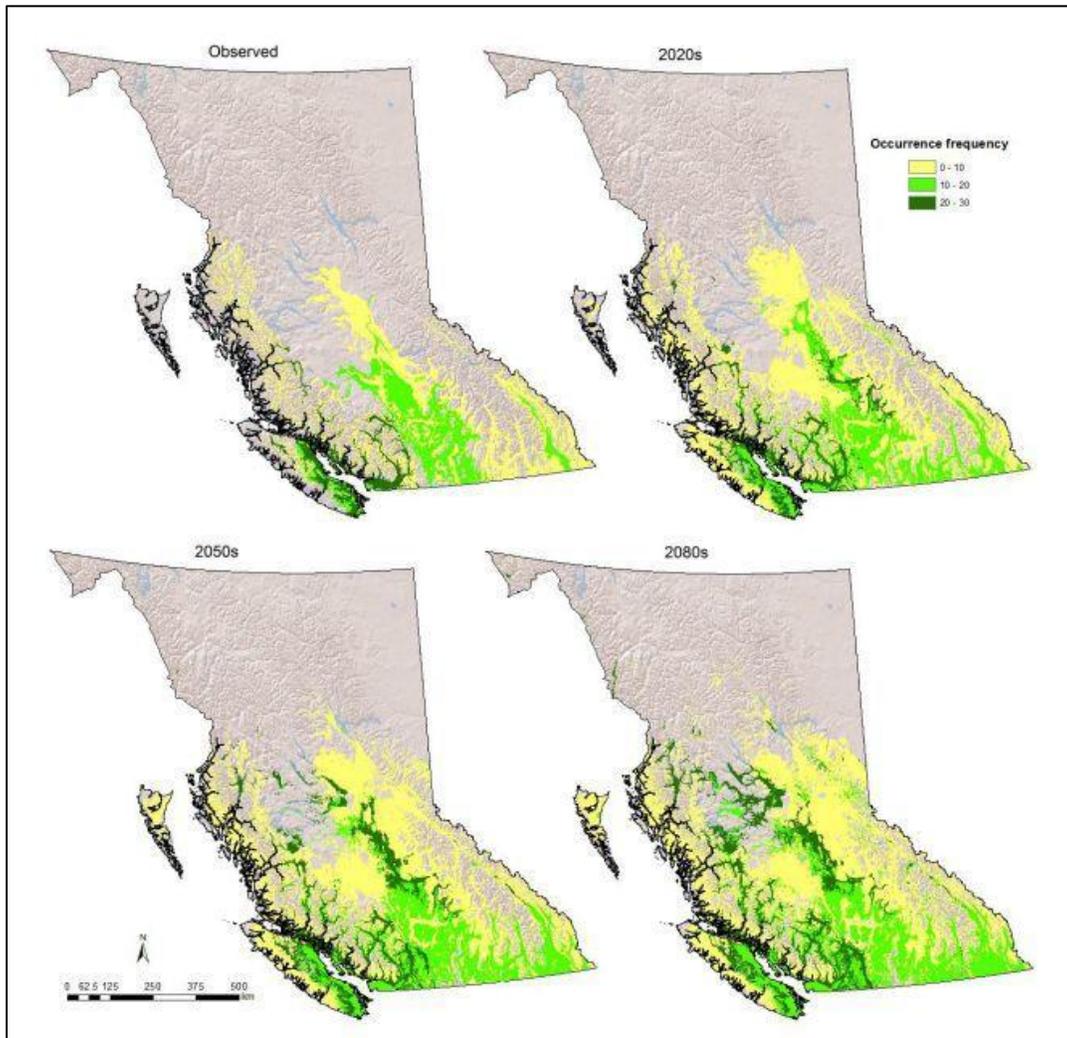


Figure 51. Random Forest model projections of the geographic distribution of the frequency of occurrence (percent of crown cover) of Douglas-fir (*Pseudotsuga menziesii*) for currently observed (2001-2009), 2020s, 2050s and 2080s. The projections were based on consensus prediction of ecological zone climate habitats and the current extent of Douglas-fir in these zones.
 Source: Reproduced from Wang et al. (2012, Figure 9, p. 34) by authors of this report.

Pacific Northwest

Based on projections of distribution of tree species and forest biomes, widespread changes in the distribution and abundance of dominant forest species are expected, although the results of modeling studies differ.¹⁵⁶³ Forest cover will change faster via disturbance and subsequent regeneration responses, rather than through slow adjustment to gradual warming.¹⁵⁶⁴

With projected increasing warming over the rest of the century, without a commensurate large increase in precipitation, the environment will be both too warm and too dry for lodgepole pine to compete well with other Northwest tree species.¹⁵⁶⁵ By 2020 a decision-tree model predicts an 8% decrease in the area suitable for the pine (approximately 3,089 square miles, mi²; 8,000 square kilometers, km²) with most of its range remaining intact (vs. 1979-2008 run with CGCM2 under A2).¹⁵⁶⁶ By 2050, however, a significant reduction in the species distribution is projected, particularly in central Oregon and central Washington.¹⁵⁶⁷ In British Columbia, large areas on the western side of the Rockies are projected to be unsuitable for lodgepole pine.¹⁵⁶⁸ By 2080, the species is projected to be almost absent from Oregon, Washington and Idaho.¹⁵⁶⁹ Even in British Columbia and Alberta, the species' range is likely to be reduced significantly.¹⁵⁷⁰ The total area deemed suitable for the pine in the 2080 period is projected to be only 5,791 mi² (15,000 km²), 17% of its current distribution.¹⁵⁷¹ Of this area, 75% is currently modeled to occupy lodgepole pine, with the remaining 25% of the projected area, new habitat for the species.¹⁵⁷²

Douglas-fir, one of the major species of Pacific Northwest forests, has a relatively long chilling period that would not be adequately met under the simulated future increases in the mean temperature of the coldest month (from 0-9 °F (0-5 °C) to 9-18 °F (5-10 °C) by 2090-99, see Chapter IV.2 and Figure 7 for more information).¹⁵⁷³ This increase in the mean temperature of the coldest month is significant because, in the event of a large disturbance such as a stand-replacing fire, lack of chilling could seriously affect seedling reestablishment and could be a catalyst for major changes in the species composition of Douglas-fir–dominated forests.¹⁵⁷⁴ The absence of below-freezing temperatures may also have an indirect effect on tree diversity as warming allows competitors that are currently excluded by freezing temperatures to move into this region.¹⁵⁷⁵

¹⁵⁶³ Verbatim from Vose et al. (2012, p. vii)

¹⁵⁶⁴ Verbatim from Vose et al. (2012, p. vii)

¹⁵⁶⁵ Verbatim from Coops & Waring (2011a, p. 323)

¹⁵⁶⁶ Nearly verbatim from Coops & Waring (2011, p. 323)

¹⁵⁶⁷ Verbatim from Coops & Waring (2011a, p. 323). Coops & Waring refer the reader to Figure 5c in the cited article for this information.

¹⁵⁶⁸ Verbatim from Coops & Waring (2011a, p. 323)

¹⁵⁶⁹ Verbatim from Coops & Waring (2011a, p. 323-324)

¹⁵⁷⁰ Verbatim from Coops & Waring (2011a, p. 324). Coops & Waring refer the reader to Figure 5d in the cited article for this information.

¹⁵⁷¹ Verbatim from Coops & Waring (2011a, p. 324)

¹⁵⁷² Verbatim from Coops & Waring (2011a, p. 324-325)

¹⁵⁷³ Nearly verbatim from Shafer et al. (2011, p. 211). Shafer et al. cite Kimmins and Lavender (1992) for this information.

¹⁵⁷⁴ Nearly verbatim from Shafer et al. (2011, p. 211)

¹⁵⁷⁵ Verbatim from Shafer et al. (2011, p. 211)

Western Washington

Simulations from General Circulation Models for the Pacific Northwest predict warmer temperatures throughout the year as well as wetter winters over the next 50–100 years, a combination that is not analogous to the broad-scale climatic regimes over the Holocene.¹⁵⁷⁶ Many of Washington’s future forests may look much like the forests that are currently present, but the most vulnerable forests may look radically different due to increased frequency and severity of disturbances.¹⁵⁷⁷ A rapid climatic shift, coupled with stand-replacing fires and other disturbances, could result in new vegetation assemblages with no historic analogues.¹⁵⁷⁸ Forest species composition will likely change chiefly in the wake of large disturbances and may be affected by climatic limitation of regenerating trees.¹⁵⁷⁹ Sudden changes to forest structure and composition caused by stand-replacing disturbances will speed up species turnover and transitions to new structural characteristics of stands and landscapes, and maintain positive feedbacks between rates of change in disturbance regimes and forest succession.¹⁵⁸⁰ Particularly in places where vegetation types shift from forest to woodland or from tundra to forest, fire regimes will be influenced by the shift in vegetation.¹⁵⁸¹ Eventually, species and stand densities that are resistant to increased summer water deficit and increased disturbance will be favored, and landscape structure and pattern will change.¹⁵⁸² Projections for future forest species composition include:

- **Statewide:** Climate will be inconsistent with the establishment of Douglas-fir, ponderosa pine, and lodgepole pine in many areas by the middle of the twenty-first century.¹⁵⁸³ Specifically, climate is projected to become unfavorable for Douglas-fir over 32% of its current range in Washington, and up to 85% of the range of some pine species may be outside the current climatically suitable range.¹⁵⁸⁴ In other words, Douglas-fir will be outside of its optimal range over considerable areas, and there are almost certainly thresholds of water deficit past which large areas of west-side forests would be at risk for large fires.¹⁵⁸⁵ Such fires do not occur in the 20th century historical record, so statistical fire models (e.g., those used by Littell et al., 2010) are incapable of projecting them.¹⁵⁸⁶
- **Southwest Olympic Mountains:** Dominant tree species are projected to shift upwards ~ 984-1970 feet (300-600 m) in elevation (using the gap model ZELIG under a 3.6 °F (2 °C) temperature increase and altered precipitation regimes, either no change in annual precipitation, a 20% increase in annual precipitation, or a 20% decrease in annual precipitation over 1000 years), with subalpine meadows and mountain hemlock forests being replaced by Pacific silver fir forests

¹⁵⁷⁶ Verbatim from Prichard et al. (2009, p. 66). Prichard et al. cite Mote et al. (2008) for information on temperature and precipitation in the next 50-100 years.

¹⁵⁷⁷ Verbatim from Littell et al. (2010, p. 149)

¹⁵⁷⁸ Verbatim from Prichard et al. (2009, p. 66)

¹⁵⁷⁹ Verbatim from Littell et al. (2010, p. 154)

¹⁵⁸⁰ Verbatim from Littell et al. (2010, p. 154)

¹⁵⁸¹ Verbatim from Littell et al. (2010, p. 149)

¹⁵⁸² Verbatim from Littell et al. (2010, p. 149)

¹⁵⁸³ Verbatim from Littell et al. (2010, p. 154)

¹⁵⁸⁴ Verbatim from Vose et al. (2012, p. vii)

¹⁵⁸⁵ Nearly verbatim from Littell et al. (2010, p. 150)

¹⁵⁸⁶ Nearly verbatim from Littell et al. (2010, p. 150)

at higher elevations and Pacific silver fir forests being replaced by western hemlock forests at lower elevations.¹⁵⁸⁷

- **Northeast Olympic Mountains:** Drought-tolerant species become dominant approximately 656 feet (200 m) lower than present, with subalpine fir dominating the north aspect and lodgepole pine the south aspect (using the same ZELIG model and same temperature-precipitation scenarios described in previous bullet).¹⁵⁸⁸

Western Oregon

Most studies of migration rates based on the establishment of new stands rely upon paleobotanical studies of range shifts over the last 25,000 years.¹⁵⁸⁹ Although estimates of historical horizontal migration rates vary widely from 6.2 miles per century (10 kilometers per century, km/century) to exceptional examples of 93.2 miles/century (150 km/century), all estimates are well below the 186 to 311 miles/century (300 to 500 km/century) required to keep pace with current climate projections for the next century.¹⁵⁹⁰

Peripheral populations at the warmer edges of a species' range that receive gene flow primarily from populations adapted to cooler climates could become increasingly maladapted to warmer climates.¹⁵⁹¹ Such might be the case for species such as Douglas-fir, western redcedar, or Sitka spruce in southwest Oregon, which might see their southern ranges move north as environments become warmer and drier.¹⁵⁹²

Areas of mixed evergreen and deciduous forest are projected to expand in the Oregon Coast Range by 2070-2099 (compared to 1961-1990, using an MC1 vegetation simulation run with the CSIRO-Mk3.0 and UKMO-HadCM3 GCMs under the B1 and A2 scenarios).¹⁵⁹³ This vegetation type represents a major floral and faunal transition from temperate to subtropical species, including broadleaf vegetation (some evergreen), and its increase could represent expansion of maple species, madrone, oak species, and various pine species that currently occur in southwestern Oregon and northern California.¹⁵⁹⁴ The simulated vegetation changes produce a decrease in vegetation carbon in western Oregon by the end of the century.¹⁵⁹⁵ This decrease is partly the result of changes in vegetation and partly the result of projected increases in the amount of biomass burned by wildfires, particularly in western Oregon.¹⁵⁹⁶

Using a dynamic vegetation model accounting for individual tree interactions, Busing et al. (2007) simulated relatively small changes in forest composition and basal area for major tree species in the South

¹⁵⁸⁷ Nearly verbatim from Zolbrod & Peterson (1999, p. 1966)

¹⁵⁸⁸ Nearly verbatim from Zolbrod & Peterson (1999, p. 1966)

¹⁵⁸⁹ Verbatim from Shafer et al. (2010, p. 192)

¹⁵⁹⁰ Verbatim from Shafer et al. (2010, p. 192). Shafer et al. cite Davis & Shaw (2001) and Aitken et al. (2008) for this information.

¹⁵⁹¹ Verbatim from Shafer et al. (2010, p. 192). Shafer et al cite Davis & Shaw (2001) and Aitken et al. (2008) for this information.

¹⁵⁹² Verbatim from Shafer et al. (2010, p. 192)

¹⁵⁹³ Nearly verbatim from Shafer et al. (2010, p. 180)

¹⁵⁹⁴ Nearly verbatim from Shafer et al. (2010, p. 180). Shafer et al. cite McLaughlin et al. (1989) for this information.

¹⁵⁹⁵ Verbatim from Shafer et al. (2010, p. 180). Shafer et al. refer the reader to Figures 5.3d and 5.3e in the cited report for this information.

¹⁵⁹⁶ Verbatim from Shafer et al. (2010, p. 180). Shafer et al. refer the reader to Figures 5.3b and 5.3c in the cited report for information on projected changes in vegetation, and Figures 5.3f and 5.3g for information on amount of biomass burned by wildfires.

Santiam River watershed in western Oregon under projected future climate changes for 2050.¹⁵⁹⁷ Their projections also indicated that some tree species, such as western hemlock and Pacific silver fir, could shift their distributions upward in elevation during this time.¹⁵⁹⁸

Northwest California

The future distribution of vegetation classes in California was projected under three future climate scenarios using the MC1 Dynamic Vegetation Model (2070-2099 vs. 1961-1990 run using the GFDL-A2, GFDL-B1, and PCM-A2 scenarios).¹⁵⁹⁹ The Evergreen Conifer Forest and Mixed Evergreen Forest vegetation classes are located in northwest California in the NPLCC region. Future distribution projections for these vegetation classes include:

- **Evergreen Conifer Forest declined under all scenarios**, but the largest declines were simulated under the warmer and drier GFDL scenarios.¹⁶⁰⁰
- **Mixed Evergreen Forest increased in extent under all three scenarios:**¹⁶⁰¹ Increases in temperature reduced the dominance of the evergreen needleleaf life-form, converting Evergreen Conifer Forest to Mixed Evergreen Forest.¹⁶⁰² The expansion of this type was particularly significant under the PCM-A2 scenario, in which higher levels of effective moisture generally promoted the expansion of forest.¹⁶⁰³

In the same modeling study, the simulated extent of forest cover for all of California (i.e., the combined extent of Evergreen Conifer Forest and Mixed Evergreen Forest) increased relative to the historical extent by 23% under the PCM-A2 scenario.¹⁶⁰⁴ However, forest cover declined by 3 and 25% under the GFDL-B1 and GFDL-A2 scenarios, respectively.¹⁶⁰⁵

Information Gaps

Further research is needed to study effective pollen flow in native stands, particularly in highly heterogeneous environments such as the mountainous areas of Oregon.¹⁶⁰⁶ Better projections of future ecosystems depend on a much better understanding of and accounting for dispersal and migration.¹⁶⁰⁷

¹⁵⁹⁷ Nearly verbatim from Shafer et al. (2010, p. 182)

¹⁵⁹⁸ Nearly verbatim from Shafer et al. (2010, p. 182)

¹⁵⁹⁹ Lenihan et al. (2008a)

¹⁶⁰⁰ Verbatim from Lenihan et al. (2008a, p. S221)

¹⁶⁰¹ Verbatim from Lenihan et al. (2008a, p. S221)

¹⁶⁰² Verbatim from Lenihan et al. (2008a, p. S221)

¹⁶⁰³ Verbatim from Lenihan et al. (2008a, p. S221)

¹⁶⁰⁴ Nearly verbatim from Lenihan et al. (2008a, p. S221)

¹⁶⁰⁵ Nearly verbatim from Lenihan et al. (2008a, p. S221)

¹⁶⁰⁶ Verbatim from Shafer et al. (2010, p. 192)

¹⁶⁰⁷ Verbatim from Pojar (2010, p. 30). Pojar cites Higgins & Harte (2006) for this information.

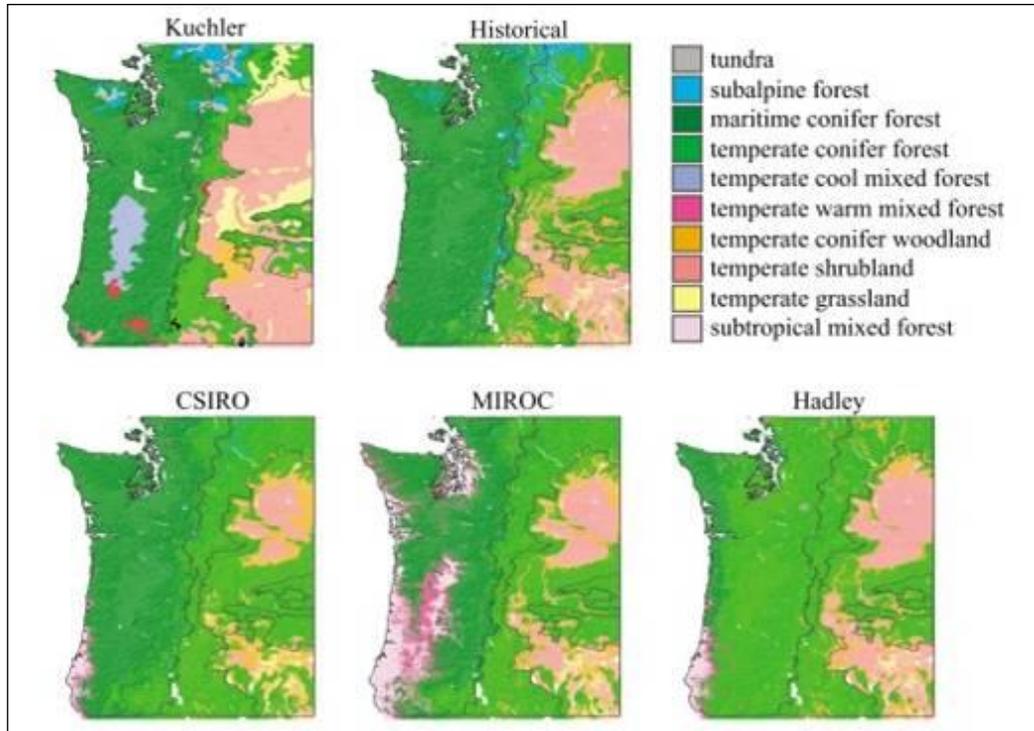


Figure 52. Simulated most common vegetation types with full fire for the historical (1971-2000) and future (2070-2099) periods under the three climatic projections: The CSIRO Mk3 [Gordon, 2002], MIROC 3.2 medres [Hasumi and Emori, 2004], and Hadley CM3 [Johns et al. 2003] models run through the A2 CO₂ emissions scenario [Nakićenović et al. 2000]. Also shown is the aggregated potential vegetation map from Kuchler [1975]. *Source: Reproduced from Rogers et al. (2011, Fig. 3, p. 5) by authors of this report.*¹⁶⁰⁸

¹⁶⁰⁸ As stated by Rogers et al (2011, p. 5), the CSIRO climate projection is cool and wet, MIROC is hot and wet, and Hadley is hot and dry.

3. Changes in the status, distribution, and connectivity of oak woodlands, savannas, prairies and grasslands

Prairies and oak savannas have historically been the dominant vegetation of the interior valleys along the Pacific coast from central California to southern British Columbia (for example, see Figure 53).¹⁶⁰⁹ A combination of wildfires during periods of drought and Native American burning maintained these extensive grasslands over millennia by preventing succession to woodland and forest.¹⁶¹⁰ For example, in much of its historic range, Oregon white oak was maintained at low densities through frequent burning by Native Americans.¹⁶¹¹ This deciduous tree frequently grows with conifers, particularly Douglas-fir.¹⁶¹² Most of these areas have been converted to other land uses through urban and agricultural development and much of what remains has been impacted by the encroachment of native conifers and the establishment of exotic herbaceous and shrub species.¹⁶¹³

Considerable conservation effort has been directed towards Oregon white oak ecosystems, particularly in the Willamette Valley of Oregon, the Puget Lowlands of Washington, Vancouver Island, and the San Juan and Gulf Islands of Puget Sound and the Georgia Basin.¹⁶¹⁴ Over 100 rare plants and animals are associated with these habitats, including western gray squirrel, Lewis' woodpecker, propretius duskywing, and golden paintbrush.¹⁶¹⁵ Climate change may add to or exacerbate existing threats to native grasslands.¹⁶¹⁶ Alternatively, new climate conditions and increased wildfire may render portions of the landscape less suitable for forests or agriculture and thus create new opportunities for prairie restoration.¹⁶¹⁷

Key Terms in this Section

Balds: *isolated grasslands typically occurring near mountain summits*

Forbs: *a vascular plant without significant woody tissues above or at the ground; an herbaceous flowering plant other than a grass*

Graminoid: *grass or grass-like plants; includes grasses, sedges, rushes, arrow-grasses, and quillworts*

Prairie: *an open habitat dominated by grasses and forbs, with little or no woody vegetation*

Savanna: *a community of scattered trees with grasses and forbs*

Woodland: *a community of scattered trees with a substantial shrub understory, grasses, and forbs*

Sources: NRCS (2013), Sinclair et al. (2006), Zald (2009)

¹⁶⁰⁹ Verbatim from Bachelet et al. (2011, p. 411)

¹⁶¹⁰ Verbatim from Bachelet et al. (2011, p. 411). Bachelet et al. cite Boyd (1999) and Walsh (2008) for this information.

¹⁶¹¹ Nearly verbatim from Gould et al. (2008, p. 26). Gould et al. cite Thilenius (1968) for this information.

¹⁶¹² Verbatim from Dunwiddie et al. (2011, p. 130)

¹⁶¹³ Verbatim from Gould et al. (2008, p. 26). Gould et al. cite Crawford & Hall (1997) and Thysell & Carey (2001) for this information.

¹⁶¹⁴ Nearly verbatim from Dunwiddie et al. (2011, p. 130). Dunwiddie et al. cite Oregon Oak Communities Working Group (2010) for information on the Willamette Valley, Chappell (2006) for information on the Puget Lowlands, and GOERT (2002) for information on the remaining areas.

¹⁶¹⁵ Nearly verbatim from Dunwiddie et al. (2011, p. 130). Dunwiddie et al. cite Dunn & Ewing (1997), Fuchs (2001), and Thysell & Carey (2001) for information on the rare plants and animals.

¹⁶¹⁶ Verbatim from Bachelet et al. (2011, p. 411)

¹⁶¹⁷ Verbatim from Bachelet et al. (2011, p. 411)

Observed Trends

Southcentral and Southeast Alaska

The native range of Oregon white oak (also known as Garry oak) does not include southcentral and southeast Alaska (Figure 53). As paleoclimate research has indicated, northward expansion of Garry oak was limited to the Georgia Depression (located in British Columbia and Washington) during the early Holocene.¹⁶¹⁸

Western British Columbia

The northern range of Garry oak (another name for Oregon white oak commonly used in British Columbia), and its associated ecosystems, is southwest British Columbia.¹⁶¹⁹ Two broad categories of Garry oak communities are generally recognized in British Columbia.¹⁶²⁰ Scrub oak ecosystems typically occur on thin rocky soils that are often excessively drained.¹⁶²¹ These communities are usually found on rocky bluffs and outcroppings, and along shorelines.¹⁶²² Parkland Garry oak communities occur on deeper soils, are usually larger in size, and support a distinct array of understory vegetation.¹⁶²³

In coastal British Columbia, the vast majority of Garry oak savannas have been developed for residential, agricultural, or industrial use.¹⁶²⁴ For example, of particular concern in the Coastal Douglas-fir biogeoclimatic zone is the loss (nearly 90%) of Garry oak woodlands, aesthetically pleasing ecosystems with high species richness and many at-risk species.¹⁶²⁵ Much of the remaining habitat is threatened by conifer encroachment or invasion by exotics.¹⁶²⁶

At Rocky Point on southern Vancouver Island, British Columbia, tree-ring analysis was used to reconstruct stand composition and structure of an oak savanna.¹⁶²⁷ At the time of European settlement, the



Figure 53. The native range of the Oregon white oak (Little 1971)

¹⁶¹⁸ Nearly verbatim from Bodtker et al. (2009, p. 17). Bodtker et al. cite Pellatt et al. (2001) for this information.

¹⁶¹⁹ Nearly verbatim from Bodtker et al. (2009, p. 1)

¹⁶²⁰ Verbatim from Gedalof et al. (2006, p. 34)

¹⁶²¹ Verbatim from Gedalof et al. (2006, p. 34). Gedalof et al. cite Roemer (1993) for this information.

¹⁶²² Verbatim from Gedalof et al. (2006, p. 34)

¹⁶²³ Verbatim from Gedalof et al. (2006, p. 34-35). Gedalof et al. cite Roemer (1993) for this information.

¹⁶²⁴ Verbatim from Gedalof et al. (2006, p. 34)

¹⁶²⁵ Nearly verbatim from Pojar (2010, p. 27). Pojar cites Austin et al. (2008) for this information.

¹⁶²⁶ Verbatim from Gedalof et al. (2006, p. 34)

¹⁶²⁷ Nearly verbatim from Gedalof et al. (2006, p. 34)

site was largely open prairie, with a few scattered oak trees.¹⁶²⁸ Establishment of Garry oak at Rocky Point began shortly after settlement of the area by Europeans—probably due to the cessation of frequent burning by indigenous peoples.¹⁶²⁹ Since the 1950s, however, Douglas-fir and grand fir have been encroaching on the Garry oak savanna.¹⁶³⁰ The causes of this invasion are unclear, but the invasion signals a clear transition in the stand structure and composition.¹⁶³¹ Current recruitment rates for Douglas-fir, grand fir, and Garry oak are available:

- **Douglas-fir recruitment:** Douglas-fir seedlings represent a small fraction of the total seedling population (53 Douglas-fir seedlings were found, representing 7% of the overall seedling population), but appear to survive to sapling sizes much more often than Garry oak.¹⁶³² Of the 53 saplings identified, 41 were Douglas-fir.¹⁶³³ Young Douglas-fir trees at Rocky Point are growing very quickly – counting branch whorls suggests that seedlings typically reach heights of ~7-10 feet (2-3 meters) in less than a decade.¹⁶³⁴
- **Grand fir recruitment:** Seven grand fir seedlings and eight grand fir saplings were found at the Rocky Point site.¹⁶³⁵ Overstory grand fir as young as twenty years old were sampled, suggesting that the understory residence time for these individuals will be relatively short.¹⁶³⁶ In spite of the low seedling abundance, recruitment of grand fir likely exceeds that of Garry oak.¹⁶³⁷
- **Oak recruitment:** Oak seedlings are abundant, but few saplings exist—suggesting that oak is not regenerating at Rocky Point.¹⁶³⁸ Of the total seedling population, 91% (678 individuals) were Garry oak.¹⁶³⁹ In contrast, oak accounts for only 6% of the 53 saplings identified.¹⁶⁴⁰ Even assuming a very short understory residence time, this rate of recruitment is not sufficient to replace the current overstory population.¹⁶⁴¹

Western Washington

In the Puget Lowland and Willamette Valley ecoregions in Washington, extant grasslands occupy 9.3% of the estimated pre-European settlement grassland extent (i.e., 9.3% of 180,444 acres, or ~16,781.3 acres; in km², 67.9 km²).¹⁶⁴² This includes native, semi-native, non-native, and unsurveyed untilled grasslands.¹⁶⁴³ Known native grasslands occupy only 2.6%, and unsurveyed grasslands 3%, of the estimated pre-settlement grassland extent.¹⁶⁴⁴

¹⁶²⁸ Verbatim from Gedalof et al. (2006, p. 34)

¹⁶²⁹ Verbatim from Gedalof et al. (2006, p. 34)

¹⁶³⁰ Verbatim from Gedalof et al. (2006, p. 34)

¹⁶³¹ Verbatim from Gedalof et al. (2006, p. 34)

¹⁶³² Verbatim from Gedalof et al. (2006, p. 42)

¹⁶³³ Verbatim from Gedalof et al. (2006, p. 42)

¹⁶³⁴ Nearly verbatim from Gedalof et al. (2006, p. 42)

¹⁶³⁵ Verbatim from Gedalof et al. (2006, p. 42)

¹⁶³⁶ Verbatim from Gedalof et al. (2006, p. 42)

¹⁶³⁷ Verbatim from Gedalof et al. (2006, p. 42)

¹⁶³⁸ Verbatim from Gedalof et al. (2006, p. 34)

¹⁶³⁹ Verbatim from Gedalof et al. (2006, p. 41)

¹⁶⁴⁰ Verbatim from Gedalof et al. (2006, p. 41)

¹⁶⁴¹ Verbatim from Gedalof et al. (2006, p. 41)

¹⁶⁴² Nearly verbatim from Chappell et al. (2001, p. 130)

¹⁶⁴³ Verbatim from Chappell et al. (2001, p. 130)

¹⁶⁴⁴ Verbatim from Chappell et al. (2001, p. 130)

The most extensive cover type is oak-conifer canopy at more than 10,000 acres (~40.5 km²). However, this cover type has the greatest uncertainty about its mapped content due to the difficulty of distinguishing it on aerial photographs.¹⁶⁴⁵ The remainder of the other categories range from about 2000 to about 6000 acres (~8.1 to 24 km²) in extent.¹⁶⁴⁶ Mean areal extent of polygons is seven acres (~0.03 km²) for oak-dominant canopy, fifteen acres (~0.06 km²) for oak-conifer polygons, 43 acres (~0.17 km²) for unsurveyed grassland, 62 acres (~0.25 km²) for native grassland, and 68 acres (~0.28 km²) for semi-native and non-native grasslands.¹⁶⁴⁷

The type, area, and composition of grassland and oak woodland habitat varies across the region:

- **San Juan Islands:** The rocky soil complex is most extensive in the San Juan Islands archipelago of San Juan, Skagit, and Whatcom counties.¹⁶⁴⁸ Extant grasslands are still numerous, though often small, as grassy balds on rocky soil complex.¹⁶⁴⁹ On Waldron Island, an open oak/Douglas-fir savanna was maintained for centuries by fires set by Native Americans.¹⁶⁵⁰ It began to infill with oak, and later Douglas-fir, in the 1800s, particularly following Euro-American settlement in the 1860s.¹⁶⁵¹ Douglas-fir encroachment continued throughout the 1900s, with a very large cohort becoming established in the early 1970s.¹⁶⁵² Oak release actions were undertaken to re-open the forest structure, and involved the removal of 55% of the trees, primarily small-diameter Douglas-fir.¹⁶⁵³ In winter 2007, Garry oak ranged in age from 27-509 years; 16% (ten trees) were more than two centuries old.¹⁶⁵⁴ Douglas-fir had a similar range, from 17-454 years; 3% (seven trees) exceeded 200

Type and composition of native grassland and oak woodland habitat in the Puget Lowland and Willamette Valley

Native grasslands and woodlands are found in dry environments formerly strongly influenced by frequent fires.

Oak woodlands may be dominated by Oregon white oak. They may also be co-dominated by Oregon white oak and Douglas-fir, Oregon ash, bigleaf maple, or Pacific madrone. Oregon white oak tends to be shade-intolerant, and also grows in open savannas and closed canopy forests.

Native grasslands are dominated or co-dominated by Roemer's fescue, red fescue, or California oatgrass. Shrubs such as Scot's broom, Nootka rose, and common snowberry and non-native grasses now dominate or co-dominate many former native grasslands. Native grasslands may occur as large prairies on level or mounded plains (especially in glacial outwash deposits) or as "balds" on shallow, rocky soils (especially on moderate to steep south- and west-facing slopes).

Source: Chappell et al. (2001), Dunwiddie et al. (2011)

¹⁶⁴⁵ Verbatim from Chappell et al. (2001, p. 129)

¹⁶⁴⁶ Verbatim from Chappell et al. (2001, p. 129)

¹⁶⁴⁷ Verbatim from Chappell et al. (2001, p. 129)

¹⁶⁴⁸ Verbatim from Chappell et al. (2001, p. 128)

¹⁶⁴⁹ Verbatim from Chappell et al. (2001, p. 128)

¹⁶⁵⁰ Nearly verbatim from Dunwiddie et al. (2011, p. 130)

¹⁶⁵¹ Verbatim from Dunwiddie et al. (2011, p. 130)

¹⁶⁵² Verbatim from Dunwiddie et al. (2011, p. 130)

¹⁶⁵³ Verbatim from Dunwiddie et al. (2011, p. 130)

¹⁶⁵⁴ Nearly verbatim from Dunwiddie et al. (2011, p. 133)

years in age.¹⁶⁵⁵ The historical density of older trees (those established before 1881) was 99 trees per hectare.¹⁶⁵⁶ The historical tree density was approximately one-tenth that present prior to restoration (oak release) activities.¹⁶⁵⁷

- **Northeast Olympic Peninsula and vicinity:** Parts of Whidbey Island, Island County, and the northeastern Olympic Peninsula, Clallam and Jefferson counties, have extensive areas of prairie soils, very little of which support extant untilled grasslands.¹⁶⁵⁸
- **South Puget Sound:** The southern Puget Sound area, primarily in Pierce and Thurston counties, has the largest areas of pre-settlement grassland soils, extant grasslands, and oak canopies.¹⁶⁵⁹ For example, oak sites cover <4% of Fort Lewis; few are >12.4 acres (>5 hectares) and many contain few oaks.¹⁶⁶⁰ Of twenty-two sites surveyed, most sites averaged >200 oak trees per hectare within the ranges of sizes, densities, and basal areas reported as normal by Stein (1990).¹⁶⁶¹ Large oaks were rare – most oaks were <12 inches in diameter at breast height (<30 cm dbh) and <66 feet (<20 meters) tall.¹⁶⁶² Oak communities were typically more diverse than either Douglas-fir forests or prairies and were transitional in species composition between them.¹⁶⁶³ However, oak communities contained numerous exotics, particularly Scot’s broom and colonial bentgrass.¹⁶⁶⁴ Most oak communities contained large-diameter Douglas-firs and other tree species and appeared to be transforming to conifer or conifer/mixed hardwood forests.¹⁶⁶⁵ With succession, exotic species become less prevalent, but the extent and abundance of oaks is diminished.¹⁶⁶⁶
- **Southern Washington and northern Willamette Valley:** The southern portion of the Puget Lowland, south of Thurston County, and the northern end of the Willamette Valley ecoregion have many small oak stands, a few fairly large areas of prairie soil, and no extant untilled grasslands.¹⁶⁶⁷ The largest contiguous areas of oak-dominant canopy occur along Scatter Creek in Thurston County and east of Washougal in Clark and Skamania counties.¹⁶⁶⁸

Western Oregon

Prairies and oak savannas likely established during the early Holocene (circa 11,000-7,250 YPB) under warm and dry conditions and were maintained over time by a combination of wildfires and Native American burning, the importance of each varying in both time and space as cooler and wetter conditions developed.¹⁶⁶⁹

¹⁶⁵⁵ Verbatim from Dunwiddie et al. (2011, p. 133)

¹⁶⁵⁶ Verbatim from Dunwiddie et al. (2011, p. 133)

¹⁶⁵⁷ Verbatim from Dunwiddie et al. (2011, p. 130)

¹⁶⁵⁸ Verbatim from Chappell et al. (2001, p. 128)

¹⁶⁵⁹ Verbatim from Chappell et al. (2001, p. 128)

¹⁶⁶⁰ Nearly verbatim from Thysell & Carey (2001, p. 229). Thysell & Carey cite Ryan & Carey (1995a,b) for information on oak site cover on Fort Lewis.

¹⁶⁶¹ Verbatim from Thysell & Carey (2001, p. 230)

¹⁶⁶² Verbatim from Thysell & Carey (2001, p. 230)

¹⁶⁶³ Verbatim from Thysell & Carey (2001, p. 219)

¹⁶⁶⁴ Verbatim from Thysell & Carey (2001, p. 219)

¹⁶⁶⁵ Verbatim from Thysell & Carey (2001, p. 219)

¹⁶⁶⁶ Verbatim from Thysell & Carey (2001, p. 219)

¹⁶⁶⁷ Verbatim from Chappell et al. (2001, p. 128)

¹⁶⁶⁸ Verbatim from Chappell et al. (2001, p. 128)

¹⁶⁶⁹ Verbatim from Bachelet et al. (2011, p. 417). Bachelet et al. cite Walsh (2008) for this information.

An analysis of Government Land Office (GLO) records indicate that approximately 1,000,000 acres (404,685.6 hectares) of prairie and 500,000 acres (202,343 hectares) of savanna extended across the Willamette Valley when early Euro-American settlers arrived in the region.¹⁶⁷⁰ At the time of Euro-American settlement (circa 1840), prairies and savannas accounted for 49% of Oregon's Willamette Valley ecoregion.¹⁶⁷¹ Today, however, they account for less than 2% and are all in degraded conditions.¹⁶⁷² Since the 1850s, alteration of historical fire regimes (cessation of Native American burning followed by active fire suppression), land use change (expansion of agriculture, livestock grazing, and urbanization), and invasion by exotic species have all contributed to the degradation of this ecosystem, which is now ranked among the most endangered in the United States.¹⁶⁷³ Bottomland prairie grasslands are among the rarest of the native communities with over 97% of the estimated 768,000 acres (310,823 hectares, ca. 1851) having been converted to agricultural and urban uses since ~1851.¹⁶⁷⁴

In an upland prairie of the Willamette Valley, the competitive dynamics between two native (*Danthonia californica* and *Deschampsia cespitosa*) and two exotic (*Schedonorus arundinaceus* and *Lolium multiflorum*) grass species under varying nutrient and moisture conditions were evaluated using paired field and greenhouse experiments:

- In the field, the experimental reduction of competition resulted in shorter, wider plants, but only the annual grass, *Lolium multiflorum*, produced more above-ground biomass when competition was reduced.¹⁶⁷⁵ In the greenhouse, the two exotic grasses produced more total biomass than the two native grasses.¹⁶⁷⁶
- Competitive hierarchies were influenced by nutrient and/or moisture treatments for the two exotic grasses (*L. multiflorum* and *S. arundinaceus*), but not for the two native grasses.¹⁶⁷⁷ Specifically, the competitive success of *L. multiflorum* and *S. arundinaceus* depended upon nutrient availability, and the competitive success of *S. arundinaceus* further depended upon moisture.¹⁶⁷⁸ *D. californica*, *D. cespitosa*, and *S. arundinaceus* all produced more biomass in high-moisture, high-nutrient environments, and *D. cespitosa*, *L. multiflorum*, and *S. arundinaceus* allocated more biomass belowground in the low nutrient treatment.¹⁶⁷⁹
- Taken together, these experiments suggest the competitive superiority of the exotic grasses, especially *L. multiflorum*, but, contrary to the researchers' hypothesis, the native grasses were not preferentially excluded from nutrient-rich, moderately wet environments.¹⁶⁸⁰

In an assessment of oak woodland resources for Lane County (the city of Eugene is located in Lane County), for the sampled oak trees, average age was 68 years (range = 39-251 years).¹⁶⁸¹ Oregon white

¹⁶⁷⁰ Verbatim from Vesely & Rosenberg (2010, p. 11). Vesely & Rosenberg cite Alverson (2006) and Sinclair et al. (2006) for this information.

¹⁶⁷¹ Verbatim from Bachelet et al. (2011, p. 411)

¹⁶⁷² Verbatim from Bachelet et al. (2011, p. 411). Bachelet et al. cite Hulse et al. (2002) for this information.

¹⁶⁷³ Verbatim from Bachelet et al. (2011, p. 411). Bachelet et al. cite Noss et al. (1995) for this information.

¹⁶⁷⁴ Nearly verbatim from Gregory et al. (2002, p. 38). Gregory et al. refer the reader to Table 16 in the cited report.

¹⁶⁷⁵ Verbatim from Pfeifer-Meister et al. (2008, p. 357)

¹⁶⁷⁶ Verbatim from Pfeifer-Meister et al. (2008, p. 357)

¹⁶⁷⁷ Nearly verbatim from Pfeifer-Meister et al. (2008, p. 357)

¹⁶⁷⁸ Nearly verbatim from Pfeifer-Meister et al. (2008, p. 364). Pfeifer-Meister et al. refer the reader to Figure 3 in their article for this information.

¹⁶⁷⁹ Verbatim from Pfeifer-Meister et al. (2008, p. 357)

¹⁶⁸⁰ Nearly verbatim from Pfeifer-Meister et al. (2008, p. 357)

oak occurred in small patches (maximum area = 5 acres, or ~2 hectares) at thirteen BLM sites, and oak crowns usually formed a minor component of the overall canopy (mean = 18 percent cover, max. = 54 percent cover).¹⁶⁸² Dominant tree canopy positions in woodland-type patches and adjacent to meadow-type patches were most often occupied by Douglas-fir, with incense-cedar and Oregon white oak occasionally codominant.¹⁶⁸³ Pacific madrone was often observed on xeric sites.¹⁶⁸⁴ Oregon ash, grand fir, and big-leaf maple were also common.¹⁶⁸⁵ Poison oak was the most frequently observed shrub (88% of patches) at oak patches.¹⁶⁸⁶ Oceanspray and Himalayan blackberry were also observed at more than half the patches surveyed.¹⁶⁸⁷ Most sites were occupied by one or more plant species listed by the BLM as nonnative plants; however, only Himalayan blackberry and Scotch broom were abundant within oak patches.¹⁶⁸⁸

Information on habitat composition is available for Jackson County (southwest Oregon) and the Rogue Valley:

- **Jackson County:** Photo pairs show a loss of high elevation grassland to woody shrub and tree domination, transition from shrubland and woodland to conifer domination, or increased density of woodland by a younger cohort of Garry oak.¹⁶⁸⁹ However, some grassland and oak dominated communities are remarkable for their lack of change over time.¹⁶⁹⁰ These include oak savannas grasslands that have retained their open structure without fire.¹⁶⁹¹
- **Rogue Valley:** Plant community maps of the Rogue Valley Basin derived from General Land Office (GLO) surveys of the mid 1800s indicate that the woodland oak structure was more prevalent than oak savanna in southwest Oregon within the extent (Rogue Valley) of GLO derived historic vegetation maps.¹⁶⁹²

In a study of the extent and spatial patterns of grass bald land cover change (grass balds are isolated grasslands which typically occur at the summits of Coast range peaks), five balds were evaluated to quantify the extent of balds in the Oregon Coast Range over the past five decades (1948-2000), determine what types of land cover balds are being converted to, quantify the spatial patterns of tree encroachment into the balds, and determine if bald vegetation patches have become more fragmented and edgier over the time period of study.¹⁶⁹³ The remote sensing nature of this study cannot determine the fundamental causes of bald decline, although prior research suggests climate change, cessation of native burning,

¹⁶⁸¹ Information obtained by the authors of this report from Chiller et al. (Table 11, p. 19).

¹⁶⁸² Nearly verbatim from Chiller et al. (2000, p. 13). Chiller et al. refer the reader to Table 7 in the cited report.

¹⁶⁸³ Verbatim from Chiller et al. (2000, p. 13). Chiller et al. refer the reader to Table 6 in the cited report.

¹⁶⁸⁴ Verbatim from Chiller et al. (2000, p. 13)

¹⁶⁸⁵ Verbatim from Chiller et al. (2000, p. 13)

¹⁶⁸⁶ Verbatim from Chiller et al. (2000, p. 14). Chiller et al. refer the reader to Table 9 in the cited report.

¹⁶⁸⁷ Verbatim from Chiller et al. (2000, p. 14)

¹⁶⁸⁸ Verbatim from Chiller et al. (2000, p. 14). Chiller et al. refer the reader to Table 10 in the cited report for a list of the plant species listed by the BLM as nonnative plants.

¹⁶⁸⁹ Verbatim from Hosten et al. (2007, p. 31)

¹⁶⁹⁰ Verbatim from Hosten et al. (2007, p. 31)

¹⁶⁹¹ Verbatim from Hosten et al. (2007, p. 31)

¹⁶⁹² Nearly verbatim from Hosten et al. (2007, p. 31)

¹⁶⁹³ Nearly verbatim from Zald (2009, p. 518). As stated by Zald, analyses used historical (1948 and 1953) aerial photographs and recent (years 1994 and 2000) digital orthophoto quadrangles (DOQ's) of the five study areas (Mount Hebo, Bald Mountain, Prairie Peak, Marys Peak, Grass Mountain) (see p. 519 in the cited article).

successional changes in response to prior wildfires, and cessation of livestock grazing all may have potential influence.¹⁶⁹⁴ Results include:

- **Extent and decline of grass balds:** From 1948/1953 to 1994/2000, five bald grasslands in the Oregon Coast Range declined from 523.6 hectares to 179.2 hectares in area (-66%).¹⁶⁹⁵ Forest encroachment into balds was the dominant type of bald decline (348.7 hectares, 95%).¹⁶⁹⁶ Conversion of balds to roads and buildings accounted for 15.4 hectares (4%), while conversion to bare ground was minor.¹⁶⁹⁷
- **Spatial patterns of grass bald change:** From 1948/1953 to 1994/2000, the number of bald patches declined at all study areas (47% total, 10-67% for individual study areas).¹⁶⁹⁸ Patch size for four out of the five balds declined (49% average, 20-66% for individual study areas).¹⁶⁹⁹ The fifth study area (Marys Peak) saw a 2% increase in patch size.¹⁷⁰⁰
- **Spatial pattern of tree encroachment:** Forest encroachment into the balds was inversely related to the distance from potential parent trees.¹⁷⁰¹ The spatial patterns of tree encroachment likely result from a combination of unfavorable tree establishment conditions due to high resource competition from graminoids (i.e., grasses), and dispersal limitation of tree seed with increased distance from the forest edge.¹⁷⁰²

Northwest California

Statewide threats to oak woodlands are many, including: urbanization, conversion to agriculture, fragmentation, low rates of regeneration, competition from introduced exotic species and sudden oak death.¹⁷⁰³ The northwest California portion of the State's oak woodlands lie geographically between the coastal mixed evergreen forests and the valley grasslands of the Central Valley.¹⁷⁰⁴ They were found in small patches (averaging 29.3 acres/patch; 11.9 hectares/patch), nested within a mosaic of annual grasslands and conifer forests, and hence contain species common to both of these vegetation types.¹⁷⁰⁵ Their extent on National Forest lands within the study area (National Forest lands in Humboldt, Trinity, Siskiyou, Mendocino, Tehama, Glenn, Colusa and Lake Counties) has been estimated at over 725,000 acres (293,397 hectares).¹⁷⁰⁶

Overall oak woodland ecological status would be rated as moderate due to the near equal cover of grasses in the native and non-native species categories and the variable early seral cover and low late seral cover

¹⁶⁹⁴ Verbatim from Zald (2009, p. 517)

¹⁶⁹⁵ Verbatim from Zald (2009, p. 520)

¹⁶⁹⁶ Verbatim from Zald (2009, p. 520)

¹⁶⁹⁷ Verbatim from Zald (2009, p. 520)

¹⁶⁹⁸ Verbatim from Zald (2009, p. 521-22)

¹⁶⁹⁹ Verbatim from Zald (2009, p. 522)

¹⁷⁰⁰ Verbatim from Zald (2009, p. 522)

¹⁷⁰¹ Verbatim from Zald (2009, p. 522). Zald refers the reader to Figure 3 in the cited article.

¹⁷⁰² Verbatim from Zald (2009, p. 523)

¹⁷⁰³ Verbatim from Jimerson & Carothers (2002, p. 705-706)

¹⁷⁰⁴ Verbatim from Jimerson & Carothers (2002, p. 706). Jimerson & Carothers cite Griffin (1988) for this information.

¹⁷⁰⁵ Verbatim from Jimerson & Carothers (2002, p. 706). Jimerson & Carothers cite Jimerson and others (2000) for information on patches in annual grasslands.

¹⁷⁰⁶ Nearly verbatim from Jimerson & Carothers (2002, p. 706)

of both forbs and grasses.¹⁷⁰⁷ The oak woodlands of northwest California were found in nearly pure stands dominated by white oak, black oak or blue oak, or in association with other tree species such as Douglas-fir, Ponderosa pine, gray pine, canyon live oak, California buckeye, and big-leaf maple.¹⁷⁰⁸ Oak woodlands had a much lower frequency of invasive weeds when compared to annual grasslands.¹⁷⁰⁹

The Bald Hills (located in Redwood National Park; ~4200 acres, 1700 acres) are dominated by Oregon white oak woodlands intermixed with grasslands, with Douglas-fir-tanoak forests occurring at woodland and grassland margins.¹⁷¹⁰ Douglas-fir-tanoak forest historically occurred on relatively mesic (i.e., of moderate moisture) sites in the Bald Hills (lower slopes, drainages, and north aspects), but has expanded dramatically since 1900 following removal of Native American tribes, widespread fire exclusion, and anthropogenic activities.¹⁷¹¹

Information on habitat composition, the effects of fire, and probability of California black oak mortality following fire in a recently burned, encroached California black oak woodland is available:

- **Habitat composition and canopy competition:** Pre-fire woodland overstory was heavily dominated by Douglas-fir, which commonly pierced and overtopped California black oak crowns.¹⁷¹² California black oak ranked second in abundance (23.9%, including focal oaks) while tanoak, Pacific madrone, canyon live oak, ponderosa pine, and sugar pine were much less common (<9% for each).¹⁷¹³ Aerial photos of the Dillon Mountain (Klamath Mountains) study site in northern California reveal substantial canopy recruitment of conifers from at least 1944 until the site burned in the 2008 Siskiyou Complex.¹⁷¹⁴
- **Effects of fire:** Fire effects were variable, leaving some areas unchanged and others with complete above-ground stem mortality.¹⁷¹⁵ Although above-ground stem mortality was generally high (71%) for California black oak, complete mortality (dead stems that failed to re-sprout) was much lower (13%).¹⁷¹⁶ The vast majority (82%) of all killed California black oak stems re-sprouted after the fire.¹⁷¹⁷
- **Probability of California black oak mortality:** The probability of California black oak mortality increased as neighboring Douglas-fir height increased and decreased with increasing heat load index.¹⁷¹⁸ In other words, at Dillon Mountain the probability of complete mortality (killed stems that did not re-sprout) of California black oak was not closely related to fire intensity (as estimated by bole char heights), but was instead better explained by encroaching tree

¹⁷⁰⁷ Verbatim from Jimerson & Carothers (2002, p. 715)

¹⁷⁰⁸ Nearly verbatim from Jimerson & Carothers (2002, p. 707)

¹⁷⁰⁹ Verbatim from Jimerson & Carothers (2002, p. 715)

¹⁷¹⁰ Nearly verbatim from Engber et al (2011, p. 35)

¹⁷¹¹ Verbatim from Engber et al (2011, p. 35). Engber et al. cite Underwood et al. (2003) and Fritschle (2008) for this information.

¹⁷¹² Verbatim from Cocking et al. (2012, p. 25). As stated on p. 29 and shown in Table 2 of the cited article, Douglas-fir dominated the canopy surrounding focal oaks, accounting for 56.6% of all tagged trees.

¹⁷¹³ Verbatim from Cocking et al. (2012, p. 29)

¹⁷¹⁴ Nearly verbatim from Cocking et al. (2012, p. 32). Cocking et al. refer the reader to Figure 2 in the cited article.

¹⁷¹⁵ Verbatim from Cocking et al. (2012, p. 25)

¹⁷¹⁶ Verbatim from Cocking et al. (2012, p. 30)

¹⁷¹⁷ Verbatim from Cocking et al. (2012, p. 30)

¹⁷¹⁸ Verbatim from Cocking et al. (2012, p. 25)

characteristics; in particular the height of neighboring Douglas-fir.¹⁷¹⁹ Probability of mortality for Douglas-fir decreased with increasing tree size, while the probability of California black oak top-kill was much higher than that for ~7.9–12 inches diameter at breast height (20–30 cm dbh) Douglas-fir across a continuous measure of char height.¹⁷²⁰ Results indicate that competitive pressure from encroaching trees may compromise California black oak’s ability to survive fire while resilience of encroaching Douglas-fir improves with greater size.¹⁷²¹

Future Projections

Southcentral and Southeast Alaska

Information needed.

Western British Columbia and Pacific Northwest

Due to the longevity of Garry oak (the oldest individual sampled is probably 300 years old, and there are reports of individuals in excess of 400 years in age), the current lack of recruitment at Rocky Point on southern Vancouver Island, British Columbia does not necessarily indicate that oak will ultimately disappear from the site.¹⁷²² Given the episodic nature of oak regeneration, stand-wide disturbance every two- to three-hundred years could be at least theoretically sufficient to maintain a viable Garry oak population.¹⁷²³

Future projections of the Random Forest model based on four GCMs (CSIRO, CGCM2, HADCM3, and CCSRNIES run under the A2 and B2 scenarios and comparing the 2020s, 2050s, and 2080s with 1961–1990) suggested that over a study area in British Columbia, Washington, and Oregon, the average climate suitability for Garry oak will increase in the future.¹⁷²⁴ However, in the case of Garry oak ecosystems, the climate of the recent past, the current distribution of Garry oak, and bioclimatic envelope modeling with the Random Forest model indicates that the climate suitability for the current Garry oak range in British Columbia will decrease in the near future.¹⁷²⁵ The model also indicates that climate suitability will improve later in the century, but will not return to current conditions.¹⁷²⁶ Spatially, the models projected higher climate suitability inland in the future, but rarely north of Washington State especially in the next few decades.¹⁷²⁷ In fact, when Bodtker et al. (2009) examined projected change in suitability at Garry oak sites by latitude, they found greater decreases in suitability the further north you go, especially in the 2020s and 2050s.¹⁷²⁸

¹⁷¹⁹ Nearly verbatim from Cocking et al. (2012, p. 32). Cocking et al. refer the reader to Figure 4 (left) and Table 4 in the cited article.

¹⁷²⁰ Verbatim from Cocking et al. (2012, p. 25)

¹⁷²¹ Verbatim from Cocking et al. (2012, p. 25)

¹⁷²² Nearly verbatim from Gedalof et al. (2006, p. 42). Gedalof et al. cite Warren (1952) for information on oaks exceeding 400 years in age.

¹⁷²³ Verbatim from Gedalof et al. (2006, p. 42)

¹⁷²⁴ Nearly verbatim from Bodtker et al. (2009, p. 13). Bodtker et al. refer the reader to Figure 5 in the cited report.

¹⁷²⁵ Nearly verbatim from Bodtker et al. (2009, p. 18)

¹⁷²⁶ Verbatim from Bodtker et al. (2009, p. 18)

¹⁷²⁷ Verbatim from Bodtker et al. (2009, p. 14). Bodtker et al. refer the reader to Figure 7 in the cited report.

¹⁷²⁸ Nearly verbatim from Bodtker et al. (2009, p. 14). Bodtker et al. refer the reader to Figure 8 in the cited report.

Bodtker et al. (2009) conclude that projections of increasing suitability in general over the whole study area were not surprising, given that Garry oak is suited to a near Mediterranean climate, much of the Pacific Northwest is currently considered temperate rainforest, and climate change is generally characterized as global warming.¹⁷²⁹ Projections of decreasing suitability in sites currently occupied by Garry oak especially in British Columbia, the northern and cooler extent of the current Garry oak range, were somewhat surprising for the same reasons.¹⁷³⁰

In the Willamette Valley-Puget Trough-Georgia Basin (WPG) ecoregion, future increased summer drought seems unlikely to disadvantage prairie and savanna communities.¹⁷³¹ Instead, it may well affect less drought-tolerant trees and other forest species adjacent to prairies, possibly resulting in prairie expansion.¹⁷³² Most WPG prairies and oak savannas are dominated by perennial grasses and forbs that senesce late in the growing season.¹⁷³³ Thus, future potential warming will likely cause a decline in soil moisture during the growing season unless species composition shifts are sufficiently extreme that annuals begin to dominate.¹⁷³⁴

Many of the aggressive exotic species that occur in both wet and dry prairies in western Pacific Northwest currently have wide range distributions in the U.S., so it is reasonable to assume that they will be relatively adaptable to changing climate.¹⁷³⁵ Consequently, they may provide even more of a competitive challenge to native Pacific Northwest prairie species in the future than they do currently.¹⁷³⁶ However, many native prairie species are well adapted to summer drought, which could give them an advantage over many exotic species as summer drought extends and intensifies.¹⁷³⁷

Increased winter rainfall seems unlikely to substantially alter grasslands that occur on well-drained glacial outwash soils, but may in fact increase the amount of wetland prairies on poorly drained soils in areas like the South Puget Sound, benefiting a suite of currently rare prairie species.¹⁷³⁸ Since grasses accumulate most of their carbon belowground, potential carbon losses through disturbances such as fire or pest outbreaks are significantly reduced in grasslands.¹⁷³⁹

Western Washington

Please see the previous section on the Pacific Northwest for information in western Washington.

Western Oregon

At five study areas in the Oregon Coast Range (Mount Hebo, Bald Mountain, Prairie Peak, Marys Peak, Grass Mountain), tree encroachment patterns and increased bald edge densities suggest increasing rates of

¹⁷²⁹ Nearly verbatim from Bodtker et al. (2009, p. 17)

¹⁷³⁰ Verbatim from Bodtker et al. (2009, p. 17)

¹⁷³¹ Nearly verbatim from Bachelet et al. (2011, p. 417)

¹⁷³² Verbatim from Bachelet et al. (2011, p. 417)

¹⁷³³ Nearly verbatim from Bachelet et al. (2011, p. 420)

¹⁷³⁴ Verbatim from Bachelet et al. (2011, p. 420)

¹⁷³⁵ Verbatim from Bachelet et al. (2011, p. 417). Bachelet et al. cite Dennehy et al. (2011) for information on the U.S. distribution of aggressive exotic species in wet and dry prairies found in the western Pacific Northwest.

¹⁷³⁶ Verbatim from Bachelet et al. (2011, p. 417)

¹⁷³⁷ Nearly verbatim from Bachelet et al. (2011, p. 417)

¹⁷³⁸ Verbatim from Bachelet et al. (2011, p. 420)

¹⁷³⁹ Verbatim from Bachelet et al. (2011, p. 420)

bald grassland loss in the future (balds are isolated grasslands which typically occur at the summits of Coast range peaks).¹⁷⁴⁰ Since the remnant bald patches are closer to forest edge, they are more likely to encounter a higher density of tree seed.¹⁷⁴¹ Higher edge density of remnant bald patches also suggests the surrounding forest matrix will have increased influence on ecological patterns and processes in the remnant patches.¹⁷⁴² In particular, increased shade from the forest edge may reduce graminoid (i.e., grass) cover that excludes conifer establishment.¹⁷⁴³

Northwest California

*Information needed. However, one reviewer noted fine-scale downscaling has been completed for California, including an assessment of climatic water deficit for Douglas-fir forest, redwood, forest, and blue oak forest/woodland in the North Bay area of the San Francisco Bay region.*¹⁷⁴⁴

Information Gaps

Information on future projections for southcentral and southeast Alaska and northwest California are needed. In addition, future projections are needed for western Oregon, as the information presented does not incorporate climate change impacts.

¹⁷⁴⁰ Nearly verbatim from Zald (2009, p. 517)

¹⁷⁴¹ Verbatim from Zald (2009, p. 525)

¹⁷⁴² Verbatim from Zald (2009, p. 525). Zald cites Saunders et al. (1991) for this information.

¹⁷⁴³ Verbatim from Zald (2009, p. 525)

¹⁷⁴⁴ Comment from reviewer. Additional information on the downscaling and application to North Bay is available in: Flint, L. E., and A. L. Flint. (2012). Downscaling future climate scenarios to fine scales for hydrologic and ecological modeling and analysis. *Ecological Processes*. 1:1-15. Available at <http://www.ecologicalprocesses.com/content/1/1/2> (accessed December 31, 2013).

4. Changes in the status, abundance, and distribution of alpine and subalpine habitats

Treelines are temperature sensitive transition zones that are expected to respond to climate warming by advancing beyond their current position.¹⁷⁴⁵ However, the sensitivity of treelines to environmental change, and in particular, to climate warming varies with local and regional topographical conditions and thus differs as to its extent, intensity, and the process of change.¹⁷⁴⁶

- **Orographic treelines** (i.e., influenced by the position and form of mountains): Orographically controlled treelines are relatively insensitive to changing climate.¹⁷⁴⁷ They will not advance to the potential climatic tree limit (greater altitude) as long as mass wasting, debris slides, and avalanches occur.¹⁷⁴⁸
- **Anthropogenic treelines** (i.e., influenced by human activity): Great sensitivity and more rapid change can be expected in anthropogenic treelines after the cessation of human activity.¹⁷⁴⁹ However, establishment of trees above the anthropogenic forest limit is more impeded by extreme microclimates resulting from the removal of the forests than is generally recognized.¹⁷⁵⁰ In many locations, the amplitude and magnitude of recent warming might not be sufficient to compensate for what is left from a detrimental arboreal history.¹⁷⁵¹
- **Climatic treelines** (i.e., influenced by climate, especially heat deficiency): The sensitivity of climatic treelines to climate warming varies both in the local and regional topographical conditions.¹⁷⁵² Climatic limits of tree growth will occur only if no other factors, such as orography

Key Terms in this Section

Alpine habitat: *habitats occupying the highest vegetated elevations, located above open subalpine parkland and below non-vegetated surfaces such as glaciers, permanent snowfields, rocky peaks, and talus slopes (i.e., slopes with a pile of rocks at their base).*

Forest line: *see Timberline*

Krummholz: *the term commonly used to refer to trees deformed by wind and harsh climate, typically short in stature and found at the treeline*

Subalpine habitat: *habitats located between the forest line and tree line. They occupy the transition zone between closed forest and alpine tundra.*

Timberline: *the altitudinal boundary between forest and woodland; the highest extent of continuous closed-canopy forest*

Treeline: *the highest extent, in both altitude and latitude, of individual upright trees; the altitudinal boundary between shrubland and woodland*

Tundra: *a common name for alpine vegetation; adapted to a short growing season controlled by temperature, extent and duration of snowpack, desiccation (i.e., drying) by wind and sun, and other factors. Common plant species include wildflowers, grasses, sedges, lichens, and mosses.*

Sources: *Aubry et al. (2011), Dial et al. (2007), Harsch et al. (2009)*

¹⁷⁴⁵ Verbatim from Harsch et al. (2009, p. 1040)

¹⁷⁴⁶ Verbatim from Holtmeier & Broll (2005, p. 405)

¹⁷⁴⁷ Verbatim from Holtmeier & Broll (2005, p. 405)

¹⁷⁴⁸ Verbatim from Holtmeier & Broll (2005, p. 405)

¹⁷⁴⁹ Verbatim from Holtmeier & Broll (2005, p. 405)

¹⁷⁵⁰ Verbatim from Holtmeier & Broll (2005, p. 405)

¹⁷⁵¹ Verbatim from Holtmeier & Broll (2005, p. 405)

¹⁷⁵² Verbatim from Holtmeier & Broll (2005, p. 395)

or human impact, prevent tree growth from reaching its climatically caused altitudinal or northern limit.¹⁷⁵³

Tree invasions into high-elevation meadows are often associated with large-scale changes in climate or disturbance regimes, but are fundamentally driven by regeneration processes influenced by interactions between climatic, topographic, and biotic factors at multiple spatial scales.¹⁷⁵⁴ Potential impacts of tree invasion will largely be determined by the spatial extent and temporal rates of tree invasion, which for many species will be fundamentally determined by seed-based regeneration processes.¹⁷⁵⁵ Subalpine meadow habitat may decrease—conifer advancement into subalpine meadows is a documented impact of climate change, with treeline advancing unevenly upward into meadow sites that become more favorable to tree establishment.¹⁷⁵⁶

Alpine plants are considered highly vulnerable to impacts associated with a warming climate and already serve as an “early warning” system for climate change effects.¹⁷⁵⁷ Climate-related factors include summer temperature, winter snowpack, movement of lower-elevation species upslope, and disturbance from insects and pathogens:

- **Summer temperature and snowpack:** Summer temperatures and the duration and extent of winter snowpack are key controlling factors for plant establishment, distribution, and survival in high-elevation landscapes, although specific limiting factors vary locally and regionally (Figure 56).¹⁷⁵⁸ Reductions in snowpack extent and duration may result in loss of habitat and increased risk of desiccation and freezing for frost-sensitive plant species adapted to wintering in the stable, near-freezing conditions found under snow.¹⁷⁵⁹
- **Movement of lower-elevation species upslope:** High-elevation habitats are expected to experience increased habitat fragmentation and increased competition from lower elevation species as a result of climate change.¹⁷⁶⁰ Conditions are expected to change more rapidly than alpine plant species will be able to adapt, and plant community composition is likely to change as different species respond differently to changing conditions.¹⁷⁶¹
- **Disturbance from insects and pathogens:** An additional threat associated with projected climate change is the potential for increased native and non-native insect and pathogen outbreaks and

¹⁷⁵³ Verbatim from Holtmeier & Broll (2005, p. 399)

¹⁷⁵⁴ Nearly verbatim from Zald et al. (2012, p. 1197)

¹⁷⁵⁵ Verbatim from Zald et al. (2012, p. 1198)

¹⁷⁵⁶ Verbatim from Aubry et al. (2011, p. 73). Aubry et al. cite Holtmeier & Broll (2005), Millar et al. (2004), Peterson et al. (2002), Rochefort & Peterson (1996), Woodward et al. (1995), and Zolbrod & Peterson (1999) for this information.

¹⁷⁵⁷ Verbatim from Aubry et al. (2011, p. 71). Aubry et al. cite Guisan & Theurillat (2000) for information on alpine plant vulnerability to a warming climate and Grabherr et al. (2010) for information on alpine plants as an “early warning” system for climate change effects.

¹⁷⁵⁸ Verbatim from Aubry et al. (2011, p. 71). Aubry et al. cite Millar et al. (2004), Peterson et al. (2002), and Woodward et al. (1995) for this information.

¹⁷⁵⁹ Verbatim from Aubry et al. (2011, p. 73-74). Aubry et al. cite Grabherr et al. (2010) for information on conditions being expected to change more rapidly than alpine plant species will be able to adapt.

¹⁷⁶⁰ Verbatim from Aubry et al. (2011, p. 73). Aubry et al. cite Walther (2005) for this information.

¹⁷⁶¹ Verbatim from Aubry et al. (2011, p. 73). Aubry et al. cite Grabherr (2003) for information on conditions being expected to change more rapidly than alpine plant species will be able to adapt.

related disturbances.¹⁷⁶² Please see Chapter IV.4 for additional information on native and non-native insect and pathogen outbreaks and related disturbances.

However, the high degree of fine-scale microhabitat variability in mountain ecosystems may provide some localized protection from climate change influences for species with slow migration rates, although the prevalence of this refugia effect is uncertain.¹⁷⁶³ Relatively mobile species, such as those with light, wind-dispersed seeds, may be able to migrate locally to more hospitable locations, shifting to cooler, moister microhabitats or to more northerly aspects.¹⁷⁶⁴

Observed Trends

Global

Response to climate warming over the last century has been mixed, with some treelines showing evidence of recruitment at higher altitudes and/or latitudes (advance) whereas others reveal no marked change in the upper limit of tree establishment.¹⁷⁶⁵ To explore this variation, Harsch et al. (2009) analyzed a global dataset of 166 sites for which treeline dynamics had been recorded since 1900 AD.¹⁷⁶⁶ They found that:

- **Advance was recorded at 52% of sites** (87 of 166 sites) with only 1% (2 sites) reporting treeline recession (Figure 54).¹⁷⁶⁷
- **Treelines that experienced strong winter warming were more likely to have advanced**, and treelines with a diffuse form (i.e., characterized by decreasing tree density with increasing altitude or latitude) were more likely to have advanced than those with an abrupt (i.e., a continuous canopy with no decline in density right up to the treeline) or krummholz form.¹⁷⁶⁸

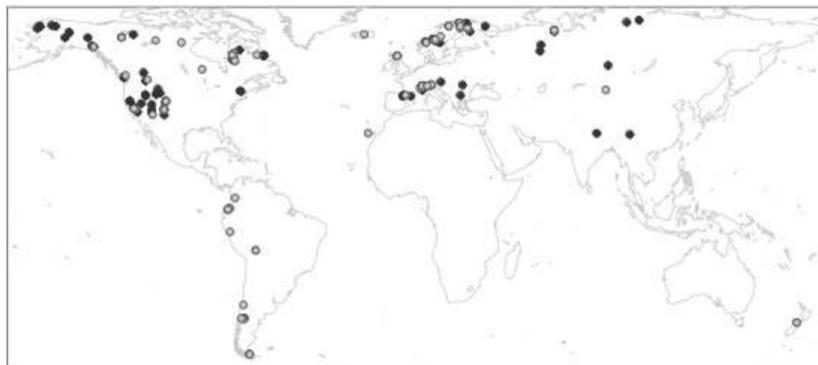


Figure 54. The location of the 166 treeline sites across the globe analyzed by Harsch et al. (2009). They are grouped according to whether they are advancing (black circles) or not advancing (grey circles). *Source: Reproduced from Harsch et al. (2009, Figure 1, p. 1042) by the authors of this report.*

¹⁷⁶² Verbatim from Aubry et al. (2011, p. 74). Aubry et al. cite Dale et al. (2001) for this information.

¹⁷⁶³ Verbatim from Aubry et al. (2011, p. 73). Aubry et al. cite Randin et al. (2009) for this information.

¹⁷⁶⁴ Verbatim from Aubry et al. (2011, p. 73). Aubry et al. cite Millar et al. (2007) for this information.

¹⁷⁶⁵ Nearly verbatim from Harsch et al. (2009, p. 1040)

¹⁷⁶⁶ Nearly verbatim from Harsch et al. (2009, p. 1040)

¹⁷⁶⁷ Nearly verbatim from Harsch et al. (2009, p. 1040). As noted on p. 1045 of the cited article, Pinaceae (the pine family) and Betulaceae (the birch family) formed the treeline at 136 sites (82%).

¹⁷⁶⁸ Nearly verbatim from Harsch et al. (2009, p. 1040)

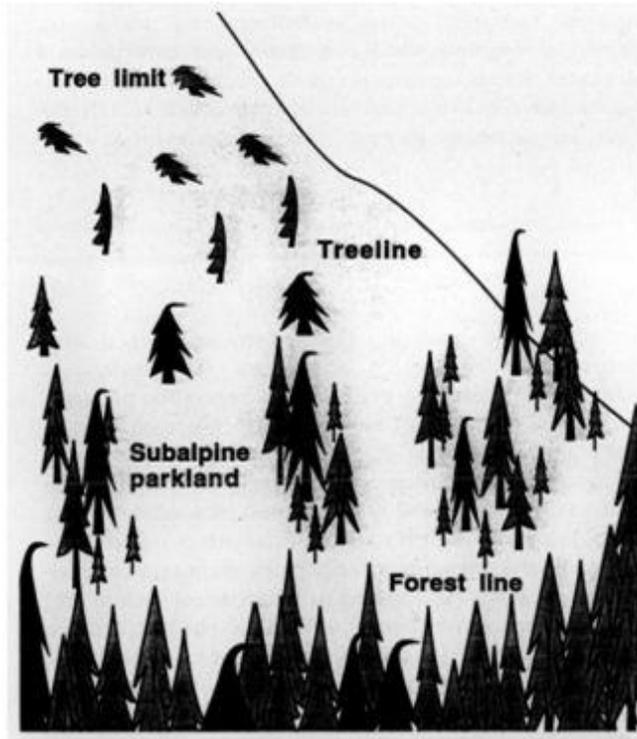


Figure 55. Diagrammatic representation of sub-alpine conifer distribution. A mosaic of trees and meadows dominates the ecotone between the continuous forest below and the treeless alpine above. *Source: Reproduced from Rochefort et al. (1994, Figure 1, p. 90) by the authors of this report.*

Western North America

Increases in tree establishment in sub-alpine meadows have been documented in mountainous areas throughout western North America.¹⁷⁶⁹ Most areas show initial forest margin expansion after AD 1890 and significant establishment peaks between 1920 and 1950.¹⁷⁷⁰ Additional peaks of establishment have also been identified in some areas.¹⁷⁷¹ Most studies conclude that recent increases in tree establishment are the result of a warmer, drier climate following the Little Ice Age.¹⁷⁷² Rochefort et al. (1994) state that although most studies conclude that these

increases were caused by warming trends, it is uncertain whether this is a long-term directional change or a short-term variation in relatively stable ecotones.¹⁷⁷³

To better understand the relationship between mountain hemlock growth and climate variability throughout its range, Gedalof and Smith (2001) analyzed chronologies from ten coastal sites located along a transect extending from northern California to southern Alaska.¹⁷⁷⁴ The chronologies exhibit significant large-scale cross-correlations, with two distinct growth regions implied: chronologies from the Cascades in California to the Queen Charlotte Islands in British Columbia are correlated with each other but are distinct from Alaskan chronologies.¹⁷⁷⁵

¹⁷⁶⁹ Verbatim from Rochefort et al. (1994, p. 94)

¹⁷⁷⁰ Verbatim from Rochefort et al. (1994, p. 94)

¹⁷⁷¹ Verbatim from Rochefort et al. (1994, p. 94)

¹⁷⁷² Verbatim from Rochefort et al. (1994, p. 94)

¹⁷⁷³ Nearly verbatim from Rochefort et al. (1994, p. 94-95)

¹⁷⁷⁴ Nearly verbatim from Gedalof & Smith (2001, p. 322)

¹⁷⁷⁵ Nearly verbatim from Gedalof & Smith (2001, p. 322)

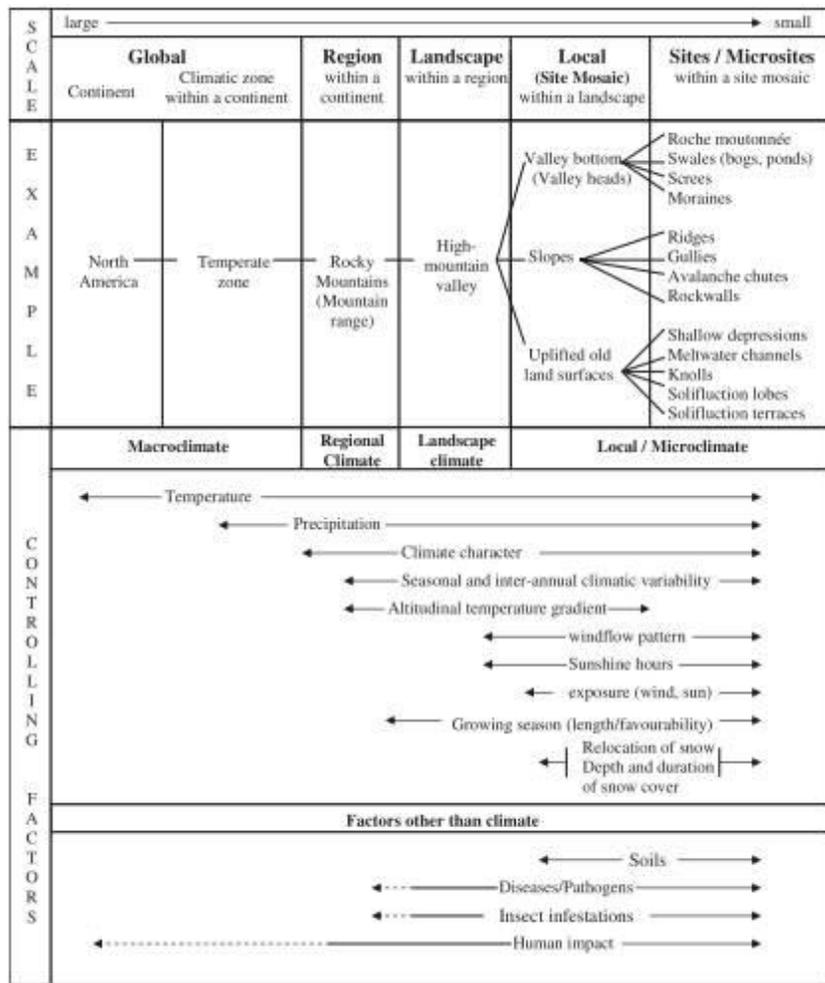


Figure 56. Treeline-controlling factors at different scales. Treeline heterogeneity increases from the global to smaller scales. *Source: Reproduced from Holtmeier & Broll (2005, Figure 1, p. 396) by the authors of this report.*

Overall, four general radial growth–climate associations were observed:¹⁷⁷⁶

- **Positive response to temperature in spring or summer of the growth year:** In the year of growth there is a positive association to at least one month of spring or summer temperature at all sites except Hemlock Knob (AK) and Mount Hood (OR).¹⁷⁷⁷
- **Negative response to summer temperature in the year preceding ring formation:** With the exception of Hemlock Knob (AK), all of the sites show a negative response to summer temperature in the year preceding growth.¹⁷⁷⁸
- **Tendency for a negative response to precipitation in the winter preceding growth:** South of the Queen Charlotte Islands (BC), four of the six sites exhibit a negative response to winter

¹⁷⁷⁶ Nearly verbatim from Gedalof & Smith (2001, p. 326)

¹⁷⁷⁷ Nearly verbatim from Gedalof & Smith (2001, p. 326)

¹⁷⁷⁸ Nearly verbatim from Gedalof & Smith (2001, p. 326)

precipitation in the season preceding growth.¹⁷⁷⁹ The association with winter precipitation may reflect the role of deep, persistent snowpacks in regulating the duration of the growing season.¹⁷⁸⁰

- **Positive response to spring precipitation in southeastern Alaska:** While Hemlock Knob (AK) exhibits a negative association with preceding November precipitation, the remaining Alaskan sites exhibit a positive response to precipitation in spring of the growth year.¹⁷⁸¹

The percentage of variation in radial growth explained by the climate response functions ranged from 38% at Mount Baker (WA) to 68% at Strathcona Park (BC).¹⁷⁸² The particularly weak association at Mount Baker may be a consequence of the substantial local variability in climate at Mount Baker and the lack of a representative meteorological station nearby.¹⁷⁸³

Southcentral and Southeast Alaska

Changes in the alpine forest-tundra ecotone in southcentral Alaska's western Kenai Mountains between 1951 and 1996 have been observed.¹⁷⁸⁴ Overall, the greatest absolute decrease in area was tundra and greatest absolute increase was shrub; the greatest relative decrease was unvegetated area (17.4%/decade) and the greatest relative increase was closed-canopy forest (14%/decade).¹⁷⁸⁵ Area of open woodland remained constant but changed location.¹⁷⁸⁶ These changes, when compared to the PDO, occurred during a period of warming and drying across the Kenai Peninsula.¹⁷⁸⁷

Information is available for specific changes in vegetation composition and structure, tundra retreat and rise in timberline, tree line and shrub line, variation in upward movement of the ecotone by aspect, and trends in recruitment:

- **Changes in vegetation composition and structure at three sites:** From 1951 to 1996, three local study sites known to have substantial changes (Mystery Hills, Russian Mountain, Skilak River) showed dramatic decreases in tundra and increases in shrub and closed canopy, with a relatively constant open woodland.¹⁷⁸⁸ Shrub was the primary exit state for tundra points with almost half of the tundra replaced by shrub (30–54% among the three sites), greater than that seen regionally (25%) or on cooler slopes (27%).¹⁷⁸⁹
- **Tundra retreat and rise in timberline, tree line, and shrub line:** Data suggest that while the forest-tundra ecotone is shifting upward, its constituent parts are doing so at differing rates, with shrub-line likely moving most rapidly, then tree line, then tundra retreat, and timberline moving

¹⁷⁷⁹ Nearly verbatim from Gedalof & Smith (2001, p. 326)

¹⁷⁸⁰ Verbatim from Gedalof & Smith (2001, p. 322)

¹⁷⁸¹ Nearly verbatim from Gedalof & Smith (2001, p. 326)

¹⁷⁸² Nearly verbatim from Gedalof & Smith (2001, p. 326). Gedalof & Smith refer the reader to Table 4 in the cited article for this information..

¹⁷⁸³ Verbatim from Gedalof & Smith (2001, p. 326). Gedalof & Smith cite Heikkinen (1985) for this information.

¹⁷⁸⁴ Dial et al. (2007)

¹⁷⁸⁵ Nearly verbatim from Dial et al. (2007, p. 6)

¹⁷⁸⁶ Verbatim from Dial et al. (2007, p. 1)

¹⁷⁸⁷ Verbatim from Dial et al. (2007, p. 12)

¹⁷⁸⁸ Nearly verbatim from Dial et al. (2007, p. 8)

¹⁷⁸⁹ Verbatim from Dial et al. (2007, p. 8). Dial et al. refer the reader to Table 1 in the cited article for information on the regional average and Table 3 in the cited article for information on the cool slope value.

slowest.¹⁷⁹⁰ Using the highest quartile elevations to estimate changes in timberline, tree line, and shrub-line from 1951 to 1996 suggested that:

- Shrub-line rose by ~190 feet (59 meters, m; ~43 feet/decade, 13 m/decade);
 - Tree line rose ~160 feet (49 m; ~36 ft/decade, 11 m/decade); and,
 - Timberline rose ~20 feet (6 m; ~4.2 ft/decade, ~1.3 m/decade).¹⁷⁹¹
 - Using the difference in the lowest quartile elevation (bottom 25%) for tundra in 1996 and 1951 implied that tundra retreated upward ~130 feet (39 m; ~26 ft/decade, 8.0 m/decade).¹⁷⁹²
- **Variation in upward movement of the ecotone by aspect:** There was evidence for upward movement of the forest-tundra ecotone on cool, northern exposures (N, NW, NE), less so or none for warm, nonnorthern exposures (S, SE, SW, E, W).¹⁷⁹³ For example, tree line, identified using upper quartiles of open woodland, rose ~164 feet (~50 meters) on cool, northerly aspects, but not on other aspects.¹⁷⁹⁴ Tundra on cool slopes decreased substantially below ~2300 feet asl (700 m asl) and on warm slopes tundra decreased mostly below ~2800 feet asl (850 m asl).¹⁷⁹⁵ Neither aspect lost tundra above ~3280 feet asl (~1000 m asl).¹⁷⁹⁶
 - **Trends in recruitment:** Results are consistent with tree establishment that is sensitive to both temperature and to moisture stress.¹⁷⁹⁷ No recruits were found from the coldest decade, 1945-1955.¹⁷⁹⁸ From 1985-1995, the second warmest decade but one of relatively high water balance, recruits established at all elevations sampled and represented the most numerous cohort.¹⁷⁹⁹ The last, hottest, and driest decade, 1995-2005, showed a sharp reduction in recruits that could be due to a sampling failure to find very small recruits.¹⁸⁰⁰

In southeast Alaska, western balsam bark beetle killed subalpine fir in 2002 in the Skagway river drainage.¹⁸⁰¹ The northern-most extension of balsam bark beetles is now in the Taiya Inlet ~0.93 miles (1.5 km) south of Skagway.¹⁸⁰²

Western British Columbia

In one of the first studies on recent increases of tree establishment in sub-alpine meadows, Brink (1959) documented establishment of subalpine fir and mountain hemlock between 1919 and 1939 in heather

¹⁷⁹⁰ Nearly verbatim from Dial et al. (2007, p. 7). Dial et al. refer the reader to Figure 3 and Table 2 in the cited article.

¹⁷⁹¹ Nearly verbatim from Dial et al. (2007, p. 6). Dial et al. refer the reader to Table 2 in the cited article for this information.

¹⁷⁹² Verbatim from Dial et al. (2007, p. 6)

¹⁷⁹³ Verbatim from Dial et al. (2007, p. 7)

¹⁷⁹⁴ Nearly verbatim from Dial et al. (2007, p. 1)

¹⁷⁹⁵ Verbatim from Dial et al. (2007, p. 7)

¹⁷⁹⁶ Verbatim from Dial et al. (2007, p. 7)

¹⁷⁹⁷ Nearly verbatim from Dial et al. (2007, p. 10)

¹⁷⁹⁸ Verbatim from Dial et al. (2007, p. 10)

¹⁷⁹⁹ Nearly verbatim from Dial et al. (2007, p. 10). Dial et al. refer the reader to Figure 1b in the cited article for information on water balance.

¹⁸⁰⁰ Nearly verbatim from Dial et al. (2007, p. 10). Dial et al. refer the reader to Figure 1b in the cited article for information on water balance.

¹⁸⁰¹ Nearly verbatim from Kelly et al. (2007, p. 54)

¹⁸⁰² Nearly verbatim from Kelly et al. (2007, p. 54). Kelly et al. cite Wittwer (2002) for this information.

communities (paddle worms/western moss heather) of the Coast Range.¹⁸⁰³ Heather communities were on topographic convexities, with earlier snowmelt and a longer growing season.¹⁸⁰⁴ Soils were also more xeric (i.e., dry) than surrounding depressions, but not as dry as south-facing forb meadows without trees.¹⁸⁰⁵

The combination of long-term fire suppression, wholesale planting of lodgepole pine, and moister summers has intensified *Dothistroma* (i.e., needle blight) epidemics in northwestern B.C.¹⁸⁰⁶ Warmer temperatures at high elevations have enabled mountain pine beetle outbreaks to spread up into parts of the whitebark pine's range where they had not occurred before.¹⁸⁰⁷ Whitebark pine is not regenerating very successfully because of:

- Widespread mortality of young trees due to the introduced white pine blister rust;
- Beetle-caused mortality of cone-bearing trees; and,
- Fewer fires that normally provide suitable sites for seedlings.¹⁸⁰⁸

In 2005, 3.5 million acres (~1.4 million hectares) of subalpine fir were infested by western balsam bark beetle in British Columbia.¹⁸⁰⁹

Pacific Northwest

The similarity in forest history across a broad region with diverse topographic settings (i.e., the Pacific Northwest) indicates that large-scale atmospheric circulation exerted strong controls over patterns of regional vegetation change.¹⁸¹⁰ The Lateglacial period (>10,000 Before Present, BP) is characterized by a diverse conifer assemblage, the early Holocene (c. 10000–6500 BP) is dominated by disturbance-adapted species (e.g., Sitka alder at high elevation, red alder and Douglas fir at low elevation), and the late Holocene (< c. 6500 BP) records the establishment of modern forest communities.¹⁸¹¹

Rocheftort et al. (2006) note less than 0.5% of Oregon and 5% of Washington lie above the continuous forest line.¹⁸¹² In the Pacific Northwest, the subalpine parkland is a broad ecotone, often ~984 to 1640 feet (300-500 meters) wide, characterized by scattered trees or tree clumps interspersed with herbaceous meadows (Box 7).¹⁸¹³ Typical forest line elevations range from ~6,990 feet (2,130 meters) at Mt. McLoughlin in southern Oregon to ~4,590 feet (1,400 meters) on Mt. Baker in northern Washington.¹⁸¹⁴

¹⁸⁰³ Nearly verbatim from Rocheftort et al. (1994, p. 95)

¹⁸⁰⁴ Verbatim from Rocheftort et al. (1994, p. 95)

¹⁸⁰⁵ Verbatim from Rocheftort et al. (1994, p. 95)

¹⁸⁰⁶ Nearly verbatim from Pojar (2010, p. 23). Pojar cites Woods et al. (2005) for this information.

¹⁸⁰⁷ Verbatim from Pojar (2010, p. 23)

¹⁸⁰⁸ Nearly verbatim from Pojar (2010, p. 23). Pojar cites Campbell & Antos (2000), Zeglen (2002), and Smith et al. (2008) for this information.

¹⁸⁰⁹ Nearly verbatim from Kelly et al. (2007, p. 54). Kelly et al. cite Westfall (2005) for this information.

¹⁸¹⁰ Verbatim from Gavin et al. (2001, p. 186). Gavin et al. cite Thompson et al. (1993) for this information.

¹⁸¹¹ Verbatim from Gavin et al. (2001, p. 186). Gavin et al. cite Whitlock (1992), McLachlan & Brubaker (1995), and Pellatt et al. (1998) for this information.

¹⁸¹² Nearly verbatim from Rocheftort et al. (2006, p. 247)

¹⁸¹³ Nearly verbatim from Rocheftort et al. (2006, p. 247). Rocheftort et al. cite Franklin & Dyrness (1987) for this information.

¹⁸¹⁴ Nearly verbatim from Rocheftort et al. (2006, p. 241)

Box 7. Alpine and subalpine plant communities in the Pacific Northwest.

Subalpine Plant Communities

1. **Heath-shrub** communities, dominated by one or two ericaceous (i.e., of the heather family) shrubs. Examples: red mountain heath, cream mountain heath, western cassiope, blueleaf huckleberry
2. **Lush herbaceous** vegetation communities, dominated by tall perennials. Examples: Sitka valerian, broadleaf lupine, false hellebore.
3. **Low herbaceous** vegetation communities, dominated by fanleaf cinquefoil and wooly everlasting. Lesser amounts of black sedge are also present.
4. **Wet sedge** communities are dominated by black sedge, showy sedge, alpine aster, and wooly everlasting. These communities are found in depressions on the landscape.
5. **Dry grass** communities, dominated by green fescue, Idaho fescue, and broadleaf lupine. These communities are found on well-drained sites and are more common east of the mountains.

Alpine Plant Communities

1. **Snowbed** communities may be dominated by alpine buckwheat-tolmie saxifrage-luetka communities, or by a variety of sedges and herbs. They have the shortest growing season due to their proximity to snowbanks.
2. **Krummholz** may be composed of any species. Subalpine fir, whitebark pine, Engelmann spruce, and mountain larch are common.
3. **Heath-dwarf shrub** community composition depends on local conditions, with pink, yellow, and mountain heathers and western cassiope generally found on moister, more protected sites than willows, crowberry, or kinnikinnick communities. The growing season is intermediate in length.
4. **Fellfield** and **talus** communities are influenced by the size and distribution of rock cover and have the longest growing season. Observed communities include creamy mountain heath ridge, more continuous sedge turf (dominated by Brewer and showy sedge, coiled lousewort), and grass species (purple reedgrass, timber danthonia).

Source: Modified from Rochefort et al. (2006, p. 243-245) by authors of this report.

Subalpine tree growth and establishment in the Pacific Northwest (primarily British Columbia, Washington, and Oregon) are affected by total and seasonal distribution of precipitation.¹⁸¹⁵

Spatiotemporal patterns of growth and establishment are generally limited by accumulation of winter snowpack and timing of snowmelt, and by low temperature and low soil moisture (at some locations) during the growing season.¹⁸¹⁶ During the past century (i.e., since 1890), widespread tree establishment has been occurring in snow-dominated subalpine meadows of the Pacific Northwest (Table 28).¹⁸¹⁷ This establishment may be related partly to warmer air temperatures since the 1890s following the end of the Little Ice Age.¹⁸¹⁸ However, on a subregional scale, periods of tree establishment are associated with

¹⁸¹⁵ Nearly verbatim from Zolbrod & Peterson (1999, p. 1967)

¹⁸¹⁶ Verbatim from Zolbrod & Peterson (1999, p. 1967). Zolbrod & Peterson cite Brink (1959), Franklin et al. (1971), Canaday & Fonda (1974), Peterson & Peterson (1994), Woodward et al. (1995), Ettl & Peterson (1995a, 1995b), Rochefort & Peterson (1996), and Peterson (1998) for information winter snowpack and the timing of snowmelt. Zolbrod & Peterson cite Little et al. (1994), Ettl & Peterson (1995a, 1995b), and Woodward et al. (1995) for information on temperature and soil moisture.

¹⁸¹⁷ Nearly verbatim from Zolbrod & Peterson (1999, p. 1967). Zolbrod & Peterson cite Brink (1959), Fonda & Bliss (1969), Franklin et al. (1971), Heikkinen (1984), Magee & Antos (1992), Rochefort et al. (1994), Woodward et al. (1995), Rochefort & Peterson (1996), Miller & Halpern (1998), and Peterson (1998) for this information.

¹⁸¹⁸ Verbatim from Zolbrod & Peterson (1999, p. 1967). Zolbrod & Peterson cite Heikkinen (1984) for this information.

specific long-term precipitation trends and the amelioration of limiting factors.¹⁸¹⁹ High-snowfall sites have high regeneration during periods of lower than average winter precipitation (ca. 1900-1950), and low-snowfall sites have high regeneration during periods of higher than average winter precipitation (ca. 1950-1990).¹⁸²⁰

In a study of mountain hemlock growth response to climatic variability at annual and decadal time scales from 1895-1991 at elevations ranging from ~3600 to ~7550 feet above sea level (1100-2300 m asl), Peterson and Peterson (2001) found that at high-elevation and midrange sites in Washington and northern Oregon, growth was negatively correlated with spring snowpack depth, and positively correlated with growth-year summer temperature and the winter Pacific Decadal Oscillation (PDO) index.¹⁸²¹ In southern Oregon, growth was negatively correlated with spring snowpack depth and previous summer temperature, and positively correlated with previous summer precipitation.¹⁸²² At the low-elevation sites, growth was mostly insensitive to annual climatic variability but displayed sensitivity to decadal variability in the PDO opposite to that found at high-elevation sites.¹⁸²³

Western Washington

Both records at Martins Lake and Moose Lake in the Olympic Mountains indicate the onset of mesic (i.e., moderate moisture) conditions in the late Holocene, which is in agreement with other paleoenvironmental records in the Pacific Northwest and paleoclimatic reconstructions that indicate moist summer conditions (see previous section).¹⁸²⁴

In western Washington, current forest line and tree line elevations vary, with the transition between forested and subalpine habitat generally taking place between 5,000 and 6,000 feet (1,520 and 1,830 meters) and alpine tundra beginning between 1,000 and 1,500 feet (300 and 460 meters) above that.¹⁸²⁵ Alpine and subalpine habitats cover approximately 859,000 acres (348,000 hectares, ha).¹⁸²⁶ Of those approximately 859,000 acres (348,000 ha), 719,000 acres (291,000 ha; 84%) are classified as subalpine parkland, and 140,000 acres (56,700 ha; 16%) are classified as alpine.¹⁸²⁷

At regional and smaller scales, sensitivity of treeline-relevant factors (e.g., tree physiognomy, seed-based regeneration, local topography) may vary in areas with different climatic characteristics.¹⁸²⁸ In the sub-alpine zone of Mt. Baker (North Cascades), which is characterized by a maritime, snow-rich climate, young growth that became established during the period 1925-1945 was most successful on ridge crests,

¹⁸¹⁹ Verbatim from Zolbrod & Peterson (1999, p. 1967)

¹⁸²⁰ Verbatim from Zolbrod & Peterson (1999, p. 1967). Zolbrod & Peterson cite Agee & Smith (1984) and Woodward et al. (1995) for this information.

¹⁸²¹ Nearly verbatim from Peterson & Peterson (2001, p. 3330)

¹⁸²² Verbatim from Peterson & Peterson (2001, p. 3330)

¹⁸²³ Verbatim from Peterson & Peterson (2001, p. 3330)

¹⁸²⁴ Nearly verbatim from Gavin et al. (2001, p. 185). Gavin et al. cite Thompson et al. (1993) for this information.

¹⁸²⁵ Verbatim from Aubry et al. (2011, p. 71)

¹⁸²⁶ Nearly verbatim from Aubry et al. (2011, p. 71). Aubry et al. refer the reader to Figure 11 in the cited report.

¹⁸²⁷ Verbatim from Aubry et al. (2011, p. 71)

¹⁸²⁸ Nearly verbatim from Holtmeier & Broll (2005, p. 402)

whereas late-lying snow and wetness impeded trees from invading valleys and other snow-rich depressions.¹⁸²⁹

The same was observed in the treeline ecotone on Mt. Rainier in the early- to mid-20th century.¹⁸³⁰ A study of the temporal and spatial distribution of trees in subalpine meadows of Mt. Rainier National Park from 1930-1990 concluded recruitment in subalpine meadows has been continuous on the west side of Mt. Rainier since about 1930, but has occurred in short, discrete periods on the east side.¹⁸³¹

Whitebark pine, western white pine, and lodgepole pine are all associated with high-elevation forests, and whitebark pine and lodgepole pine are often found in subalpine habitats.¹⁸³² An example of a subalpine habitat vulnerable to climate change is the whitebark pine community found in all three of western Washington's national forests (i.e., Olympic, Gifford Pinchot, and Mt. Baker-Snoqualmie National Forests).¹⁸³³ On the Mt. Baker-Snoqualmie and Gifford Pinchot National Forests, whitebark pine populations occur primarily near the Cascade Crest, and to a greater extent east of the crest.¹⁸³⁴ On the Olympic National Forest, the Buckhorn Wilderness contains the only known population of whitebark pine on the forest, as well as the Buckhorn Research Natural Area (RNA), both of which provide areas for assessing current condition and monitoring climate change effects on high-elevation ecosystems.¹⁸³⁵ In addition, recent warming trends resulted in range expansion and population outbreaks of mountain pine beetle, a native bark beetle, that have led to widespread mortality in high-elevation pines (e.g., whitebark pine, western white pine, lodgepole pine) and led to a short-term risk of increased fire intensity.¹⁸³⁶

Western Oregon

In a subalpine meadow complex in the Mount Jefferson Wilderness (Willamette National Forest, central Cascades), proportion of meadow occupied by trees increased from 8% in 1950 to 35% in 2007.¹⁸³⁷ Trees occupied 7.75 % of the total meadow landscape in 1950, increased at an average rate of 0.49 % per year, with 34.71 % occupied in 2008.¹⁸³⁸

Larger landforms, topography, and tree canopies interactively mediated regional climatic controls of tree invasion by modifying depth and persistence of snowpack, while tree canopies also influenced seed source availability.¹⁸³⁹ Specifically:

¹⁸²⁹ Nearly verbatim from Holtmeier & Broll (2005, p. 403). Holtmeier & Broll cite Heikkinen (1984) for this information.

¹⁸³⁰ Nearly verbatim from Holtmeier & Broll (2005, p. 403). Holtmeier & Broll cite Lowery (1972) and Franklin & Dyrness (1973) for this information.

¹⁸³¹ Nearly verbatim from Rochefort & Peterson (1996, p. 52)

¹⁸³² Nearly verbatim from Aubry et al. (2011, p. 74)

¹⁸³³ Nearly verbatim from Aubry et al. (2011, p. 71)

¹⁸³⁴ Verbatim from Aubry et al. (2011, p. 71)

¹⁸³⁵ Verbatim from Aubry et al. (2011, p. 71)

¹⁸³⁶ Nearly verbatim from Aubry et al. (2011, p. 74). Aubry et al. cite Logan et al. (2003) and Williams & Leibhold (2002) for information on mortality in high-elevation pines due to outbreaks of mountain pine beetle.

¹⁸³⁷ Nearly verbatim from Zald et al. (2012, p. 1197)

¹⁸³⁸ Nearly verbatim from Zald et al. (2012, p. 1203)

¹⁸³⁹ Verbatim from Zald et al. (2012, p. 1197)

- In Jefferson Park, tree invasion has been largely absent in wet meadows at low topographic positions over the past fifty years, while seed dispersal limitations may constrain tree invasion and treeline movement for select species.¹⁸⁴⁰
- On glacial landforms, tree invasion was negatively associated with spring snowfall, but on debris flows tree invasion was not associated with snowfall.¹⁸⁴¹
- By 2008, meadow landscape occupancy was 33.68 and 38.82 % on glacial and debris flow landforms, respectively.¹⁸⁴²

Northwest California

Information needed.

Table 28. Summary of recent sub-alpine tree invasion attributed to climate for British Columbia and the Pacific Northwest.

Species	Location	Period of invasion	Author(s)
Subalpine fir Mountain hemlock	Coast Mountains (BC)	1919-1939	Brink (1959)
Subalpine fir Subalpine larch Mountain hemlock	Cascade Mountains (WA)	1919-1937	Arno (1970)
Pacific silver fir Subalpine fir Yellow-cedar Mountain hemlock	Cascade Mountains (WA)	1920-1950	Lowery (1982)
Pacific silver fir Mountain hemlock	Cascade Mountains (WA)	1923-1943	Douglas (1972)
Mountain hemlock Subalpine fir Mountain hemlock	Cascade Mountains (WA)	1925-1934 1940-1944	Heikkinen (1984)
Subalpine fir	Mt. Rainier National Park, Cascade Mountains (WA)	1930-1990	Rocheftort & Peterson (1996)
Subalpine fir Subalpine larch Mountain hemlock	Cascade Mountains (WA, OR)	1894-1920 1925-1950	Franklin et al. (1971)
Mountain hemlock	Olympic Mountains (WA)	1920-1950	Agee & Smith (1984)
Subalpine fir Mountain hemlock	Olympic Mountains (WA)	1923-1933 1943-1948 1953-1960	Fonda & Bliss (1969)

Source: Modified from Rocheftort et al. (1994, Table 2, p. 95) by the authors of this report.

¹⁸⁴⁰ Verbatim from Zald et al. (2012, p. 1210)

¹⁸⁴¹ Verbatim from Zald et al. (2012, p. 1197)

¹⁸⁴² Nearly verbatim from Zald et al. (2012, p. 1204)

Future Projections

Global

In the long term, continued global warming will facilitate treeline advance to greater altitude and latitudes.¹⁸⁴³ However, the sensitivity of treelines to environmental change, and in particular, to climate warming varies with local and regional topographical conditions and thus differs as to its extent, intensity, and the process of change.¹⁸⁴⁴

Southcentral and Southeast Alaska

If current conditions continue for the next 50-100 years, the Kenai forest-tundra ecotone will markedly change to a far woodier landscape with less tundra and more closed-canopy forest.¹⁸⁴⁵ According to the model (i.e., Markov models of stochastic [i.e., randomized] transition matrices to estimate future distributions of cover classes for the years 2041 and 2086 compared to 1951), by the end of the 21st century, cool aspects are likely to be more than half tree-covered, while warm aspects will be about one-third tree covered, the difference in cover being principally shrub.¹⁸⁴⁶ These model results are suggestive at best, based on an assumption of unchanging transition probabilities.¹⁸⁴⁷ Their principle purpose is to highlight the differences between warm and cool aspects as their transitions compound into the future.¹⁸⁴⁸

In Alaska, models predict that 75%-90% of the area that was tundra in 1922 will be replaced by boreal and temperate forest by the end of the 21st century.¹⁸⁴⁹ By then, one can expect lower elevation alpine/tundra habitat in southeastern Alaska to be largely replaced by shrubs and trees.¹⁸⁵⁰

Western British Columbia

Ecosystem productivity could increase in the north and at high elevations, where cold air and soil temperatures and short growing seasons currently limit plant growth.¹⁸⁵¹ In such energy-limited environments, warmer temperatures combined with increased CO₂ should result in longer growing seasons, higher rates of photosynthesis, and increased primary production, decomposition, and rates of mineral cycling.¹⁸⁵² However, unsuitable conditions for regeneration (for example, lack of mineral soils in high mountains and northern muskeg), slow migration, and other factors such as nutrient limitations will likely retard the emergence of productive forests in these regions.¹⁸⁵³

¹⁸⁴³ Verbatim from Holtmeier & Broll (2005, p. 405)

¹⁸⁴⁴ Verbatim from Holtmeier & Broll (2005, p. 405)

¹⁸⁴⁵ Verbatim from Dial et al. (2007, p. 1)

¹⁸⁴⁶ Nearly verbatim from Dial et al. (2007, p. 11)

¹⁸⁴⁷ Verbatim from Dial et al. (2007, p. 11-12)

¹⁸⁴⁸ Verbatim from Dial et al. (2007, p. 12)

¹⁸⁴⁹ Nearly verbatim from Kelly et al. (2007, p. 52). Kelly et al. cite Bachelet et al. (2005) for this information.

¹⁸⁵⁰ Nearly verbatim from Kelly et al. (2007, p. 52)

¹⁸⁵¹ Verbatim from Pojar (2010, p. 24)

¹⁸⁵² Verbatim from Pojar (2010, p. 24). Pojar cites Waring & Running (1998) for this information.

¹⁸⁵³ Verbatim from Pojar (2010, p. 24). Pojar cites Campbell et al. (2008) for this information.

Pacific Northwest

Increasing atmospheric CO₂ concentrations could produce warmer temperatures and reduced snowpack depths in the next century.¹⁸⁵⁴ Such changes would likely increase mountain hemlock growth and productivity throughout much of its range in Washington and northern Oregon.¹⁸⁵⁵ New pulses of seedling establishment in wet subalpine and alpine meadows and upward movement of the alpine tree line would also be likely, as these have occurred during warm periods of the past century.¹⁸⁵⁶ Increased summer drought stress and reduced productivity would be likely, however, in mountain hemlock forests of southern Oregon and near the species lower elevation limit at some sites.¹⁸⁵⁷ There could also be increased risk of frost damage if earlier snowmelt causes shoot growth to commence earlier in the spring.¹⁸⁵⁸ Regeneration could be increasingly limited to periods when decadal variability in climate produces a series of summers with reduced temperature and moisture stress.¹⁸⁵⁹

Western Washington

In a vulnerability assessment for western Washington terrestrial habitats, several high-elevation tree species ranked among the most vulnerable to climate change.¹⁸⁶⁰ Among those species, subalpine fir and mountain hemlock are associated with subalpine habitat.¹⁸⁶¹ They are important components of the patchy habitat structure of subalpine environments, and are commonly dominant species below the subalpine zone.¹⁸⁶² In the case of mountain hemlock, habitat affinity was the greatest contributor to its high overall vulnerability score; for subalpine fir, insects and disease was the most influential factor.¹⁸⁶³ These results demonstrate some of the potential differences among species in relative vulnerability to climate change.¹⁸⁶⁴ In addition, fire frequency is expected to increase with future climate warming, and may be exacerbated in subalpine habitats by increased tree mortality from mountain pine beetle.¹⁸⁶⁵

In a modeling study of the response of high-elevation forests in a southwest and northeast region of the Olympic Mountains (using the gap model ZELIG run under three scenarios, a 3.6 °F (2 °C) temperature increase and either no change in annual precipitation, a 20% increase in annual precipitation, or a 20% decrease in annual precipitation over 1000 years), for all transects, trees establish in the subalpine

¹⁸⁵⁴ Verbatim from Peterson & Peterson (2001, p. 3330)

¹⁸⁵⁵ Verbatim from Peterson & Peterson (2001, p. 3330)

¹⁸⁵⁶ Verbatim from Peterson & Peterson (2001, p. 3341). Peterson & Peterson cite Rochefort et al. (1994) and Rochefort & Peterson (1996) for this information.

¹⁸⁵⁷ Verbatim from Peterson & Peterson (2001, p. 3330)

¹⁸⁵⁸ Verbatim from Peterson & Peterson (2001, p. 3342). Peterson & Peterson cite Cannell & Smith (1986) for this information.

¹⁸⁵⁹ Verbatim from Peterson & Peterson (2001, p. 3342)

¹⁸⁶⁰ Verbatim from Aubry et al. (2011, p. 73)

¹⁸⁶¹ Verbatim from Aubry et al. (2011, p. 73)

¹⁸⁶² Verbatim from Aubry et al. (2011, p. 73)

¹⁸⁶³ Verbatim from Aubry et al. (2011, p. 73)

¹⁸⁶⁴ Verbatim from Aubry et al. (2011, p. 73)

¹⁸⁶⁵ Nearly verbatim from Aubry et al. (2011, p. 74). Aubry et al. cite Littell et al. (2009a) and Westerling et al. (2006) for information on projected increases in fire frequency and Littell et al. (2009b) for information on potentially exacerbated fire frequency in subalpine habitats.

meadows in the warmer climatic scenario, continuing the pattern of tree establishment documented for the 20th century.¹⁸⁶⁶ Specific projections are available:

- **Northeast region:** In the northeast region, the high-elevation meadows on both the north and south aspects are dominated by lodgepole pine stands in 150-200 years.¹⁸⁶⁷ However, the establishment of forest in the northeast meadows is contrary to predictions that warmer summers would increase evapotranspiration and drought during the growing season, thereby increasing moisture stress in seedlings and reducing regeneration.¹⁸⁶⁸
- **Southwest region:** In the southwest region, the subalpine meadows are dominated by stands of large Pacific silver fir with western hemlock and mountain hemlock subdominant in about 200 years.¹⁸⁶⁹ The establishment of forest in the southwest matches predictions for a warmer climate in a high precipitation regime.¹⁸⁷⁰

Also in the Olympic Mountains, the Martins Lake and Moose Lake pollen records have at least two important implications for subalpine forest responses to future climatic warming.¹⁸⁷¹ First, warmer summer temperatures may not cause an upward shift in elevational tree-line, as evidenced by lower than present tree-line near Martins Lake during the early Holocene (see observed trends in this section for more information).¹⁸⁷² Second, subalpine forests will probably not respond to climatic change uniformly over space because mountain environments can modify regional climatic forcing to produce complex spatial variability in local climates that affect both the direction and rate of local population responses.¹⁸⁷³ Overall, the Martins Lake and Moose Lake records demonstrate that the local expression of regional climatic change varies spatially in the Olympic Mountains, indicating that vegetation response to future climatic change will be complex in such areas.¹⁸⁷⁴

Western Oregon

In future vegetation simulations produced by MC1, areas of subalpine forest and alpine tundra in Oregon are projected to decrease as temperatures increase at higher elevations by 2070-2099 (compared to 1961-1990, using the CSIRO-Mk3.0 and UKMO-HadCM3 GCMs under the B1 and A2 scenarios).¹⁸⁷⁵ Species that currently occur at lower elevations may expand upward in elevation over time.¹⁸⁷⁶

¹⁸⁶⁶ Nearly verbatim from Zolbrod & Peterson (1999, p. 1970-1971). Zolbrod & Peterson cite Agee & Smith (1984), Rochefort et al. (1994), Woodward et al. (1995), Rochefort & Peterson (1996), Miller & Halpern (1998), and Peterson (1998) for this information.

¹⁸⁶⁷ Nearly verbatim from Zolbrod & Peterson (1999, p. 1971). Zolbrod & Peterson refer the reader to Table 3 in the cited article for this information.

¹⁸⁶⁸ Verbatim from Zolbrod & Peterson (1999, p. 1971). Zolbrod & Peterson cite Little et al. (1994), Soll (1994), and Woodward et al. (1995) for this information.

¹⁸⁶⁹ Nearly verbatim from Zolbrod & Peterson (1999, p. 1971)

¹⁸⁷⁰ Verbatim from Zolbrod & Peterson (1999, p. 1971). Zolbrod & Peterson cite Franklin et al. (1971), Little et al. (1994), Woodward et al. (1995), and Rochefort & Peterson (1996) for this information.

¹⁸⁷¹ Nearly verbatim from Gavin et al. (2001, p. 186)

¹⁸⁷² Verbatim from Gavin et al. (2001, p. 186)

¹⁸⁷³ Verbatim from Gavin et al. (2001, p. 186)

¹⁸⁷⁴ Verbatim from Gavin et al. (2001, p. 186)

¹⁸⁷⁵ Nearly verbatim from Shafer et al. (2010, p. 180). Shafer et al. refer the reader to Figures 5.3b and 5.3c in the cite report for this information.

¹⁸⁷⁶ Verbatim from Shafer et al. (2010, p. 195)

In a subalpine meadow complex in the Mount Jefferson Wilderness (Willamette National Forest, central Cascades), while regional climatic changes are likely to accelerate tree invasion, finer scale topographic and biotic factors influencing tree invasion will persist in the future.¹⁸⁷⁷ These fine scale spatial constraints on tree invasion may result in high elevation persistence of meadows and meadow obligate species that may be overlooked at larger spatial scales.¹⁸⁷⁸ However, lower snow depth and rapid tree invasion on debris flows that was not associated with annual and spring snowfall suggests a threshold of snow depth and persistence may exist, below which rapid tree invasion may occur.¹⁸⁷⁹

The importance of snow, uncertain climate change impacts on snow, and mediation of snow by interacting and context dependent factors in complex mountain terrain poses substantial hurdles for understanding how these ecotones (i.e., subalpine meadow complexes) may respond to future climate conditions.¹⁸⁸⁰

Northwest California

Information needed.

Information Gaps

Site-specific management requires site-specific information, but alpine and subalpine habitats are not well-mapped, due in part to difficulties of scale.¹⁸⁸¹ Uncertainty in regional and global climate models is often greatest for precipitation and snowfall, especially in areas with complex mountainous terrain and ocean-land interactions.¹⁸⁸² Current climate modeling is limited to resolutions too coarse to be useful in complex high-elevation topography, and also misses these important small-scale landscape and habitat variations.¹⁸⁸³ These localized habitats include dry meadows, wet meadows, wetlands, seasonal ponds, lichen-covered rocks and cliffs, talus slopes, krummholz, shrub thickets, tree islands, and other small ecosystems.¹⁸⁸⁴ Holtmeier and Broll (2005) suggest research on the factors controlling spatial and temporal patterns of establishment and survival of seedlings and young growth should be intensified.¹⁸⁸⁵ Also lacking are inventories of existing non-native invasive plant (noxious weed) infestations in high-elevation environments.¹⁸⁸⁶

Direct monitoring of climate-sensitive factors will provide better information for assessing alpine and subalpine responses to climate change.¹⁸⁸⁷ For instance, threshold snow levels could greatly alter understanding of potential tree invasion (e.g., in subalpine meadow complexes) in the future, but

¹⁸⁷⁷ Nearly verbatim from Zald et al. (2012, p. 1210)

¹⁸⁷⁸ Verbatim from Zald et al. (2012, p. 1210). Zald et al. cite Randin et al. (2009) for this information.

¹⁸⁷⁹ Nearly verbatim from Zald et al. (2012, p. 1210)

¹⁸⁸⁰ Verbatim from Zald et al. (2012, p. 1197)

¹⁸⁸¹ Verbatim from Aubry et al. (2011, p. 74)

¹⁸⁸² Nearly verbatim from Zald et al. (2012, p. 1210). Zald et al. cite Good & Lowe (2006) and Salathé et al. (2008) for this information.

¹⁸⁸³ Verbatim from Aubry et al. (2011, p. 75). Aubry et al. cite Bachelet (2010a) for this information.

¹⁸⁸⁴ Verbatim from Aubry et al. (2011, p. 74). Aubry et al. cite Malanson et al. (2007) for this information.

¹⁸⁸⁵ Nearly verbatim from Holtmeier & Broll (2005, p. 405)

¹⁸⁸⁶ Verbatim from Aubry et al. (2011, p. 75)

¹⁸⁸⁷ Verbatim from Aubry et al. (2011, p. 75)

observational and experimental evidence regarding threshold snow effects on tree invasion are lacking.¹⁸⁸⁸ The duration and extent of annual snowpack can be tracked using existing aerial imagery and remote sensing.¹⁸⁸⁹ Changes in tree density and establishment in subalpine meadows can also be tracked using aerial imagery.¹⁸⁹⁰ Holtmeier & Broll (2005) suggest the search for treelines suitable for monitoring for the first effects of present climate change at the regional, landscape, or local scales should focus on treelines undisturbed by orographic effects and human impact.¹⁸⁹¹ Satellite imagery and other remote sensing techniques can facilitate the identification of those treelines that are most appropriate for this type of field research, even in remote areas.¹⁸⁹²

Local temperature and precipitation data are available from the existing system of weather stations maintained by various agencies, such as the Western Regional Climate Center (www.wrcc.dri.edu/index.html).¹⁸⁹³ Consistent observation of these data, combined with a review of historical data, would offer clues as to which elements of alpine and subalpine habitats might be most vulnerable to the effects of climate change.¹⁸⁹⁴ Gaps in the network of weather stations could be identified and filled to provide a more complete picture of patterns of climate change in alpine and subalpine habitats.¹⁸⁹⁵

¹⁸⁸⁸ Nearly verbatim from Zald et al. (2012, p. 1210)

¹⁸⁸⁹ Nearly verbatim from Aubry et al. (2011, p. 75)

¹⁸⁹⁰ Verbatim from Aubry et al. (2011, p. 75)

¹⁸⁹¹ Nearly verbatim from Holtmeier & Broll (2005, p. 405)

¹⁸⁹² Verbatim from Holtmeier & Broll (2005, p. 405)

¹⁸⁹³ Verbatim from Aubry et al. (2011, p. 75)

¹⁸⁹⁴ Verbatim from Aubry et al. (2011, p. 75)

¹⁸⁹⁵ Verbatim from Aubry et al. (2011, p. 75)

VII. Implications for Species, Populations, & Communities

Rapid climate change in the twenty-first century threatens biodiversity, ecosystem services, and human welfare.¹⁸⁹⁶ While climate change *per se* is a pervasive feature of earth history, the pace of change currently forecast for the next 100 years is virtually unparalleled in its speed, magnitude, and global extent.¹⁸⁹⁷ If the rate of change exceeds the pace of biological response, especially the capacity of populations to migrate or undergo adaptive evolutionary change, impacts on species distributions, community structure, and ecosystem function may be profound.¹⁸⁹⁸ Species may be negatively affected by physiological stress caused by changes in temperature, water availability, and other environmental shifts, and/or indirectly by habitat degradation and negative interactions with species that benefit from climate change (diseases, parasites, predators, and competitors).¹⁸⁹⁹ Because there is a broad range of possibilities regarding the degree to forthcoming climate change, especially regarding the response of complex biological systems, the severity of predicted responses is unknown, even though the direction of such changes is more certain.¹⁹⁰⁰

Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations, the following general implications of climate change for species, populations, and communities in the NPLCC region have been identified:

1. Shifts in species range and distribution
2. Altered phenology
3. Altered growth and development
4. Shifts in biodiversity, species richness, abundance, competition, survival, and community composition
5. Altered interaction with invasive and non-native species

Chapter VIII provides information specific to mammals, birds, invertebrates, lichens, and mosses. The following structure will be used to present information on the implications of climate change for the NPLCC region's terrestrial species, populations, and communities:

- **Observed Trends** – observed changes for southcentral and southeast Alaska, western British Columbia, the Pacific Northwest, western Washington, the Klamath Mountains, western Oregon, and northwest California. For context, summary information on observed changes globally or for western North America is also provided.
- **Future Projections** – projected direction and/or magnitude of change for southcentral and southeast Alaska, western British Columbia, the Pacific Northwest, western Washington, western

¹⁸⁹⁶ Verbatim from Ackerly (2012, p. 1)

¹⁸⁹⁷ Verbatim from Ackerly (2012, p. 1). Ackerly et al. cite Barnosky (2009) and Willis et al. (2010) for this information.

¹⁸⁹⁸ Verbatim from Ackerly (2012, p. 1)

¹⁸⁹⁹ Verbatim from Hixon et al. (2010, p. 269)

¹⁹⁰⁰ Verbatim from Hixon et al. (2010, p. 269)

Oregon, and northwest California. For context, summary information on future projections globally or for western North America is also provided.

- **Information Gaps** – information and research needs identified by literature searches, as well as our summary of the sections missing information in this chapter.

1. Shifts in species range and distribution

Many species are shifting their geographic ranges in response to rapid changes in temperature and precipitation regimes.¹⁹⁰¹ Often populations track temperature gradients by moving poleward, up in elevation, or to increased depths in the oceans.¹⁹⁰² Changes in distribution are often asymmetrical with species invading faster from lower elevations or latitudes than resident species are receding upslope or poleward.¹⁹⁰³ The result is a (presumably transient) increase in species richness of the community in question as a consequence of the variability in rates at which species shift their ranges.¹⁹⁰⁴ However, not all species movements have been poleward or up in elevation.¹⁹⁰⁵

Range shifts may raise the probability of persistence of species and populations; however the ability to disperse or migrate to new areas does not guarantee survival as there are additional factors such as species interactions and land use change that may influence populations.¹⁹⁰⁶ Species-specific differences in physiological, behavioral, and morphological plasticity may allow individuals and populations to respond *in situ* and delay or eliminate the need for range shifts; however, in many cases, these responses may be difficult to predict.¹⁹⁰⁷ Recent estimates of the velocity of climate change, described by Loarie et al. (2009) as the speed and residence time of temperature change over space and time, are faster than was previously thought; this has raised concern as to whether species migration rates will be fast enough to track future environmental conditions.¹⁹⁰⁸

For migratory species, in addition to suitable habitat at either end of their journey, many migratory species require an ecologically coherent habitat network that they can use en route.¹⁹⁰⁹ Changes in any area used by a migratory species are likely to affect all populations of a species, even those that do not use them directly, because of density-dependent habitat selection and mortality.¹⁹¹⁰

Observed Trends

Global

Ranges and abundances of terrestrial species shifted dramatically during the last deglaciation.¹⁹¹¹ Species varied widely in the timing, magnitude, and direction of these responses, and communities did not

¹⁹⁰¹ Verbatim from Staudinger et al. (2012, p. 2-17)

¹⁹⁰² Verbatim from Staudinger et al. (2012, p. 2-17)

¹⁹⁰³ Verbatim from Walther et al. (2002, p. 391). Walther et al. cite Pounds et al. (1999) for information on species invading from lower elevations and Sagarin et al. (1999) for information on species invading from lower latitudes.

¹⁹⁰⁴ Verbatim from Walther et al. (2002, p. 391)

¹⁹⁰⁵ Verbatim from Staudinger et al. (2012, p. 2-17)

¹⁹⁰⁶ Verbatim from Staudinger et al. (2012, p. 2-18). Staudinger et al. cite Hoffmann & Sgró (2011) for this information.

¹⁹⁰⁷ Verbatim from Staudinger et al. (2012, p. 2-18). Staudinger et al. cite Doak & Morris (2010) for information on species-specific responses enabling *in situ* responses and delaying or eliminating the need for range shifts.

¹⁹⁰⁸ Verbatim from Staudinger et al. (2012, p. 2-22). Staudinger et al. cite Pearson (2006) for this information.

¹⁹⁰⁹ Verbatim from Robinson et al. (2008, p. 91). *Travelling through a warming world: climate change and migratory species.*

¹⁹¹⁰ Verbatim from Robinson et al. (2008, p. 91). Robinson et al. cite Sutherland (1996) and Newton (2006) for this information.

¹⁹¹¹ Verbatim from Williams & Jackson (2007, p. 476)

migrate as intact units.¹⁹¹² Similar responses occurred during earlier periods of climate change and individualistic behavior is documented for species responding to current climate changes.¹⁹¹³ Initial analyses using pollen records showed post-glacial migration rates of up to 656 feet per year (200 meters per year), but chloroplast DNA evidence of low-density refugial populations of angiosperm (i.e., flowering plant) trees much farther north than previously thought has caused these estimates to be revised.¹⁹¹⁴ With seeds spreading both from the northern edge of the continuous species range and from previously unidentified, disjunct refugial populations, actual migration rate estimates have been revised to less than 328 feet per year (100 meters per year).¹⁹¹⁵ Rare long-distance seed dispersal events have likely played a crucial role in increasing effective migration rates relative to the effects of average seed dispersal distances, but such events are hard to quantify or model.¹⁹¹⁶

It is now clear that poleward and upward shifts of species ranges have occurred across a wide range of taxonomic groups and geographical locations during the 20th century (Table 29).¹⁹¹⁷ Whereas the magnitude of elevational shifts of alpine plant species lags behind the isothermal shift of 26-33 feet per decade (8-10 meters per decade), butterflies appear to track decadal warming quickly, matching the upwards and northwards shifts of temperature isotherms.¹⁹¹⁸

Southcentral and Southeast Alaska

Information needed.

Western British Columbia

Figure 57 shows the biogeoclimatic zones of British Columbia.

Pacific Northwest

Please see Chapters VI (sections 2 through 4) and VIII for additional information on species range shifts.

Northwest California

Information needed.

¹⁹¹² Verbatim from Williams & Jackson (2007, p. 476). Williams & Jackson cite Gleason (1926), Davis (1981), FAUNMAP Working Group (1996), and Jackson and Overpeck (2000) for this information.

¹⁹¹³ Verbatim from Williams & Jackson (2007, p. 476). Williams & Jackson cite Wing et al. (2005) for information on similar responses during earlier periods of climate change and Walther et al. (2002) for information on the individualistic behavior of species responding to current climate changes.

¹⁹¹⁴ Nearly verbatim from Aitken et al. (2008, p. 96). Aitken et al. cite McLachlan & Clark (2004) and McLachlan et al. (2007) for this information.

¹⁹¹⁵ Verbatim from Aitken et al. (2008, p. 96)

¹⁹¹⁶ Verbatim from Aitken et al. (2008, p. 96). Aitken et al. cite Clark et al. (2003) and Petit et al. (2004) for this information.

¹⁹¹⁷ Verbatim from Walther et al. (2002, p. 391). Walther et al. refer the reader to Table 2 in the cited article for this information. Walther et al. also cite Hughes (2000), McCarty (2001), Walther et al. (2001), and Easterling et al. (2000) for this information.

¹⁹¹⁸ Verbatim from Walther et al. (2002, p. 391). Walther et al. cite Grabherr et al. (1994) for information on alpine plant species, Parmesan et al. (1999) and Parmesan (1996) for information on butterflies, and Karl et al. (1996) for specific information on matching upwards and northward shifts in temperature. Walther et al. also refer the reader to Table 2 in the cited article to compare this data.

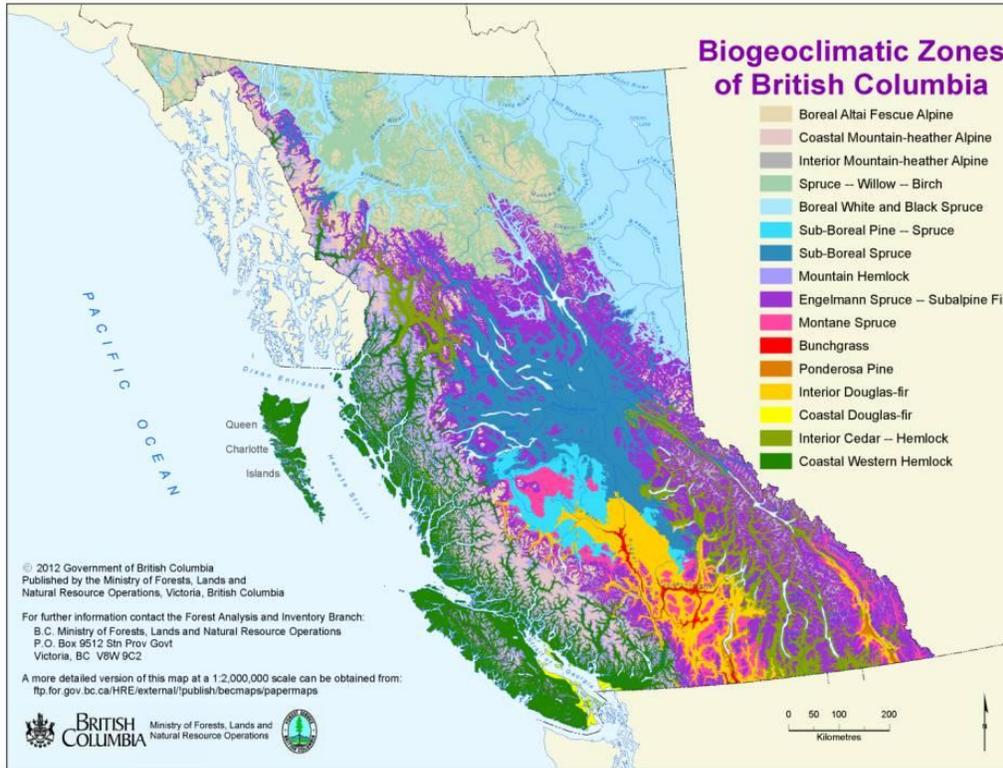


Figure 57. Biogeoclimatic Zones of British Columbia. *Source: Downloaded from BC Forest Service Research Branch, [Biogeoclimatic Ecosystem Classification Program](#) (March 6, 2013) by authors of this report.*

Future Projections

Global

Climate change will lead to loss of range for many species, and thus to loss of genetic diversity crucial for their long-term persistence.¹⁹¹⁹ Forecasts of terrestrial biomes estimate that the velocity of global temperature shifts will be lowest in topographically complex montane systems (0.05 miles per year; 0.08 km per year) whereas systems with much less topography such as flooded grasslands and deserts, will show higher rates of change (0.783 miles per year; 1.26 km per year).¹⁹²⁰

Alsos et al. (2011) analyzed range-wide genetic diversity in 9581 samples from 1200 populations of 27 northern plant species (i.e., those typically occurring in the bioclimatic zones at the tree line and beyond – the alpine and arctic zones), to assess genetic consequences of range reduction and potential association with species traits.¹⁹²¹ The expected range reduction in these 27 northern species was larger than reported for temperate plants, and all were predicted to lose genetic diversity according to at least one scenario.¹⁹²² Loss of genetic diversity varied considerably among species, and this variation could be explained by dispersal adaptation (up to 57%) and by genetic differentiation among populations (up to 61%).¹⁹²³

¹⁹¹⁹ Verbatim from Alsos et al. (2011, p. 1). *Genetic consequences of climate change for northern plants.*

¹⁹²⁰ Verbatim from Staudinger et al. (2012, p. 2-22). Staudinger et al. cite Loarie & others (2009) for this information.

¹⁹²¹ Nearly verbatim from Alsos et al. (2011, p. 1)

¹⁹²² Verbatim from Alsos et al. (2011, p. 1)

¹⁹²³ Nearly verbatim from Alsos et al. (2011, p. 1)

Specific results include:

- **Range reduction:** Range reduction was on average higher under emission scenario A2 (36-43% reduction) than under B2 (26-32% reduction), as expected as the A2 scenario anticipates a more severe climate change than the B2 scenario (Figure 58).¹⁹²⁴ The range gain was generally considerably lower than the range reduction, and on average the range change was -24% for A2 CCM3, -30% for A2 HadCM3, -16% for B2 CCM3 and -22% for B2 HadCM3 (2071-2100 vs. 1961-1990).¹⁹²⁵
- **Effect of dispersal adaptation:** Alsos et al.'s (2011) estimates indicated that species without adaptations to long-distance dispersal (and/or herbaceous species) will lose genetic diversity at about twice the rate of species adapted to long-distance dispersal by animals or wind (and/or woody species).¹⁹²⁶ However, dispersal adaptation was strongly correlated with growth form in the set of species; thus, the effect of these two traits could not be distinguished.¹⁹²⁷ Further, herbs lacking adaptations for long-distance dispersal were estimated to lose genetic diversity at a higher rate than dwarf shrubs adapted to long-distance dispersal.¹⁹²⁸
- **Loss of genetic diversity:** In the worst case scenario, assuming that the model estimating the maximum range reduction will be realized, and that the corresponding loss of genetic diversity will be at the maximum value, all species were expected to lose some genetic diversity, one-third of them greater than 50%.¹⁹²⁹ Species expected to lose more of their range were also prone to more severe genetic loss: range reduction alone explained 66–74% of the variation in estimated loss of genetic diversity among species.¹⁹³⁰ *For more information on shifts in biodiversity, please see Chapter VII.4.*

Similarly, amongst insects and seabirds, those species with greater dispersal are better able to respond adaptively to warming temperatures.¹⁹³¹ Birds, insects and many marine species ride winds or currents to aid their migratory journeys, making some of the longest distance migrations possible.¹⁹³² Alteration of these currents or winds might make journeys easier, but is more likely to increase energy demands and/or deliver individuals to the wrong locations or at the wrong time.¹⁹³³

¹⁹²⁴ Nearly verbatim from Alsos et al. (2011, p. 5). Alsos et al. refer the reader to Table 2 in the cited article for this information.

¹⁹²⁵ Nearly verbatim from Alsos et al. (2011, p. 5). Alsos et al. refer the reader to Table S5 in the cited article's electronic supplementary material for this information.

¹⁹²⁶ Nearly verbatim from Alsos et al. (2011, p. 5). Alsos et al. refer the reader to Figure 2 and Table 1 in the cited article for this information.

¹⁹²⁷ Nearly verbatim from Alsos et al. (2011, p. 5). Alsos et al. refer the reader to Table 2 in the cited article and p. S2 in the cited article's electronic supplementary material for information on the correlation between dispersal adaptation and growth form.

¹⁹²⁸ Nearly verbatim from Alsos et al. (2011, p. 1)

¹⁹²⁹ Nearly verbatim from Alsos et al. (2011, p. 5). Alsos et al. refer the reader to Table 2 in the cited article for this information. Alsos et al. note the worst case scenario is the crossing point between the right red bar and upper dashed line in Figure 2 in the cited article.

¹⁹³⁰ Nearly verbatim from Alsos et al. (2011, p. 5)

¹⁹³¹ Verbatim from Robinson et al. (2008, p. 5). Robinson et al. cite Warren et al. (2001) for information on insects and Oedekoven et al. (2001) for information on seabirds.

¹⁹³² Verbatim from Robinson et al. (2008, p. 91). Robinson et al. cite Wirth & Bernatchez (2003) and Deveson et al. (2005) for this information.

¹⁹³³ Verbatim from Robinson et al. (2008, p. 91). Robinson et al. cite Liechti (2006) for this information.

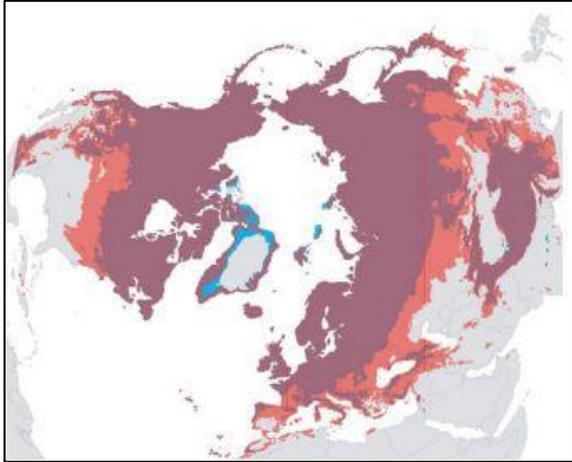


Figure 58. Estimating loss of genetic diversity and range reduction, exemplified by data for bog blueberry. Potential present and future (year 2080) distribution habitats overlaid to show lost (**red**), stable (**purple**) and future new habitat (**blue**). In this example, a 26% range reduction was estimated for the A2 emission scenario and CCM3 global circulation model, and there were 53 grid cells of 500 x 500 km that contained samples. The predicted loss of 26% of the range corresponded to a loss of 14 grid cells.

Source: Reproduced from Alsos et al. (2011, Figure 1b, p. 2) by authors of this report.

Southcentral and Southeast Alaska

Populations of species strongly associated with alpine/tundra ecosystems will be reduced in number, fragmented, or eliminated as temperatures increase.¹⁹³⁴

Western British Columbia

Information needed.

Pacific Northwest

Changes in USDA plant hardiness zones have already been recorded in much of Oregon and will result in concomitant shifts in terrestrial plant communities and open habitats to invasion.¹⁹³⁵ Plants and animals eventually occupy landscapes vacated by glacial ice, and new alpine lakes often remain after the ice is gone.¹⁹³⁶ *For additional information on future projections for species range and distribution, please see Chapters VI (sections 2 through 4) and Chapter VIII.*

Northwest California

Information needed.

Information Gaps

A key area of uncertainty is in understanding the mechanisms through which climate change will affect populations, which is an area of active research, particularly in understanding how climate impacts at one point in the life-cycle affect demographic parameters at later points.¹⁹³⁷ Such cross-seasonal impacts will often be modulated by density-dependent effects, and documenting these will be important in order to assess the fate of migrants under changing climates.¹⁹³⁸ Traditional approaches, such as climate envelopes and global vegetation models, can be applied to estimate shifts in breeding grounds and non-breeding areas, but as migratory species move between different areas, the uncertainties in predictions are multiplied, particularly when biotic interactions are taken into account.¹⁹³⁹

¹⁹³⁴ Nearly verbatim from Kelly et al. (2007, p. 52)

¹⁹³⁵ Nearly verbatim from Hixon et al. (2010, p. 325). Hixon et al. refer the reader to the Map on p. 326 of the cited report for information on the change in plant hardiness zones.

¹⁹³⁶ Verbatim from Burkett et al. (2005, p. 368)

¹⁹³⁷ Verbatim from Robinson et al. (2008, p. 96). Robinson et al. cite Jonzén et al. (2007) as an example of the active research in understanding the mechanisms through which climate change will affect populations.

¹⁹³⁸ Verbatim from Robinson et al. (2008, p. 96). Robinson et al. cite Ratikainen et al. (2008) for this information.

¹⁹³⁹ Verbatim from Robinson et al. (2008, p. 95-96). Robinson et al. cite Araújo & Luoto (2007) and Martine et al. (2007) for this information.

2. Altered phenology

Climate change is altering the phenology of many species and the timing of their interactions with other species, but the impacts of these phenological shifts on species interactions remain unclear.¹⁹⁴⁰ In general, the effects of phenological shifts on interacting species seem to be largely determined by (1) how the interaction type and/or strength changes over their ontogenies (i.e., the development of an organism) and (2) the relative phenologies of the interacting species.¹⁹⁴¹ Given that species interactions can strongly determine the structure and dynamics of many natural communities, some of the most profound effects of climate change are likely to be driven by changes in the timing of biotic interactions between species.¹⁹⁴² The effects of these altered interactions can be as strong or stronger than the direct abiotic effects of climate change.¹⁹⁴³ For example, decoupled trophic interactions due to climate change may compromise population sustainability and, in some cases, affect species range changes.¹⁹⁴⁴ Changes in the timing of migration could also have profound impacts, particularly with regard to mismatch between trophic levels.¹⁹⁴⁵ Further, the existence of trophic mismatch in prey-predator and host-parasite systems or the collapse of one partner in the interaction will thus have nontrivial demographic effects and cause complex population and range dynamics, generally depending on the relative environmental niches of species from different trophic levels.¹⁹⁴⁶

Phenology is the seasonal timing of life events. Examples include leaf out, flowering and blooming in plants, and the spawning, breeding and migration of animals. Changes in phenology such as earlier flowering or later migration may occur in response to changes in temperature, precipitation, photoperiod, or other factors. When such changes occur, species that depend on a particular timing of life events in other species are often affected, resulting in phenological mismatches.

Sources: Lavergne et al. (2010), Staudinger et al. (2012), Yang & Rudolf (2010)

The exchanges of energy and CO₂ between the biosphere and the atmosphere, via the biophysical and biogeochemical pathways, respectively, are strongly influenced by phenology, that is the timing of the onset and eventual loss (offset), of leaves.¹⁹⁴⁷ Leaf phenology regularly alters land-surface boundary conditions by changing surface albedo, roughness, and surface water and energy fluxes.¹⁹⁴⁸ Leaf onset and offset mark the bounds of the growing season and therefore annual carbon uptake depends strongly on leaf phenology.¹⁹⁴⁹

¹⁹⁴⁰ Verbatim from Yang & Rudolf (2010, p. 1). *Phenology, ontogeny and the effects of climate change on the timing of species interactions.*

¹⁹⁴¹ Nearly verbatim from Yang & Rudolf (2010, p. 4)

¹⁹⁴² Verbatim from Yang & Rudolf (2010, p. 1)

¹⁹⁴³ Verbatim from Yang & Rudolf (2010, p. 1). Yang & Rudolf cite Parmesan (2006) for this information.

¹⁹⁴⁴ Verbatim from Lavergne et al. (2010, p. 332). *Biodiversity and climate change: integrating evolutionary and ecological responses of species and communities.* Lavergne et al. cite Schweiger et al. (2008) for this information.

¹⁹⁴⁵ Verbatim from Robinson et al. (2008, p. 93)

¹⁹⁴⁶ Verbatim from Lavergne et al. (2010, p. 332). Lavergne et al. cite Schweiger et al. (2008) for this information.

¹⁹⁴⁷ Verbatim from Arora & Boer (2005, p. 39)

¹⁹⁴⁸ Verbatim from Arora & Boer (2005, p. 39). Arora & Boer cite Hogg et al. (2000) and Molod et al. (2003) for this information.

¹⁹⁴⁹ Verbatim from Arora & Boer (2005, p. 39). Arora & Boer cite Goulden et al. (1996) and White et al. (1999) for this information.

Observed Trends

Global

Numerous ecological studies have now pointed to an important general pattern of species responses to climate change around the world: on average, seasonal life-history events such as leaf unfolding, flowering, insect emergence, or the arrival of migratory birds are occurring earlier than they have in the historical past (Table 29).¹⁹⁵⁰ Despite this prevailing trend, however, it has also become evident that species within the same community often show variable phenological responses to climate change.¹⁹⁵¹ For example, an unusually warm spring in northern Japan lead to substantial phenological advances in the flowering of several spring-ephemeral plants relative to their pollinating bees, resulting in dramatically decreased seed production of bee-pollinated species.¹⁹⁵²

In general, while many species have shown advances in the seasonal timing of their life-history events to varying degrees, some species have shown no discernible phenological changes, and others have demonstrated delayed seasonal phenologies (Table 29).¹⁹⁵³ Studies reveal different proportions of bird species which advance, delay or do not change autumn migration, and trends of leaf colouring of trees at neighbouring stations often show contradictory signals.¹⁹⁵⁴ In Europe, for example, leaf color changes show a progressive delay of 0.3 – 1.6 days per decade, whereas the length of the growing season has increased in some areas by up to 3.6 days per decade over the past 50 years.¹⁹⁵⁵ *For additional information on changes in the length of the growing season, please see Chapter IV.2*

These differential responses across species indicate that climate change is altering the relative timing of species interactions and influencing which ontogenetic stages interact with each other.¹⁹⁵⁶ For example, a recent long-term study in the Netherlands showed different phenological responses to climate change for the relative timing of oak leaf unfolding, the peak biomass of caterpillars, the breeding of insectivorous birds and the breeding of an avian predator, resulting in the disruption of stage-structured interactions across four trophic levels.¹⁹⁵⁷

Western North America

Cayan et al. (2001) analyzed flowering data for honeysuckles and common purple lilacs in the western U.S., including data from Oregon, and reported earlier first bloom dates in the 1980s and 1990s as

¹⁹⁵⁰ Verbatim from Yang & Rudolf (2010, p. 1). Yang & Rudolf cite Dunn & Winkler (1999), Walther et al. (2002), Parmesan & Yohe (2003), and Gordo & Sanz (2005) for this information.

¹⁹⁵¹ Verbatim from Yang & Rudolf (2010, p. 1). Yang & Rudolf cite Visser & Both (2005), Miller-Rushing & Primack (2008), and Both et al. (2009) for this information.

¹⁹⁵² Verbatim from Yang & Rudolf (2010, p. 1). Yang & Rudolf cite Kudo et al. (2004) for this information.

¹⁹⁵³ Verbatim from Yang & Rudolf (2010, p. 1). Yang & Rudolf cite Beebee (1995), Parmesan & Yohe (2003), and Gordo & Sanz (2005), and Both et al. (2009) for this information.

¹⁹⁵⁴ Verbatim from Walther et al. (2002, p. 389). Walther et al. cite Gatter (1992) for information on birds and Menzel et al. (2001) for information on leaf coloring of trees.

¹⁹⁵⁵ Verbatim from Walther et al. (2002, p. 389). Walther et al. cite Menzel & Estrella (2001) and Menzel & Fabrian (1999) for this information.

¹⁹⁵⁶ Verbatim from Yang & Rudolf (2010, p. 1). Yang & Rudolf cite Visser & Both (2005), Memmott et al. (2007), and Both et al. (2009) for this information.

¹⁹⁵⁷ Verbatim from Yang & Rudolf (2010, p. 1). Yang & Rudolf cite Both et al. (2009) for this information.

compared with data from the 1960s and 1970s.¹⁹⁵⁸ They attributed these earlier bloom dates to increased spring temperatures across the region at the end of the 20th century.¹⁹⁵⁹

Another prominent example of phenological shifts revealed through long-term observations of lilac flowering indicates that the onset of spring has advanced one day earlier per decade across the Northern Hemisphere in response to increased winter and spring temperatures and by 1.5 days per decade earlier in the western U.S.¹⁹⁶⁰

Table 29. Evidence of recent phenological changes in various plant species.

Location	Observed Changes	Time Period	# of species observed	Sources (as provided by Khanduri et al.)
Hungary	0.2-0.6 days/decade earlier flowering	1851-1944 (144 years)	1	Walkovsky (1998)
Wisconsin	Earlier flowering by ~0.5-1.2 days/decade	1936-1998 (63 years)	25	Bradley et al. (1999)
Europe	1.7 days/decade leaf unfolding and 1.4 days/decade delayed leaf coloring and leaf fall	1959-1993 (35 years)	1	Menzel & Fabian (1999)
USA	1.7 days/decade earlier flowering and leaf unfolding	1959-1993 (35 years)	1	Schwartz & Reiter (2000)
Canada	2.7 days/decade earlier flowering	1900-1997 (98 years)	1	Beaubien & Freeland (2000)
Europe	1.7 days/decade earlier flowering and leaf unfolding and 1.2 days/decade delayed leaf coloring and leaf fall	1959-1996 (38 years)	1	Menzel (2000)
Washington DC	Flowering occurring 0.8-1.5 days/decade earlier	1970-1999 (30 years)	100	Abu-Asab et al. (2001)
Europe	2.7 days/decade earlier leaf unfolding and 0.8 days/decade delayed leaf fall	1969-1998 (30 years)	4	Chmielewski & Ratzer (2001)
England	Advance flowering by 4.5 days during the past decade compared to the previous four decades	1954-2000 (47 years)	385	Fitter & Fitter (2002)
Mediterranean region	Earlier flowering and leaf unfolding occurring by 1.2 & 3.3 days/decade and leaf fall by 2.7 days/decade later	1952-2000 (49 years)	64	Penuelas et al. (2002)
Japan	0.8 days/decade earlier leaf unfolding and 1.7 days/decade delayed leaf fall	1953-2000 (48 years)	1	Matsumoto et al. (2003)
Australia	Earlier flowering occurring 21 days/decade	1983-2002 (20 years)	4	Keatley et al. (2004)
China	Phenological growing season extended by 14 days/decade	1982-1993 (12 years)	--	Xiaoqiu (2004)

Source: Reproduced from Khanduri et al. (2008, Table 1, p. 144) by authors of this report.

Southcentral and Southeast Alaska

Information needed.

¹⁹⁵⁸ Nearly verbatim from Shafer et al. (2010, p. 177-178)

¹⁹⁵⁹ Verbatim from Shafer et al. (2010, p. 178)

¹⁹⁶⁰ Nearly verbatim from Staudinger et al. (2012, p. 2-14). Staudinger et al. cite Schwartz & others (2006) for information on the Northern Hemisphere and Ault & others (2011) for information on the western U.S.

Western British Columbia

Information needed.

Pacific Northwest

Across the Northwestern and interior Western U.S., time of first bloom for lilac and honeysuckle (*Lonicera tatarica* and *L. korolkowii*) showed a trend toward earlier flowering (average advances of 7.5 days for lilac and 10 for honeysuckle) over an almost 40-year period.¹⁹⁶¹ Earlier blooming was especially strong from 1970 to 1994 and corresponded with the pulse of spring snowmelt.¹⁹⁶²

Northwest California

Information needed.

Future Projections

Global

Please see Chapter VIII for information on global future projections for phenology in birds, invertebrates, and lichens and mosses.

Southcentral and Southeast Alaska

Information needed.

Western British Columbia

Information needed.

Pacific Northwest

Information needed.

Northwest California

Information needed.

Information Gaps

In contrast to spring, there is much less information available on autumn phenology.¹⁹⁶³

¹⁹⁶¹ Verbatim from Leicht-Young et al. (2013, p. 1). *Observed changes in phenology across the United States – Pacific Northwest: Washington, Oregon, and Idaho.*

¹⁹⁶² Verbatim from Leicht-Young et al. (2013, p. 1)

¹⁹⁶³ Verbatim from Khanduri et al. (2008, p. 145)

3. Altered growth & development

Climate change could affect the growth and development of plant and animal species in a multitude of ways, including:

- **Rising CO₂ concentrations will likely increase tree growth rates and carbon sequestration** through a fertilization effect in the short term, but increases may decline subsequently due to soil nutrient limitations.¹⁹⁶⁴ Enhanced CO₂ should also increase water-use efficiency (net carbon fixed per unit water) in both the short and long term.¹⁹⁶⁵ Increases in the length of the snow-free season and changes in atmospheric evaporative demand are likely to increase plant transpiration, assuming soil water is available.¹⁹⁶⁶
- **Effects on limiting factors:** Climatic variability can alter temperature or precipitation such that limiting factors (e.g., light, temperature, water, nutrients) are exacerbated or mitigated for years or decades at a time.¹⁹⁶⁷ Energy-limiting factors are chiefly light (e.g., in productive forests where competition reduces light to most individuals or climates where cloud cover limits light) and temperature (e.g., high-latitude or high-elevation forests).¹⁹⁶⁸ Plant growth is reduced when one or more resources are limiting.¹⁹⁶⁹ At broad scales, forests of western North America can be partitioned into two climatically mediated classes of limitation: energy-limited versus water-limited domains.¹⁹⁷⁰ Limiting factors can of course shift within a species range, or between seasons, as water demands abate and energy needs increase.¹⁹⁷¹ Limiting factors can therefore also be transient, particularly for populations at the transition between energy and water limitation.¹⁹⁷²
- **Effects on chilling and heating requirements:** For tree populations, climate change will not alter photoperiodic cues for growth cessation and bud set, but may delay the satisfaction of chilling requirements in winter, or accelerate the satisfaction of heat sum requirements, and may also change the degree of synchrony of reproductive bud development among populations, affecting the potential for long distance gene flow via pollen.¹⁹⁷³
- **Effects on successional pathways:** Beyond its direct effects on the dynamics of forest recovery through physiological mechanisms, climate change may also impact successional pathways indirectly by altering the frequency, timing, severity, and spatial extent of disturbances including fires, droughts, storms, floods, and herbivore or pathogen outbreaks.¹⁹⁷⁴ Changes in demographic

¹⁹⁶⁴ Verbatim from Aitken et al. (2008, p. 103). Aitken et al. cite Millard et al. (2007) for this information.

¹⁹⁶⁵ Verbatim from Aitken et al. (2008, p. 103)

¹⁹⁶⁶ Verbatim from Pike et al. (2010, p. 713)

¹⁹⁶⁷ Verbatim from Littell et al. (2010, p. 131)

¹⁹⁶⁸ Verbatim from Littell et al. (2010, p. 131)

¹⁹⁶⁹ Nearly verbatim from Littell et al. (2010, p. 131)

¹⁹⁷⁰ Verbatim from Littell et al. (2010, p. 131). Littell et al. cite Stephenson (1990, 1998), Milne et al. (2002), Running et al. (2004), Littell & Peterson (2005), and Littell et al. (2008) for this information.

¹⁹⁷¹ Verbatim from Littell et al. (2010, p. 131). Littell et al. cite Peterson & Peterson (2001) for information on shifts in limiting factors within a species range. Littell et al. cite Stephenson (1990, 1998) and Lutz (2008) for information on seasonal changes in limiting factors.

¹⁹⁷² Verbatim from Littell et al. (2010, p. 131)

¹⁹⁷³ Nearly verbatim from Aitken et al. (2008, p. 102)

¹⁹⁷⁴ Verbatim from Anderson-Teixeira et al. (2013, p. 10). Anderson-Teixeira et al. cite Dale et al. (2001), Westerling et al. (2006), Allen et al. (2010), and Sturrock et al. (2011) for this information.

rates, when compounded over time, can alter forest structure, composition, and function.¹⁹⁷⁵ Further, age- and species-dependent responses provide a mechanism by which climate change may push some forests past critical thresholds such that they fail to recover to their previous state following disturbance.¹⁹⁷⁶

- **Effects on migration:** Climatic impacts on migration are likely to be most important for the pre-breeding migration because timing of arrival in the breeding areas is critical.¹⁹⁷⁷ Moreover, any additional mortality, or loss of condition, will have a direct effect on breeding population size, unlike mortality on post-breeding migration, which may be compensated for by density-dependent mortality during the non-breeding period.¹⁹⁷⁸ For migratory animal species, the quality of habitats (i.e., those used for any part of migration) is particularly important for migrants that use a limited number of widely separated, and often highly productive, stop-over sites.¹⁹⁷⁹ Species that need to cross an ecological barrier, such as desert, mountains or ocean, require a large amount of high quality food in a short period of time to ensure they are able to cross the barrier and arrive in good physical condition.¹⁹⁸⁰ Failure to arrive in good condition may result in reduced survival or fecundity at later stages in the life-cycle, which may be exacerbated by positive feedback mechanisms, with individuals using the best non-breeding areas able to return to the best breeding sites, because they migrate earlier or faster.¹⁹⁸¹

Observed Trends

Global

Tree-ring records have revealed increasing growth rates in numerous forests including high-elevation forests in western Washington, conifers in the white mountains of California, ponderosa pine forests in the U.S. Pacific Northwest, aspen secondary forests in Wisconsin, fir and oak forests in France, and numerous other forests throughout Europe.¹⁹⁸² These increased growth rates are generally attributable to increased atmospheric CO₂, temperature, or moisture.¹⁹⁸³ In contrast, tree growth rates have decreased in response to warming or drought stress in many other forests around the world, including white spruce in

¹⁹⁷⁵ Verbatim from van Mantgem et al. (2009, p. 521). van Mantgem et al. cite Kobe (1996) for this information.

¹⁹⁷⁶ Nearly verbatim from Anderson-Teixeira et al. (2013, p. 1)

¹⁹⁷⁷ Verbatim from Robinson et al. (2008, p. 91). Robinson et al. cite Kokko (1999) for this information.

¹⁹⁷⁸ Verbatim from Robinson et al. (2008, p. 91)

¹⁹⁷⁹ Nearly verbatim from Robinson et al. (2008, p. 5)

¹⁹⁸⁰ Verbatim from Robinson et al. (2008, p. 91). Robinson et al. cite Berthold (2001) and Bairlein & Hüppop (2004) for this information.

¹⁹⁸¹ Verbatim from Robinson et al. (2008, p. 91). Robinson et al. cite Gill et al. (2001), Baker et al. (2004), and Norris et al. (2004) for information on the effects of failing to arrive in good condition. Robinson et al. cite Gunnarsson et al. (2005) for information on the effects of positive feedback mechanisms.

¹⁹⁸² Verbatim from Anderson-Teixeira et al. (2013, p. 8-9). Anderson-Teixeira et al. cite Graumlich et al. (1989) for information on western Washington, Lamarche et al. (1984) and Salzer et al. (2009) for information on California, Soulé & Knapp (2006) for information on ponderosa pine, Cole et al. (2010) for information on Wisconsin, Becker (1989) and Becker (1994) for information on France, and Spiecker (1999) and Babst et al. (2013) for information on other European forests.

¹⁹⁸³ Verbatim from Anderson-Teixeira et al. (2013, p. 9). Anderson-Teixeira et al. cite Graumlich et al. (1989), Soulé & Knapp (2006), Salzer et al. (2009), and Cole et al. (2010) for this information.

interior Alaska, conifers in the southwest United States, and tropical forests in Panama, Malaysia, and Costa Rica.¹⁹⁸⁴

Rates of forest recovery generally increase with CO₂, temperature, and water availability.¹⁹⁸⁵ For example, tree growth and carbon cycling in young forests are generally accelerated under combined CO₂, warmer, and wetter conditions.¹⁹⁸⁶ Drought reduces growth and live biomass in forests of all ages, having a particularly strong effect on seedling recruitment and survival.¹⁹⁸⁷ Responses of individual trees and whole-forest ecosystems to CO₂ and climate manipulations often vary by age, implying that forests of different ages will respond differently to climate change.¹⁹⁸⁸ Although there is strong evidence that CO₂ fertilization increases the rate of biomass accrual in young forests, a question remains as to whether elevated CO₂ increases the biomass and productivity of mature forests.¹⁹⁸⁹

Western North America

In the strongly maritime mountains in western North America, seed-based regeneration depends, as a rule, on the length of the snow-free season, whereas moisture conditions are the controlling factor in the drier regions.¹⁹⁹⁰ Koenig & Knops (2000) tested whether annual seed production (masting or mast fruiting) in Northern Hemisphere trees is an evolved strategy or a consequence of resource tracking by comparing masting patterns with those of annual rainfall and mean summer temperatures, two environmental variables likely to correlate with available resources.¹⁹⁹¹ In combination with the switching between growth and reproduction documented by Koenig and Knops (1998), as well as prior work on particular systems, Koenig & Knops' (2000) results support the hypothesis that annual seed production by forest trees is generally an evolved strategy.¹⁹⁹² Although seed production is often likely to be correlated with environmental factors in either case, temporal autocorrelation and patterns of variability do not strongly

¹⁹⁸⁴ Verbatim from Anderson-Teixeira et al. (2013, p. 9). Anderson-Teixeira et al. cite Allen et al. (2010) for information on global declines in tree growth rates in response to warming or drought stress, Barber et al. (2000) for information on white spruce in Alaska, Williams et al. (2013) for information on conifers in the southwest U.S., and Feeley et al. (2007b) and Clark et al. (2010) for information on tropical forests.

¹⁹⁸⁵ Verbatim from Anderson-Teixeira et al. (2013, p. 1)

¹⁹⁸⁶ Nearly Verbatim from Anderson-Teixeira et al. (2013, p. 8). Anderson-Teixeira et al. refer the reader to Tables S1-S3 in the cited article for this information. Anderson-Teixeira et al. also cite Wan et al. (2004), Comstedt et al. (2006), Slaney et al. (2007), Tingey et al. (2007), and Bauweraerts et al. (2013) for this information.

¹⁹⁸⁷ Verbatim from Anderson-Teixeira et al. (2013, p. 1)

¹⁹⁸⁸ Verbatim from Anderson-Teixeira et al. (2013, p. 1)

¹⁹⁸⁹ Nearly verbatim from Anderson-Teixeira et al. (2013, p. 5). Anderson-Teixeira refer the reader to Figure 1 in the cited article for this information. Anderson-Teixeira also cite Körner et al. (2005), Hyvönen et al. (2007), and Norby & Zak (2011) for this information.

¹⁹⁹⁰ Nearly verbatim from Holtmeier & Broll (2005, p. 402-403). Holtmeier & Broll cite Fonda & Bliss (1969), Kuramoto & Bliss (1970), Woodward et al. (1995), Holmgren & Tjus (1996), Rochefort & Peterson (1996), Peterson (1998), Holtmeier (2000, 2003), and Holtmeier et al. (2003) for this information.

¹⁹⁹¹ Nearly verbatim from Koenig & Knops (2000, p. 59). *Patterns of annual seed production by Northern Hemisphere trees: A global perspective.*

¹⁹⁹² Nearly verbatim from Koenig & Knops (2000, p. 67). Koenig & Knops cite Norton & Kelly (1988), Sork et al. (1993), Kelly (1994), and Tapper (1996) for information on prior work on similar systems. *Note: The in-text citation for Koenig & Knops (1998) is that cited by Koenig & Knops (2000). In the cited article, the exact citation is for Koenig & Knops (1998a).*

match those exhibited by either annual rainfall or mean temperature, two environmental factors likely to correlate with available resources in a given year.¹⁹⁹³

The large geographic scale on which seed production patterns are often synchronized, both within and between genera, has important implications for wildlife populations dependent on the seeds of forest trees for food.¹⁹⁹⁴ In general, resident populations of birds and mammals dependent on mast are likely to be affected synchronously over large geographic areas by both bumper crops providing abundant food and, perhaps even more dramatically, by crop failures.¹⁹⁹⁵

Southcentral and Southeast Alaska

Information needed.

Western British Columbia

Information needed.

Western Washington

Information needed.

Western Oregon

Information needed.

Northwest California

Throughout the coast redwood ecosystem (i.e., north to central California coast), nocturnal foliar uptake increased the leaf water content of western sword fern by 7.2%, and Limm & Dawson (2010) estimated that the western sword fern canopy can absorb $5 \pm 3\%$ (mean \pm standard error) of intercepted fog precipitation.¹⁹⁹⁶ Strikingly, western sword fern had the highest foliar uptake capacity in the center of the ecosystem and may absorb 10% more of the fog its canopy intercepts in this region relative to other regions studied.¹⁹⁹⁷ Specifically, the summertime water subsidy potentially obtained through fog drip acquisition appears 10% higher in the center of the redwood forest range than in the north where total canopy area for fog drip interception is higher or in the south where water is more limiting and demand for fog may be greater.¹⁹⁹⁸ Conversely, western sword fern had no foliar uptake capacity in the southern end of the ecosystem.¹⁹⁹⁹ These findings suggest that the western sword fern at the southern tip of the redwood ecosystem (i.e., central California coast) may suffer most from low summertime water availability because it had no potential to acquire fog as an aboveground water subsidy.²⁰⁰⁰

¹⁹⁹³ Verbatim from Koenig & Knops (2000, p. 67-68)

¹⁹⁹⁴ Nearly verbatim from Koenig & Knops (2000, p. 68)

¹⁹⁹⁵ Verbatim from Koenig & Knops (2000, p. 68)

¹⁹⁹⁶ Nearly verbatim from Limm & Dawson (2010, p. 1121)

¹⁹⁹⁷ Verbatim from Limm & Dawson (2010, p. 1121)

¹⁹⁹⁸ Nearly verbatim from Limm & Dawson (2010, p. 1125)

¹⁹⁹⁹ Verbatim from Limm & Dawson (2010, p. 1121)

²⁰⁰⁰ Nearly verbatim from Limm & Dawson (2010, p. 1121)

Future Projections

Global

For tree populations, widespread species with high fecundity occurring in large populations will likely be able to adapt to climate change in relatively few generations, and will likely survive in the interim as major competitors will be facing the same fate of short-term maladaptation.²⁰⁰¹ High rates and distances of seed and pollen dispersal will also contribute positively to their capacity to both adapt and migrate.²⁰⁰² Species that occur in small, fragmented populations, or those with low fecundity or late age of sexual maturity, reproductive characteristics more typical of later successional species and high-elevation habitats, will likely suffer greater adaptational lag.²⁰⁰³

Quintero & Wiens (2013) estimated absolute rates of climatic niche evolution for 540 species in 17 clades of terrestrial vertebrates, including groups of mammals, birds, lizards, snakes, turtles, crocodylians, salamanders, and frogs (2090–2100 vs. 2000; six GCMs run under A2).²⁰⁰⁴ Matching projected changes for 2100 would require rates of niche evolution that are greater than 10,000 times faster than rates typically observed among species, for most variables and clades.²⁰⁰⁵

Western North America

Populations of temperate and boreal trees show moderate to strong clines (i.e., gradual phenotypic or genetic differences in a species over a geographic area) in phenology and growth along temperature gradients, indicating substantial local adaptation.²⁰⁰⁶ Many ecologically and economically important genera in temperate and boreal regions contain species pairs capable of interspecific hybridization (i.e., typically, hybrids formed from two species in the same genus), including spruce, pine, poplar, and oak.²⁰⁰⁷ This possibility is of particular interest in western North America, where several pairs of maritime and more continental taxa have distributions largely separated by major north–south mountain ranges, but have some opportunity for genetic contact through a few major east–west river valleys or over the crest of lower parts of these ranges (e.g., Sitka spruce and white spruce, lodgepole pine and jack pine, and coast Douglas-fir and Rocky Mountain Douglas-fir).²⁰⁰⁸ Hybridization followed by backcrossing (i.e., crossing a hybrid with one of its parents or a genetically similar individual to achieve genetic composition closer to the parent) or further introgression (i.e., movement of a gene from one species into the gene pool of another through repeated backcrossing) and selection (i.e., for a particular gene or trait) can lead to transgressive segregation (i.e., extreme phenotypes), whereby some individuals can have phenotypes

²⁰⁰¹ Nearly verbatim from Aitken et al. (2008, p. 107–108)

²⁰⁰² Verbatim from Aitken et al. (2008, p. 108)

²⁰⁰³ Verbatim from Aitken et al. (2008, p. 108)

²⁰⁰⁴ Nearly verbatim from Quintero & Wiens (2013, p. 1096). *Rates of projected climate change dramatically exceed past rates of climatic niche evolution among vertebrate species.*

²⁰⁰⁵ Nearly verbatim from Quintero & Wiens (2013, p. 1095)

²⁰⁰⁶ Nearly verbatim from Aitken et al. (2008, p. 95)

²⁰⁰⁷ Nearly verbatim from Aitken et al. (2008, p. 101)

²⁰⁰⁸ Verbatim from Aitken et al. (2008, p. 101). Aitken et al. cite Benuah et al. (2004) for information on Sitka and white spruce, Rweyongeza et al. (2007) for information on lodgepole and jack pine, and St. Clair et al. (2005) for information on Coast and Rocky Mountain Douglas-fir.

outside of the range of parental species due to complementary allelic effects.²⁰⁰⁹ This may offer a rapid evolutionary path to adaptation to novel environments, as demonstrated for sunflower species.²⁰¹⁰

Southcentral and Southeast Alaska

Information needed.

Western Washington

Information needed.

Western Oregon

Information needed.

Northwest California

Given that winter precipitation input to California ecosystems will likely change in the coming decades, understanding the fog drip acquisition potential of fern populations may aid predicting how western sword fern abundance will be affected by climate change.²⁰¹¹ If rainfall decreases, western sword fern may rely more on fog water during the summer months to sustain the current frond size, crown density, and total canopy cover.²⁰¹² If foliar uptake is a plastic trait, fog drip absorption efficiency may increase in response to higher demand for fog if rainfall decreases.²⁰¹³ However, if western sword fern differs genotypically in foliar uptake capacity in the ecosystem today, climatic changes may drive local extinctions of populations unable to efficiently absorb fog water as demand for water increases.²⁰¹⁴ Because western sword fern depends on fog-water subsidies to maintain optimal summertime water status in many areas, the future canopy cover and distribution of western sword fern in the redwood forest ecosystem may change with further fog loss, affecting the understory ecosystem it helps define.²⁰¹⁵

Information Gaps

Systematic comparison of responses of forests of different ages to experimental CO₂ or climate manipulation and to natural climate variability will be crucial to understanding and modeling climate change impacts on forests of all ages.²⁰¹⁶ It will also be important to understand how altered biogeochemical dynamics and community composition shape successional pathways and the states toward which forests converge as they mature.²⁰¹⁷

Although detailed representation of forest recovery dynamics in global models is infeasible, Anderson-Teixeira et al. (2013) believe that two advances will be important to improving the treatment of forest

²⁰⁰⁹ Nearly verbatim from Aitken et al. (2008, p. 101). Aitken et al. cite Lexer et al. (2004) for this information.

²⁰¹⁰ Verbatim from Aitken et al. (2008, p. 101). Aitken et al. cite Rieseberg et al. (2003) for this information.

²⁰¹¹ Verbatim from Limm & Dawson (2010, p. 1126). Limm & Dawson cite Hayhoe et al. (2004) and Loarie et al. (2008, 2009) for this information.

²⁰¹² Verbatim from Limm & Dawson (2010, p. 1126)

²⁰¹³ Verbatim from Limm & Dawson (2010, p. 1126)

²⁰¹⁴ Verbatim from Limm & Dawson (2010, p. 1126)

²⁰¹⁵ Verbatim from Limm & Dawson (2010, p. 1126)

²⁰¹⁶ Verbatim from Anderson-Teixeira et al. (2013, p. 16)

²⁰¹⁷ Nearly verbatim from Anderson-Teixeira et al. (2013, p. 16)

regeneration.²⁰¹⁸ First, the most important stand age-dependent physiology and allocation strategies (driven by aging of dominant species and changes in species composition) should be identified and incorporated.²⁰¹⁹ Second, although modeling individual species in ecosystem and earth system models is infeasible, it will be necessary to represent the consequences of demonstrated variability in species responses to climate change and inevitable resultant shifts in community composition and ecosystem processes.²⁰²⁰

²⁰¹⁸ Nearly verbatim from Anderson-Teixeira et al. (2013, p. 16)

²⁰¹⁹ Verbatim from Anderson-Teixeira et al. (2013, p. 16)

²⁰²⁰ Verbatim from Anderson-Teixeira et al. (2013, p. 16)

4. Shifts in biodiversity, species richness, abundance, competition, survival & community composition

Climate change impacts on biodiversity are projected to increase in magnitude and pervasiveness as CO₂ levels and temperatures continue to rise, and extreme events (for example, heat and storms) increase in frequency and intensity.²⁰²¹ Climate change will increase the vulnerability of species across the globe to population loss and extinction.²⁰²² Species confronting rapid environmental change will either go extinct or survive in one of three ways: by acclimatizing, evolving, or migrating to suitable habitats elsewhere.²⁰²³ Often, more than one of these responses will occur concurrently.²⁰²⁴ The extinction risk increases if suitable habitat conditions either disappear entirely or, as is more likely, if habitats shift more rapidly than resident species can migrate.²⁰²⁵ For many organisms, evolution probably will not occur rapidly enough to keep up with the current and anticipated rapid pace of climate change, especially if habitats have already been degraded by various land uses.²⁰²⁶

Paleoecological evidence indicates that species respond individually to climate change; and thus, the mix of species with which any one species interacts will change as climate changes.²⁰²⁷ Changing species distributions may bring a species into contact with other taxa with which it has never interacted, and entirely new competitive interactions may result.²⁰²⁸ Conversely, climate change may eliminate an important predator, allowing a species to greatly expand its range.²⁰²⁹ Perhaps the most significant interspecies interaction will be with humans due to the impact of our land-use activities on habitat and species distributions and abundances.²⁰³⁰

Key Terms in this Section

Abundance: *total number of individuals of a given taxon or taxa in an area, population, or community*

Biodiversity: *the variability among living organisms from all sources, including diversity within species, between species, and between ecosystems*

Ecological community: *an assemblage of species often linked by biotic interactions such as competition or predation and occurring in the same space or time*

Ecological surprises: *unexpected and often disproportionately large consequences of changes in the abiotic or biotic environment*

Hybridization: *the blending or homogenization of genetically distinct linkages, occasionally resulting in the development of a new species*

Keystone species: *species exerting a disproportionately large influence on ecosystems, larger than would be expected from their abundance*

Sources: Millenium Ecosystem Assessment (2005), Pojar (2010)

²⁰²¹ Verbatim from Staudinger et al. (2012, p. 2-20). Staudinger et al. cite IPCC (2007) for this information.

²⁰²² Verbatim from Klausmeyer et al. (2011, p. 1)

²⁰²³ Verbatim from Pojar (2010, p. 30)

²⁰²⁴ Verbatim from Running & Mills (2009, p. 11)

²⁰²⁵ Verbatim from Pojar (2010, p. 26). Pojar cites Williams et al. (2007) for information on extinction risk related to the disappearance of habitat and Parmesan (2006) for information on extinction risk related to shifts in habitat.

²⁰²⁶ Verbatim from Pojar (2010, p. 26). Pojar cites Jump & Peñuelas (2005) for information on the pace of evolution compared to the current and anticipated rapid pace of climate change.

²⁰²⁷ Verbatim from Shafer et al. (2011, p. 212). Shafer et al. cite Webb (1995) and Huntley (1995) for information on species individualistic response to climate change.

²⁰²⁸ Verbatim from Shafer et al. (2011, p. 212)

²⁰²⁹ Verbatim from Shafer et al. (2011, p. 212-3)

²⁰³⁰ Verbatim from Shafer et al. (2011, p. 213). Shafer et al. cite Dale (1997) for this information.

Climate change is having both direct and indirect effects on the way species interact over spatial and temporal scales, with sometimes profound impacts on ecosystem structure and function.²⁰³¹ Species interactions often influence responses to climate and climate-related traits can evolve rapidly.²⁰³² Adaptation to new climates could moderate the dire predictions of biodiversity loss whereas species interactions could enhance or diminish extinction risks depending on interaction type.²⁰³³ As species tend to respond to climate change in very individualistic ways, one of the main impacts of climate change on animal populations will be mediated through the synchrony with their food and habitat resources.²⁰³⁴ Altered synchrony between prey and predators will generally have negative fitness consequences on predator populations.²⁰³⁵ The fertilization effect of increased CO₂ concentrations could significantly alter competitive interactions among species.²⁰³⁶ Higher temperatures can affect food-web interactions by increasing vital rates such as growth and consumption.²⁰³⁷

For migratory species, as with any environmental change, inevitably there will be winners and losers.²⁰³⁸ The winners are likely to be those species with greater phenotypic flexibility that use widespread habitats and perhaps display weaker migratory connectivity (individuals from one breeding population may migrate to one of many non-breeding areas and vice versa).²⁰³⁹ Thus, common species are likely to become commoner, and scarce species scarcer, resulting in a general decline in biodiversity.²⁰⁴⁰

More Key Terms in this Section

Phenotype: *an individual's observable characteristics, resulting from the interaction of its genotype (i.e., the genetic composition of an organism) with the environment*

Phenotypic plasticity: *within a genotype, modification of an individual's phenotype across a reaction norm and expressed via changes in behavior, morphology, or physiology; also known as acclimation, especially when referring to plants*

Relative abundance: *total number of individuals in a taxon compared with the total number of individuals of all other taxa in an area, volume, or community*

Species richness: *the number of species within a given sample, community, or area*

Threshold: *a point or level at which new properties emerge in a system*

Sources: Millenium Ecosystem Assessment (2005), Pojar (2010), Running & Mills (2009)

²⁰³¹ Verbatim from Staudinger et al. (2012, p. 2-18). Staudinger et al. cite Walther (2010), Singer & Parmesan (2010), and Yang & Rudolf (2010) for this information.

²⁰³² Verbatim from Norberg et al. (2012, p. 747). *Eco-evolutionary responses of biodiversity to climate change*. Norberg et al. cite Tylianakis et al. (2008) for information on species interactions influencing responses to climate and Franks et al. (2007) and Balanya et al. (2006) for information on rapid evolution of climate-related traits.

²⁰³³ Verbatim from Norberg et al. (2012, p. 747). Norberg et al. cite Skelly et al. (2007) for information on adaptation moderating dire predictions of biodiversity loss and Brooker et al. (2007) and Münkemüller & Bello (2011) for information on the role of species interactions in extinction risk.

²⁰³⁴ Verbatim from Lavergne et al. (2010, p. 332). Lavergne et al. refer the reader to the next section in the cited article for information on individualistic species responses to climate change. Lavergne et al. cite Parmesan (2006) for a review of this information.

²⁰³⁵ Verbatim from Lavergne et al. (2010, p. 332). Lavergne et al. cite Visser & Both (2005) for this information.

²⁰³⁶ Verbatim from Shafer et al. (2011, p. 213)

²⁰³⁷ Verbatim from Staudinger et al. (2012, p. 2-18)

²⁰³⁸ Verbatim from Robinson et al. (2008, p. 92)

²⁰³⁹ Verbatim from Robinson et al. (2008, p. 92)

²⁰⁴⁰ Verbatim from Robinson et al. (2008, p. 92). Robinson et al. cite Warren et al. (2001) and Julliard et al. (2004) for this information.

Human-induced global change is causing ecological communities to rapidly lose some species and gain others, resulting in interchanges of species, their traits and interactions, and alteration of ecosystem functioning and services.²⁰⁴¹ Species gain is derived from colonization and establishment of new species, processes that are increasing in frequency and intensity at global scales via cross-continental introduction, land use change, and climate warming, with demonstrated effects at the ecosystem level.²⁰⁴²

Populations isolated geographically or environmentally from the main range of their species can evolve genetically distinct races or subspecies.²⁰⁴³ Climate change could increase between-population genetic diversity, insofar as insularity increases (for example, in the alpine zone as treeline moves upward, or on the coast as sea level rises), as disjunctions increase (for example, by long-distance dispersal), or as currently continuous, widespread species distributions become fragmented.²⁰⁴⁴ Hybridization probably will increase as climate changes, as species and populations migrate and come into contact with related species or populations from which they were previously isolated, and as habitats themselves become mixed up, recombined, and effectively hybridized.²⁰⁴⁵ Although this mechanism has the potential to help species persist as environmental conditions change, an increase in interspecific hybridization could reduce species richness and diversity, and has important consequences for ecosystem function.²⁰⁴⁶

Community composition responds to a complex set of factors including the direct effects of climate, differential species dispersal, and indirect effects associated with changes in disturbance regimes, land use, and interspecific interactions.²⁰⁴⁷ Despite a general trend for species expanding their ranges northward and/or upward or advancing their phenology, the signature of environmental change on communities seems to be driven by a subset of highly responsive species.²⁰⁴⁸ This heterogeneity in species responses to climate change will strongly alter the composition of local communities and induce the formation of non-analog communities, where extant species co-occur in historically unknown combinations.²⁰⁴⁹ However, in many systems, the observed state of the community is not the only possible stable state; a variety of empirical results demonstrate the existence of alternative stable states in

²⁰⁴¹ Verbatim from Wardle et al. (2011, p. 1273)

²⁰⁴² Verbatim from Wardle et al. (2011, p. 1273). Wardle et al. refer the reader to Figure 2 in the cited article for this information.

²⁰⁴³ Verbatim from Pojar (2010, p. 36)

²⁰⁴⁴ Nearly verbatim from Pojar (2010, p. 36). Pojar cites Krajick (2004) for information on insularity in the alpine zone.

²⁰⁴⁵ Nearly verbatim from Pojar (2010, p. 38). Pojar cites Anderson (1948) for this information.

²⁰⁴⁶ Verbatim from Staudinger et al. (2012, p. 2-18). Staudinger et al. cite Seehausen & others (2008) for this information.

²⁰⁴⁷ Verbatim from Joyce et al. (2001, p. 504). Joyce et al. cite Peters (1992) for this information.

²⁰⁴⁸ Verbatim from Lavergne et al. (2010, p. 332). Lavergne et al. cite Parmesan (2006) and Parmesan & Yohe (2003) for information on range expansion and advancing phenology. Lavergne et al. cite Cleland et al. (2006), Lavergne et al. (2005b, 2006), le Roux & McGeoch (2008), Miller-Rushing et al. (2008), Miller-Rushing & Primack (2008), and Tingley et al. (2009) for information on the signature of environmental change being driven by a subset of highly responsive species.

²⁰⁴⁹ Verbatim from Lavergne et al. (2010, p. 332). Lavergne et al. cite Hobbs et al. (2009) and Kullman (2006) for this information.

nature.²⁰⁵⁰ Systems that are structured by disturbance and are susceptible to abiotic forcing (such as regenerating forests) may be more likely to display alternative stable states.²⁰⁵¹

Observed Trends

Global

In general, land use change has been the main driver of terrestrial biodiversity loss during the past century.²⁰⁵² For example, conversion of relatively undisturbed terrestrial ecosystems to agricultural, urban systems or other highly human dominated systems, also referred to as “habitat loss”, is currently the main driver of changes in species abundance globally.²⁰⁵³ Because local-scale losses of native species and ingress of new species occur simultaneously, both net gains and losses of species richness are occurring.²⁰⁵⁴ Although the Earth is experiencing substantial losses of biodiversity at the global level, both increases and decreases in community diversity are commonly observed at regional and local scales.²⁰⁵⁵

The well documented no-analog plant communities (i.e., communities that are compositionally unlike any found today) of late-glacial North America are closely linked to “novel” climates also lacking modern analogs, characterized by high seasonality of temperature.²⁰⁵⁶ No-analog fossil assemblages are pervasive in Quaternary paleoecological records (i.e., from approximately 2.6 million years ago to the present), documented for plants, mammals, coleopterans (i.e., beetles), mollusks, and foraminifera.²⁰⁵⁷

Southcentral and Southeast Alaska

The muskrat feeds on sedges, which benefit (due to their use of C₃ photosynthetic pathway) as warming continues, while competitors feeding on grasses (C₄ photosynthetic pathway) will be at a disadvantage.²⁰⁵⁸ *For additional information on observed trends for mammals and birds in southcentral and southeast Alaska, please see Chapter VIII.1 and VIII.2, respectively.*

²⁰⁵⁰ Nearly verbatim from Anderson-Teixeira et al. (2013, p. 10). Anderson-Teixeira et al. cite D’Antonio & Vitousek (1992), Savage & Mast (2005), Schröder et al. (2005), Odion et al. (2010), and Scheffer et al. (2012) for this information.

²⁰⁵¹ Nearly verbatim from Anderson-Teixeira et al. (2013, p. 10). Anderson-Teixeira et al. cite Didham et al. (2005) for this information.

²⁰⁵² Verbatim from Leadley et al. (2010, p. 12). *Biodiversity scenarios: Projections of 21st century change in biodiversity and associated ecosystem services.*

²⁰⁵³ Nearly verbatim from Leadley et al. (2010, p. 15)

²⁰⁵⁴ Verbatim from Wardle et al. (2011, p. 1273). Wardle et al. cite Sax & Gaines (2003) and Bardgett & Wardle (2010) for this information.

²⁰⁵⁵ Verbatim from Wardle et al. (2011, p. 1273). Wardle et al. cite the Millenium Ecosystem Assessment (2005) for information on global biodiversity loss and Sax & Gaines (2003) for information on changes in community diversity at regional and local scales.

²⁰⁵⁶ Nearly verbatim from Williams & Jackson (2007, p. 475)

²⁰⁵⁷ Nearly verbatim from Williams & Jackson (2007, p. 476-477). Williams & Jackson cite Overpeck et al. (1992) and Jackson & Williams (2004) for information on plants, Stafford et al. (1999) and Graham (2005) for information on mammals, Morgan & Morgan (1980) for information on coleopterans, Kitamura (2004) for information on mollusks, and Cannariato et al. (1999) and Mix et al. (1999) for information on foraminifera.

²⁰⁵⁸ Nearly verbatim from Kelly et al. (2007, p. 63). Kelly et al. cite Inkley et al. (2004) for this information.

Western British Columbia

In British Columbia, the majority of the forest-associated red-listed species occur in the Coastal Western Hemlock, Coastal Douglas-fir, and Interior Douglas-fir biogeoclimatic zones (Figure 57).²⁰⁵⁹ Specifically, the four lower elevation biogeoclimatic zones (Coastal Douglas-fir, Bunchgrass, Ponderosa Pine, Interior Douglas-fir) of southern B.C. host the most species diversity and concentrations of species at risk.²⁰⁶⁰ The same four zones plus parts of the Coastal Western Hemlock zone, particularly Vancouver Island and Haida Gwaii (both heavily logged), are most significant with respect to stewardship species (i.e., the ~100 of the 3,841 species assessed for conservation status in B.C. that have all or >50% of their global range, area, or population within B.C.²⁰⁶¹).²⁰⁶² *Additional species-specific information for caribou, moose, elk, grizzly bear, cougar, Vancouver Island marmot, Pacific water shrew, spotted owl, pileated woodpecker, and marbled murrelet is available and can be found in Chapter VIII.1 (Mammals) and VIII.2 (Birds).*

Pacific Northwest

Information needed.

Klamath Mountains

The coniferous and mixed evergreen forests of the Klamath-Siskiyou region are widely recognized for their globally outstanding levels of biodiversity.²⁰⁶³ Most native species and communities have evolved with fire and many are adapted to, if not dependent on, fire's periodic occurrence.²⁰⁶⁴

Northwest California

Information needed.

Future Projections

Global

To date, only a few species of amphibians, birds, fishes, and gastropods are known to have gone extinct due to the impacts of climate change; however, widespread losses of global biodiversity are projected by numerous studies using a range of modeling approaches and climate scenarios.²⁰⁶⁵ For example, in the short term, increasing temperatures are likely to lead to increased resource availability in northern polar

²⁰⁵⁹ Nearly verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 66)

²⁰⁶⁰ Nearly verbatim from Pojar (2010, p. 27)

²⁰⁶¹ Pojar (2010, p. 26) cites Austin et al. (2008) for this information and notes "B.C. has stewardship responsibility for all of its species known to have more than 50% of their range in the province. However, only 3,841 of B.C.'s 50,000 species have been assessed. Therefore, many other species may have more than 50% of their range in the province, and we just don't know that yet" (Pojar 2010, footnote 185, p. 85).

²⁰⁶² Nearly verbatim from Pojar (2010, p. 27)

²⁰⁶³ Verbatim from Frost & Sweeney (2000, p. 3). Frost & Sweeney cite DellaSala et al. (1999), Wagner (1997), and Whittaker (1961) for this information.

²⁰⁶⁴ Verbatim from Frost & Sweeney (2000, p. 2). Frost & Sweeney cite Barbour & Minnich (1999), Martin (1997), and Kauffman (1990) for this information.

²⁰⁶⁵ Verbatim from Staudinger et al. (2012, p. 2-22 to 2-23). Staudinger et al. cite Monzón & others (2011) for information on species extinctions due to climate change to date.

regions and hence increased populations, but, in the longer term, it is thought likely that many species will experience significant resource or habitat loss.²⁰⁶⁶

Global biodiversity models project that terrestrial species extinctions (Figure 61), loss of natural habitat, and changes in the distribution and abundance of species, species groups and biomes will continue throughout this century, with land use change being the main threat in the short term, and climate change becoming progressively much more important over the next several decades.²⁰⁶⁷ Future extinctions could be worse than projected in the most pessimistic scenarios in Figure 61 because the non-linear dynamics of tipping points have not been fully accounted for.²⁰⁶⁸ Global models project that mean species abundance will decrease during the first half of the century between 9% and 17% (Figure 60).²⁰⁶⁹

Specific results include:

- Using quantitative projections of changes in land use and climate from the four Millennium Ecosystem Assessment scenarios, results from van Vuuren et al. (2006) show that in tundra, boreal forests, and cool conifer forest, climate change is projected to be the major cause of biodiversity loss, varying from 5% to almost 15% species loss at equilibrium.²⁰⁷⁰ Note, however, that for these biomes, land-use change has relatively low impact in comparison with other biomes.²⁰⁷¹ In contrast, land-use change is the main driver of biodiversity loss in temperate forests, warm mixed forests, savannah, and tropical forest, leading to a 7% to nearly a 25% species loss at equilibrium.²⁰⁷² The contribution of climate change for plant diversity loss in these ecosystems varies between 1% and 7% loss of species.²⁰⁷³ After 2050, climate change will become increasingly important.²⁰⁷⁴
- In a study projecting extinctions of endemic species from global biodiversity hotspots, Malcolm et al. (2006) projected percent extinctions ranged from <1 to 43% of the endemic biota (average 11.6%), with biome specificity having the greatest influence on the estimates (i.e., narrowly or broadly defined), followed by the global vegetation model (i.e., either MAPSS or BIOME3) and then by migration and biome classification assumptions (2 x CO₂ vs. 1 x CO₂, where CO₂ is an undefined current level; 14 scenarios run with MAPSS and BIOME3 and seven GCMs).²⁰⁷⁵
- Using projections of species' distributions for future climate scenarios (i.e., a climate-envelope model approach), Thomas et al. (2004) found minimum expected climate change scenarios for 2050 produce fewer projected "committed extinctions" (18%; average of three area methods and two dispersal

²⁰⁶⁶ Verbatim from Robinson et al. (2008, p. 89). Robinson et al. cite Jensen et al. (2008) for information on the effects of increasing temperatures in the short-term, and Zöckler & Lysenko (2000) and Meltofte et al. (2007) for information on the effects of increasing temperature in the longer term.

²⁰⁶⁷ Verbatim from Leadley et al. (2010, p. 11)

²⁰⁶⁸ Nearly verbatim from Leadley et al. (2010, p. 14). Leadley et al. are referring to Figure 2 in the cited report for this information. Leadley et al. also refer the reader to the following sections of the cited report for additional information on tipping points..

²⁰⁶⁹ Verbatim from Leadley et al. (2010, p. 15). Leadley et al. refer the reader to Figure 5A in the cited report for this information.

²⁰⁷⁰ Nearly verbatim from van Vuuren et al. (2006, p. 33)

²⁰⁷¹ Verbatim from van Vuuren et al. (2006, p. 33)

²⁰⁷² Verbatim from van Vuuren et al. (2006, p. 33)

²⁰⁷³ Verbatim from van Vuuren et al. (2006, p. 33)

²⁰⁷⁴ Nearly verbatim from van Vuuren et al. (2006, p. 25)

²⁰⁷⁵ Nearly verbatim from Malcolm et al. (2006, p. 538). *Global warming and extinctions of endemic species from biodiversity hotspots.*

scenarios, universal and no dispersal; CO₂ = 500 ppm by volume, ppmv) than mid-range projections (24%; CO₂ = 500-550 ppmv), and about half of those predicted under maximum expected climate change (35%; CO₂ > 550 ppmv).²⁰⁷⁶ It should also be kept in mind that most models project the proportion of species that are “committed to extinction” at some future time because their habitat or range size shrinks, but the lag time between becoming “committed to extinction” and actually going extinct may range from decades to many millennia.²⁰⁷⁷

In both studies, (i.e., Malcolm et al. 2006 and Thomas et al. 2004) extinction risks were higher when species were modeled under limited dispersal scenarios, situations that reflect both the inherent biological constraints of many organisms and the ways in which habitat fragmentation may impede species dispersal.²⁰⁷⁸ van Vuuren et al. (2006) found that land-use change rather than climate change is likely a more dominant driver of biodiversity loss in the next fifty years, consistent with the qualitative assessment of Sala et al. (2000), but inconsistent with the results of Thomas et al. (2004).²⁰⁷⁹

In an assessment of climate-induced change in the geographic ranges of 2,954 species of birds, mammals, and amphibians in the Western Hemisphere (2071-2100 vs. 1961-1990; 30 AOGCMs run with B1 and A2), although all three taxonomic groups (birds, mammals, amphibians) were predicted to experience large changes at high northern latitudes, and in the Andes, Mexico, and Central America, amphibians were uniquely predicted to also undergo a high degree of turnover in the central and eastern United States.²⁰⁸⁰ The largest changes in fauna are predicted for the tundra, Central America, and the Andes Mountains where, assuming no dispersal constraints, specific areas are likely to experience over 90% turnover, so that faunal distributions in the future will bear little resemblance to those of today.²⁰⁸¹

No-analog communities (communities that are compositionally unlike any found today) occurred frequently in the past and will develop in the greenhouse world of the future.²⁰⁸² In climate simulations for the IPCC A2 and B1 emission scenarios (2080-2099 vs. 1980-1999), novel climates arise by 2100 AD, primarily in tropical and subtropical regions.²⁰⁸³ These future novel climates are warmer than any present climates globally, with spatially variable shifts in precipitation, and increase the risk of species reshuffling into future no-analog communities and other ecological surprises.²⁰⁸⁴ Individualistic species dynamics and the formation of no-analog communities can be explained by a niche-based conceptual framework (Figure 59).²⁰⁸⁵

²⁰⁷⁶ Nearly verbatim from Thomas et al. (2004, p. 147)

²⁰⁷⁷ Verbatim from Leadley et al. (2010, p. 14). Leadley et al. cite Sala et al. (2005) for this information.

²⁰⁷⁸ Nearly verbatim from Staudt et al. (2012, p. 5-13)

²⁰⁷⁹ Verbatim from van Vuuren et al. (2006, p. 37)

²⁰⁸⁰ Nearly verbatim from Lawler et al. (2009, p. 592). *Projected climate-induced faunal change in the Western Hemisphere.*

²⁰⁸¹ Verbatim from Lawler et al. (2009, p. 588)

²⁰⁸² Verbatim from Williams & Jackson (2007, p. 475)

²⁰⁸³ Verbatim from Williams & Jackson (2007, p. 475)

²⁰⁸⁴ Verbatim from Williams & Jackson (2007, p. 475)

²⁰⁸⁵ Verbatim from Williams & Jackson (2007, p. 476). Williams & Jackson refer the reader to Figure 1 in the cited article for this information. Williams & Jackson also cite Jackson & Overpeck (2000) for this information.

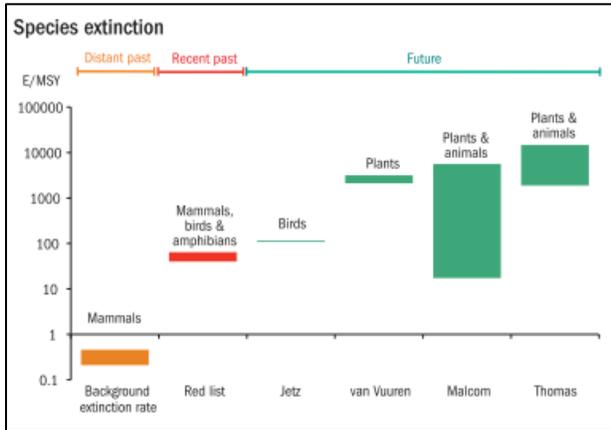


Figure 61. Historical extinction rates and scenario projections for the 21st century. Extinctions per million species years (E/MSY) for distant past, recent past and future. “Distant past” refers to the background extinction rate of mammals obtained from the fossil record (MA 2005). “Recent past” refers to documented extinctions registered in the 20th century, by the Red List — mammals (upper bound), amphibians (lower bound) and birds (in between) (Baillie et al. 2004). “Future” refers to projections of species “committed to extinction” according to different global scenarios: birds (Jetz et al. 2007, for the period of 2000–2050), vascular plants (van Vuuren et al. 2006 for the period 1995–2050) and various taxa (Thomas et al. 2004 for the period 2000–2050 and Malcolm et al. 2006 for the period 2000–2100). This figure shows that projected extinction rates have large uncertainties (both intra and inter-study), but are nonetheless higher than recent extinction rates. Source: Reproduced from Leadley et al. (2010, Figure 2, p. 12) by authors of this report.

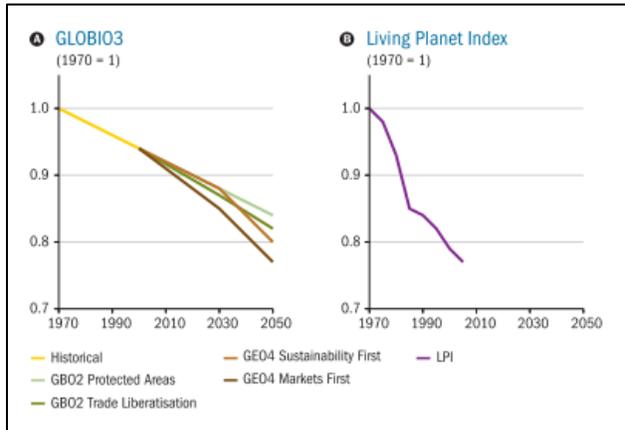


Figure 60. Observed changes and scenario projections to 2050 in abundance of terrestrial species. A) Modelled changes in terrestrial mean species abundance (MSA) using the GLOBIO model (Alkemade et al. 2009) for the GEO4 and GBO2 scenarios from 1970 to 2050. B) The Living Planet Index (LPI) for terrestrial species is based on observed changes in the population sizes of well-studied terrestrial vertebrates from 1970 to 2005 (Source: Jonathan Loh, WWF). These two indicators assess changes in species abundances, but are calculated differently so they are not directly comparable. Nevertheless, they suggest that species abundances have been declining globally, and will continue to do so in the examined scenarios. The scenario that has the least biodiversity loss is the one where effective protected areas are implemented and expanded globally. Source: Reproduced from Leadley et al. (2010, Figure 5, p. 15) by authors of this report.

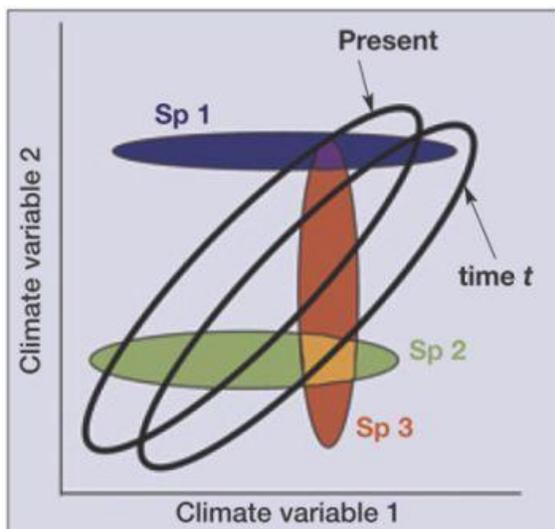


Figure 59. A conceptual diagram showing how no-analog combinations of species arise in response to novel climates. The set of climates in existence at two periods, “present” and an arbitrary “time t”, are represented as open ellipses. The fundamental niches for three species are shown as colored ellipses. Associations between species can occur only when their fundamental niches overlap with one another and with the set of climates in existence at a particular time period. A present-day ecologist would therefore sometimes observe communities containing both Species 1 and 2, but would never observe co-occurrences of Species 2 and 3 (nor Species 1 and 3). If the right climates arise, however, Species 2 and 3 could co-occur, forming a “no-analog” community from the perspective of the present-day ecologist. Adapted from Figure 5 in Jackson and Overpeck (2000). Source: Reproduced from Williams & Jackson (2007, Figure 1, p. 476) by authors of this report.

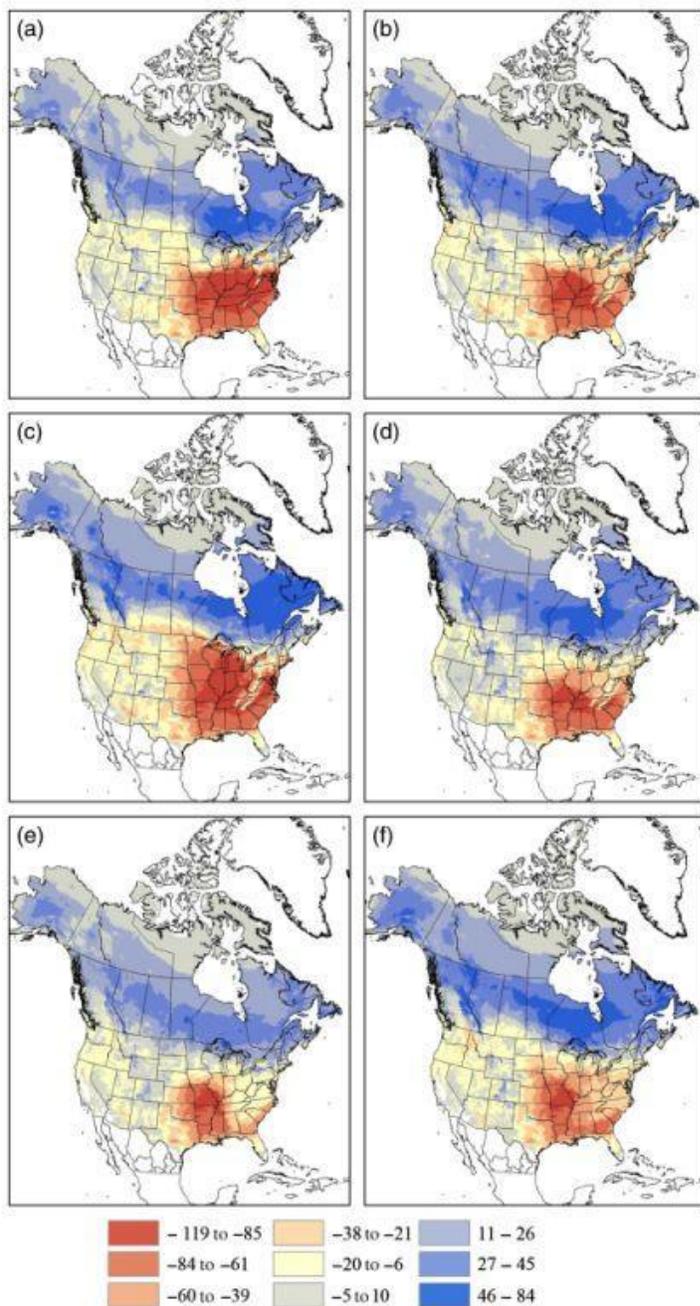


Figure 62. Differences between current (1971-2000) and future (2071-2100) tree climate envelope richness (i.e., number of tree species) for: (a) CGCM2, (b) CGCM3.1, (c) CSIRO-mk2, (d) CSIRO-mk3.5, (e) PCM, and (f) CCSM3.0.

Source: Reproduced from McKenney et al. (2011, Figure 3, p. 2727) by authors of this report.

²⁰⁸⁶ Nearly verbatim from Shafer et al. (2011, p. 212)

²⁰⁸⁷ Nearly verbatim from McKenney et al. (2011, p. 2726). *Revisiting projected shifts in the climate envelopes of North American trees using updated general circulation models.*

²⁰⁸⁸ Nearly verbatim from McKenney et al. (2011, p. 2726)

Western North America

Increasing temperatures will alter competitive interactions between deciduous and evergreen species by allowing increased rates of photosynthesis by evergreen species during winter months.²⁰⁸⁶ In a study of tree species richness using climate envelope modeling of 130 tree species, all of the AOGCMs project substantial reductions in climate envelope richness across the eastern half of the United States, gains in climate envelope richness for much of Canada, and relatively little change across much of the mountainous regions of the United States (Figure 62; 2071-2100 vs. 1971-2000 run with CGCM2, CGCM3.1, CSIRO-mk2, CSIRO-mk3.5, PCM, and CCSM3.0 under A2).²⁰⁸⁷ These maps only indicate where suitable climatic conditions will exist for the 130 tree species under study; the extent to which trees will actually shift with climate is of course highly uncertain.²⁰⁸⁸

Southcentral and Southeast Alaska

Information needed.

Western British Columbia

Species of unusual specialized habitats (for example, archaeobacteri and mollusks in hot springs, ferns (for example, Kruckeberg's hollyfern, mountain holly fern) restricted to ultrabasic bedrock, and subterranean cave species) are more likely to persist—as long as their special habitats

continue to exist.²⁰⁸⁹ The Grand Canyon of the Stikine, the ultrabasic bedrock of the Shulaps Range, hot springs, coastal dunes, karst on Vancouver Island and Haida Gwaii, and spray zones of waterfalls will continue to support some sort of regionally unusual biota almost regardless of how much the climate changes.²⁰⁹⁰ In addition, British Columbia species that live at the edge of their range as peripheral populations (for example, burrowing owl), and species that harbor genetically distinct and reproductively isolated populations as cryptic species (for example, seaside juniper), will be important genetic resources in the future.²⁰⁹¹

Pacific Northwest

For information on implications for species, populations, and communities in the Pacific Northwest, please see Chapters VI (habitats) and VIII (mammals, birds, invertebrates, and lichens and mosses).

Northwest California

Of 25 global hotspots analyzed, the California Floristic Province (i.e., most of northern and central CA) was identified to be one of the areas most vulnerable to climate change (2 x CO₂ vs. 1 x CO₂; CO₂ is an undefined current level; 14 scenarios run with MAPSS and BIOME3 global vegetation models and 7 GCMs).²⁰⁹²

Klausmeyer et al. (2011) estimated the vulnerability of biodiversity to climate change impacts across broad areas using landscape-scale indicators.²⁰⁹³ After combining the stress metrics for precipitation and temperature to estimate climate stress, areas with the highest stress include the Klamath Basin, the Modoc, the Sacramento Valley, and various locations in the Mojave and Sonoran Deserts.²⁰⁹⁴ Areas with the highest exposure (i.e., landscape exposure) include the flatter inland portions of the state, portions of the Mojave and Sonoran Deserts, and the Imperial Valley, while the coastal mountain ranges have the lowest exposure.²⁰⁹⁵ Adaptive constraints are significant in the coastal ecoregions and portions of the Klamath and Sierra Nevada mountains.²⁰⁹⁶

Regions of California that show the greatest decline of species richness of California native plants by the end of the century (2071-2100 vs. 1971-2000) include the Coast and Transverse ranges, as well as the transition zone between the Central Valley and the high Sierra (Figure 63) (GFDL and PCM, A2).²⁰⁹⁷

Information Gaps

Basic information on species and population traits ranging from physiology to behavior, life history characteristics, current distributions, dispersal abilities, and ecological relationships is needed to

²⁰⁸⁹ Nearly verbatim from Pojar (2010, p. 28)

²⁰⁹⁰ Nearly verbatim from Pojar (2010, p. 28)

²⁰⁹¹ Nearly verbatim from Pojar (2010, p. 38)

²⁰⁹² Nearly verbatim from Staudt et al. (2012, p. 5-13). Staudt et al. cite Malcolm & others (2006) for this information.

²⁰⁹³ Nearly verbatim from Klausmeyer et al. (2011, p.1)

²⁰⁹⁴ Verbatim from Klausmeyer et al. (2011, p.10). Klausmeyer et al. refer the reader to Figure 4A in the cited article for a map of climate stress.

²⁰⁹⁵ Nearly verbatim from Klausmeyer et al. (2011, p.10)

²⁰⁹⁶ Verbatim from Klausmeyer et al. (2011, p.12)

²⁰⁹⁷ Nearly verbatim from Hannah et al. (2012, p. 14)

understand why some species and populations are able to adjust to the impacts of climate change (while others decline), and will be critical for building better models to forecast future biological responses and vulnerabilities.²⁰⁹⁸ Additional experimental and field research is needed to improve our abilities to detect, attribute, and predict changes in these relationships (i.e. trophic mismatches) as well as the emergence of novel interactions and species assemblages.²⁰⁹⁹ Further, there is a need for experimental, observational, and modeling studies to identify the conditions under which such shifts (i.e., climate-driven regime shifts) are likely and the mechanisms through which they may occur.²¹⁰⁰ There is also an incomplete knowledge of the impact of connections between ecosystems and their responses to climate and other global environmental challenges.²¹⁰¹ Although species gains and losses occur simultaneously in many communities, there is still a dearth of knowledge about the net consequences of the two processes occurring in tandem for terrestrial ecosystems functioning.²¹⁰² The advancement of this topic will require studies that explicitly consider both species invasion and extinction, as well as their interactions, environmental drivers, and temporal dynamics.²¹⁰³

A critical barrier to investigating how multiple stressors interact is the lack of national data networks that combine climate, biological, and stressor information, including explicit data on population structure and abundance for invasive, rare, threatened, endangered, and other key species.²¹⁰⁴ Such data networks would allow researchers to combine information on projected climate changes with species biological data to understand possible future range shifts, and also to consider how other environmental stressors can influence future species distributions.²¹⁰⁵

Most ecological models are at least partially parameterized from modern observations and so may fail to accurately predict ecological responses to these novel climates.²¹⁰⁶ Important drivers that are currently missing or only partially treated in current models include invasive species and overexploitation in terrestrial systems; dam construction, pollution and invasive species in freshwater systems; and, habitat degradation and pollution in coastal and marine systems.²¹⁰⁷ Predicting where mitigation and adaptation responses will occur, and how they will impact biodiversity will also be a critical step in developing credible future climate change impact scenarios.²¹⁰⁸ Although many tools for forecasting climate change impacts on ecosystem services exist, fewer methods for anticipating how people will respond to those impacts have been developed or incorporated into projected impacts on biodiversity.²¹⁰⁹

²⁰⁹⁸ Verbatim from Staudinger et al. (2012, p. 2-39). Staudinger et al. cite McMahan & others (2011) for this information.

²⁰⁹⁹ Nearly verbatim from Staudinger et al. (2012, p. 2-40)

²¹⁰⁰ Nearly verbatim from Anderson-Teixeira et al. (2013, p. 16)

²¹⁰¹ Nearly verbatim from Grimm et al. (2012, p. 3-37)

²¹⁰² Nearly verbatim from Wardle et al. (2011, p. 1277)

²¹⁰³ Nearly verbatim from Wardle et al. (2011, p. 1277)

²¹⁰⁴ Verbatim from Staudt et al. (2012, p. 5-24)

²¹⁰⁵ Verbatim from Staudt et al. (2012, p. 5-24)

²¹⁰⁶ Verbatim from Williams & Jackson (2007, p. 475)

²¹⁰⁷ Verbatim from Leadley et al. (2010, p. 36)

²¹⁰⁸ Nearly verbatim from Staudinger et al. (2012, p. 2-40)

²¹⁰⁹ Verbatim from Staudinger et al. (2012, p. 2-40). Staudinger et al. cite Kareiva & others (2011) for information on the many tools for forecasting climate change impacts on ecosystem services.

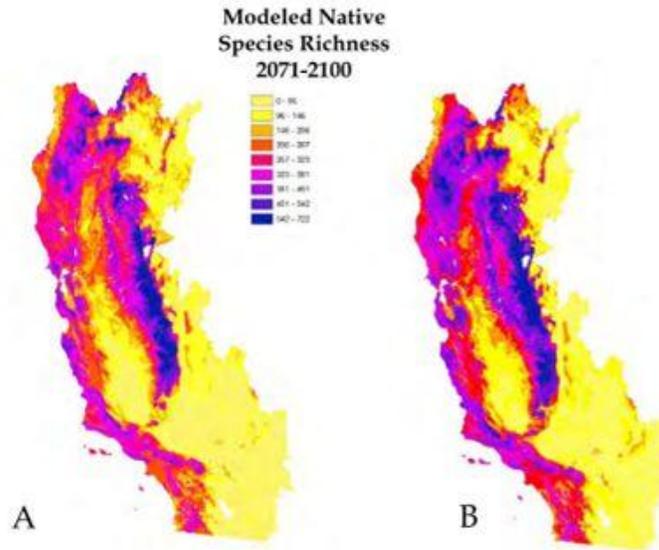


Figure 1.10: Modeled Native Species Richness as Determined by Summed 800 m Resolution Binary Range Maps Produced under the A2 emissions scenario for 2071–2100. Panel A = GFDL; Panel B = PCM.

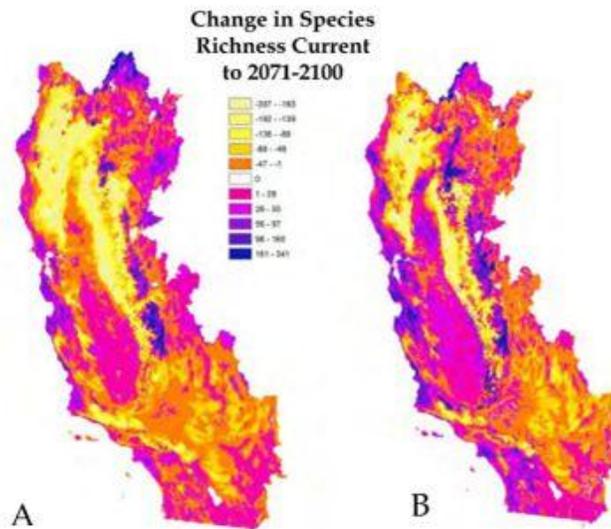


Figure 1.11: Change in Modeled Species Richness from Current Climate to 2071–2100 A2 emissions scenario. Light colors (Yellow to Orange) show decline in species richness and darker colors (Pink to Deep Blue) show an increase in modeled richness. Panel A = GFDL; Panel B = PCM.

Figure 63. Projected changes in California native plant species richness. (top) Modeled Native Species Richness for 2071-2100. (bottom) Change in Modeled Species Richness from Current Climate (1971-2000) to 2071-2100. *Source: Reproduced from Hannah et al. (2012, Figures 1.10 and 1.11, p. 15) by authors of this report.*

5. Altered interaction with invasive & non-native plant and animal species

The impact of introduced species on ecosystems is influenced by such climatic factors as temperature, drought, and cloud cover.²¹¹⁰ Introduced species can affect forests through herbivory, predation, habitat change, competition, alteration of gene pools via hybridization with natives, and disease (as either pathogens or vectors).²¹¹¹ Introduced species can alter the diversity, nutrient cycles, forest succession, and fire frequency and intensity of some ecosystems.²¹¹²

Further, developmental rates will be modified by temperature change.²¹¹³ In general, one might expect a larger fraction of survivors when the climate is warmer; introduced species comprise a far larger fraction of the biota in the warmer areas of the United States.²¹¹⁴

Climate change will modify the distributions of many introduced species.²¹¹⁵ Rather than simply enhancing invasion risk, climate change may also reduce invasive plant competitiveness if conditions become climatically unsuitable.²¹¹⁶ The great majority of introduced species do not survive.²¹¹⁷ Many fail because the climate is unsuitable at their points of arrival.²¹¹⁸ In some areas, currently invaded lands may also become climatically unsuitable, creating potential retreat areas which may provide opportunities for ecological restoration.²¹¹⁹ Further, although community and ecosystem impacts of invasive plants may be initially strong because of their novel traits and strengthen through selection, they may not be sustained in the longer term as decomposers, herbivores, and pathogens in the invaded range adapt.²¹²⁰ Thus, a changed climate will lead to a different mix of surviving and failing species.²¹²¹ Plants with C₃ photosynthetic biochemistry that grow in habitats that are dominated by plants with C₄ biochemistry may gain a competitive advantage with an increase in CO₂, even though there is no clear link between CO₂-responsiveness and invasiveness.²¹²²

Key Terms in this Section

Eradication: *complete removal of all individuals of a distinct population*

Introduced species or population: *a species or population that arrives at a specific location with intentional or accidental human assistance*

Invasive species or population: *an introduced species or population that spreads and maintains itself without human assistance*

Sources: Simberloff et al. (2012)

²¹¹⁰ Verbatim from Dale et al. (2008, p. 727). Dale et al. cite Ayres (1993) for this information.

²¹¹¹ Verbatim from Dale et al. (2008, p. 727)

²¹¹² Verbatim from Dale et al. (2008, p. 727)

²¹¹³ Verbatim from Dale et al. (2008, p. 727)

²¹¹⁴ Verbatim from Dale et al. (2008, p. 728). Dale et al. cite Simberloff (1997) for this information.

²¹¹⁵ Verbatim from Dale et al. (2008, p. 727)

²¹¹⁶ Verbatim from Bradley et al. (2009, p. 1511). *Climate change and plant invasions: restoration opportunities ahead?*

²¹¹⁷ Verbatim from Dale et al. (2008, p. 728). Dale et al. cite Williamson (1999) for this information.

²¹¹⁸ Verbatim from Dale et al. (2008, p. 728)

²¹¹⁹ Verbatim from Bradley et al. (2009, p. 1512). Bradley et al. refer the reader to Figure 1c in the cited article for this information.

²¹²⁰ Verbatim from Wardle et al. (2011, p. 1273, 1275). *Terrestrial ecosystem responses to species gains and losses*. Wardle et al. cite Lankau et al. (2009) for this information.

²¹²¹ Verbatim from Dale et al. (2008, p. 728)

²¹²² Verbatim from Hixon et al. (2010, p. 326). Hixon et al. cite Dukes (2000) for this information.

Observed Trends

Western North America

Eurasian forbs in the genus *Centaurea* are the most abundant invasive plants in the western U.S., covering over 17 million acres (7 million hectares, ha) (7 million acres, or 3 million ha in California).²¹²³

Collectively known as knapweeds and star-thistles, 12 *Centaurea* species are listed as noxious in at least one U.S. state (5 species account for most of the damage).²¹²⁴ Although these species are usually associated with grasslands, they also affect forest ecosystems, particularly in open areas and after fire or other disturbances.²¹²⁵

Yellow star-thistle became established in western North America in the mid-1800s and now infests more than 9.9 million acres (4 million ha), primarily in California, Oregon, Idaho, and Washington.²¹²⁶ Yellow star-thistle infests annual and perennial grasslands, shrub steppe, oak savannas, open woodlands, and modified habitats such as pastures, hayfields, orchards, and vineyards.²¹²⁷ Climatically suitable habitat currently includes much of California, eastern Oregon, and parts of eastern Washington.²¹²⁸ Analysis indicates the distribution of yellow star-thistle in the western United States is most constrained by summer precipitation, spring precipitation, winter minimum temperature, and spring minimum temperature.²¹²⁹ Yellow star-thistle has a strong growth and competitive response to elevated carbon dioxide.²¹³⁰ In one study, its aboveground biomass increased more than sixfold in response to elevated CO₂, which allowed it to compete aggressively with native species, although supplemental precipitation reduced its establishment in the field.²¹³¹

Southcentral and Southeast Alaska

A beetle induced die-off of white spruce trees in the Copper River Basin, improved habitat for some birds but reduced the densities of the ruby-crowned kinglets and red squirrels.²¹³²

Alaskan forests are becoming increasingly susceptible to non-native plant invasions as the climate warms and the amount of land disturbance (anthropogenic and natural) increases, which could collectively promote the establishment of invasive plant species into remote regions of Alaska.²¹³³ The rate of new introductions of exotic plant taxa has increased from roughly one to three species per year (1941–1968 and 1968–2006, respectively).²¹³⁴ Table 30 provides additional information on invasive plant species in

²¹²³ Verbatim from Ryan et al. (2012, Box 2.5, p. 30)

²¹²⁴ Verbatim from Ryan et al. (2012, Box 2.5, p. 30)

²¹²⁵ Verbatim from Ryan et al. (2012, Box 2.5, p. 30)

²¹²⁶ Verbatim from Roché & Thill (2001, p. 439). *Biology of common crupina and yellow starthistle, two Mediterranean winter annual invaders in western North America*. Roché & Thill cite Thomsen et al. (1996) for information on the size of the yellow star thistle infestation.

²¹²⁷ Verbatim from Roché & Thill (2001, p. 439)

²¹²⁸ Verbatim from Bradley et al. (2009, p. 1514). Bradley et al. refer the reader to Figure 2a in the cited article for this information.

²¹²⁹ Verbatim from Bradley et al. (2009, p. 1514)

²¹³⁰ Verbatim from Ryan et al. (2012, Box 2.5, p. 30). Ryan et al. cite Dukes et al. (2011) for this information.

²¹³¹ Verbatim from Ryan et al. (2012, Box 2.5, p. 30). Ryan et al. cite Dukes et al. (2011) for this information.

²¹³² Nearly verbatim from Kelly et al. (2007, p. 54). Kelly et al. cite Matsuoka et al. (2001) for this information.

²¹³³ Verbatim from Wolken et al. (2011, p. 3). Wolken et al. cite Villano & Mulder (2008) for this information.

²¹³⁴ Verbatim from Wolken et al. (2011, p. 3). Wolken et al. cite Carlson & Shephard (2007) for this information.

Alaska's coastal temperate rainforest region and ecological implications expected to increase with projected changes in climate.

Western British Columbia

The 18 or so species of European earthworms invading B.C.'s forests, which since Pleistocene glaciation have retained a very few native species of earthworms, show how introduced species can profoundly change ecosystems.²¹³⁵ These earthworms have changed the way nutrients cycle, leading to a change in community composition and reducing abundance of understory plants.²¹³⁶ *For more information on earthworms and climate change, please see Chapter VIII.3.*

Western Washington

Information needed.

Western Oregon

Several non-native, mammalian species have become widespread in uplands in the Willamette Valley.²¹³⁷ Eastern gray-squirrels and the house mouse have been reported to occur primarily in urban areas, whereas the eastern cottontail and Virginia opossum are common throughout the Willamette Valley, particularly in shrubby vegetation, including within oak and prairie habitats.²¹³⁸ Non-native bird species that commonly occur in prairie and oak habitats of the Willamette Valley include wild turkey, ring-necked pheasant, and European starling.²¹³⁹ Nonnative plants make up more than half of the total vegetation in the riparian zone of the Willamette River mainstem.²¹⁴⁰

Comparing native and non-native plant growth, Hebel et al. (2009) investigated the chemical and biotic factors associated with severely burned "red" soil and less severely burned "black" soil from a recently burned forest on the eastern slope of the Cascade Range in Oregon.²¹⁴¹ The study revealed red soils were highly nutrient-limited and exhibited reduced microbial abundance, arbuscular mycorrhizal (AM) fungal propagules, and plant growth.²¹⁴² The findings suggest that some native species may out-compete non-native species in low-resource environments, such as severely burned red soil, where organic matter, soil nutrients and soil microbes are reduced by severe soil heating.²¹⁴³ *For additional information on nutrient limitation and microbial abundance, please see Chapter V.2.*

²¹³⁵ Verbatim from Pojar (2010, p. 23). Pojar cites Marshall & Fender (2007) for information on the number of species of European earthworms, Marshall & Fender (1998) for information on BC's native earthworms, and Campbell et al. (2008) for information on ecosystem change.

²¹³⁶ Verbatim from Pojar (2010, p. 23). Pojar cites Bohlen et al. (2004) and Hale et al. (2006) for this information.

²¹³⁷ Verbatim from Vesely & Rosenberg (2010, p. 16)

²¹³⁸ Verbatim from Vesely & Rosenberg (2010, p. 16). Vesely & Rosenberg cite Verts & Carraway (1998) for this information.

²¹³⁹ Verbatim from Vesely & Rosenberg (2010, p. 18)

²¹⁴⁰ Verbatim from Apostol & Berg (2006, p. 130). Apostol & Berg cite Oregon Progress Board (2000) for this information.

²¹⁴¹ Nearly verbatim from Hebel et al. (2009, p. 150)

²¹⁴² Nearly verbatim from Hebel et al. (2009, p. 158)

²¹⁴³ Verbatim from Hebel et al. (2009, p. 150)

Northwest California

Yellow star thistle is an annual forb that dominates California grasslands and has become a serious agricultural pest, particularly due to its use of water resources.²¹⁴⁴ Yellow star thistle was accidentally introduced as a seed contaminant in the mid-1800s.²¹⁴⁵

Future Projections

Western North America

Predictive models project various changes in the range of *Centaurea* species (i.e., knapweeds and star-thistles) in a warmer climate.²¹⁴⁶ Broennimann and Guisan (2008) projected a northern shift and reduced invasion extent for spotted knapweed by 2080 using the hot, dry HadCM-A1FI scenario (baseline not provided), but Bradley et al. (2009) suggested that the distribution of yellow-star thistle was likely to increase in a warming West.²¹⁴⁷ Specific results from Bradley et al. (2009) include:

- **Invasion risk and restoration potential:** Climate change is likely to expand invasion risk from yellow star-thistle to include more of California and Nevada (2090-2100 vs. 1970-2000 run with 10 AOGCMs under A1B).²¹⁴⁸ Lands currently occupied by invasive populations of yellow star thistle in California, Oregon, and Washington have low potential for restoration (Figure 64).²¹⁴⁹
- **Climatic suitability of land for invasion:** Of the currently invaded lands, only 1% are no longer climatically suitable by 2100 in any of the 10 AOGCMs tested by Bradley et al. (2009).²¹⁵⁰ Eighty-eight percent (88%) of currently invaded lands maintained climatic suitability in five or more of the 10 AOGCMs.²¹⁵¹

Southcentral and Southeast Alaska

Projected increases in temperature in boreal forests in southcentral and Kenai Peninsula, Alaska will likely increase the probability of establishment of invasive plant species.²¹⁵² Several invasive plant species in the coastal temperate forest region of Alaska could reduce the growth and density of native species via competition and alter forest structure and function, and salmon habitat (Table 30).²¹⁵³

²¹⁴⁴ Verbatim from Bradley et al. (2009, p. 1512). Bradley et al. cite DiTomaso (2000) and Pitcairn et al. (2006) for this information.

²¹⁴⁵ Verbatim from Bradley et al. (2009, p. 1512)

²¹⁴⁶ Nearly verbatim from Ryan et al. (2012, Box 2.5, p. 30)

²¹⁴⁷ Nearly verbatim from Ryan et al. (2012, Box 2.5, p. 30)

²¹⁴⁸ Verbatim from Bradley et al. (2009, p. 1514). Bradley et al. refer the reader to Figure 2b in the cited article for this information. *Note: The 10 AOGCMs used in the study are CCCMA-CGCM3.1, CNRM-CM3, GFDL-CM2.1, GISS-AOM, INM-CM3, IPSL-CM4, MIROC3.2(hi-res), MPI-ECHAM5, NCAR-CCSM3, and UKMO-HadCM3.*

²¹⁴⁹ Verbatim from Bradley et al. (2009, p. 1514-1515). Bradley et al. refer the reader to Figure 2c in the cited article for this information.

²¹⁵⁰ Nearly verbatim from Bradley et al. (2009, p. 1515)

²¹⁵¹ Nearly verbatim from Bradley et al. (2009, p. 1515). Bradley et al. refer the reader to Table 1 in the cited article for this information.

²¹⁵² Verbatim from Staudt et al. (2012, p. 5-15). Staudt et al. cite Wolken & others (2011) for this information.

²¹⁵³ Nearly verbatim from Wolken et al. (2011, p. 18). Wolken et al. refer the reader to Table 3 in the cited article for this information.

Western British Columbia

Information needed.

Western Washington

Information needed.

Western Oregon

Information needed.

Northwest California

Information needed.

Information Gaps

Invasion biology is not yet adept at forecasting impacts of invasions.²¹⁵⁴ The complex interactions among introduced species, native communities, managed and intensely harvested forests, and climate change compound this forecasting problem.²¹⁵⁵

²¹⁵⁴ Verbatim from Dale et al. (2008, p. 727). Dale et al. cite Williamson (1999) for this information.

²¹⁵⁵ Verbatim from Dale et al. (2008, p. 727). Dale et al. cite Simberloff (2000) for this information.

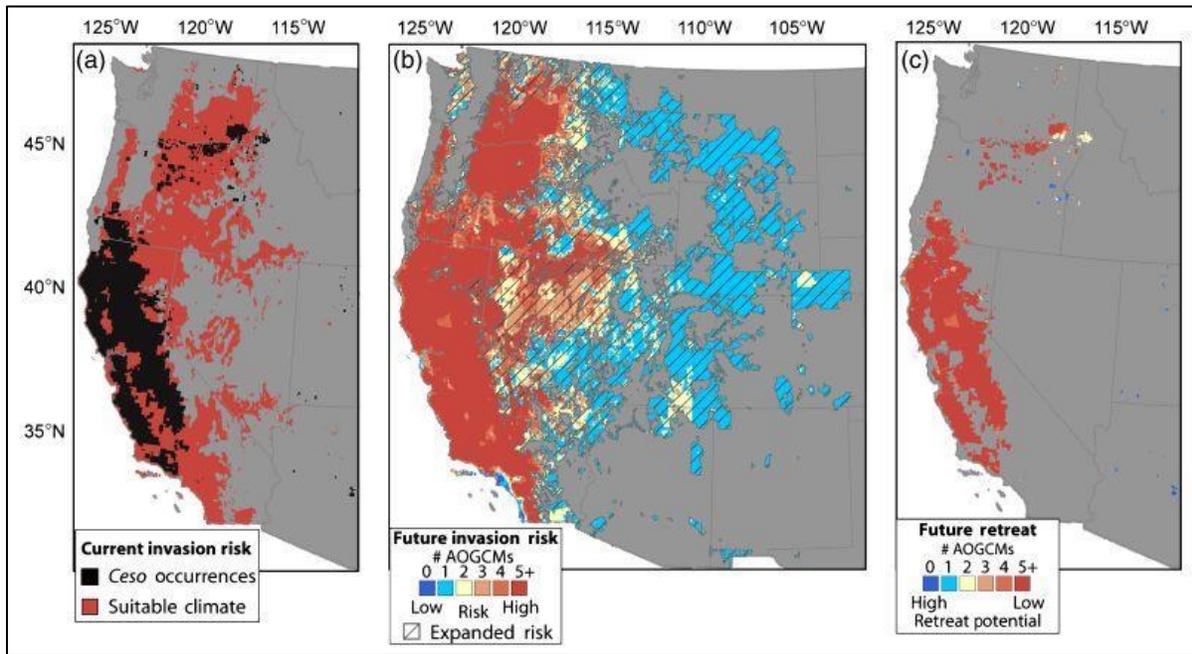


Figure 64. Climate change is likely to expand invasion risk of yellow star thistle, creating minimal retreat potential by 2100. (a) Yellow star thistle dominated lands in the western United States and climatically suitable habitat based on Mahalanobis distance. (b) Change in future invasion risk based on the number of atmosphere–ocean general circulation models (AOGCMs) that project maintained climatic suitability. Colors represent risk of invasion based on the number of AOGCMs that project climatic suitability; black lines denote regions of expanded risk. (c) Retreat potential of currently invaded lands. Note that most areas currently suitable for yellow star thistle maintain their climatic suitability in five or more of the 10 AOGCMs tested.

Source: Reproduced from Bradley et al. (2009, Figure 2, p. 1514) by authors of this report.

Table 30. Invasive plant species in Alaska’s coastal temperate forest region and ecological implications expected to increase with projected changes in climate.		
Invasive Plant	Ecological implications	Sources (as provided by Wolken et al.)
Garlic mustard	Invades urban forest understory; could eliminate native species through competition and/or allelopathy (i.e., chemical inhibition of one plant by another through the release of germination or growth inhibitors)	Meekins & McCarthy (1999), Prati & Bossdorf (2004), Lamb & Shepard (2007)
Knotweed complex	Found along roadsides, stream banks, and beach meadows; reduces nutrient quality of litter input to aquatic habitats; could depress cover and density of native species and change forest structure and function of riparian forests and aquatic habitats	Lamb & Shepard (2007), Urgenson et al. (2009)
Orange hawkweed*	Spreads vegetatively and by seed; forms monospecific stands and displaces native vegetation; currently spreading into meadows and open areas where it has escaped cultivation	Lapina & Carlson (2004), IWAC (2006)
White sweetclover*	Spreads aggressively; invades heavily burned areas; decreases survival and pollination of native plants; alters primary succession on glacial floodplains by modifying nitrogen status	Cortes-Burns et al. (2008), Conn et al. (2008), Spellman (2008), Villano & Mulder (2008)
European mountain ash	Escaped from ornamental plantings; now a dominant species of coastal rainforest plant communities	Dickinson & Campbell (1991), Rapp (2006)

*Orange hawkweed is also found in the southcentral boreal forest region of Alaska. White sweetclover is also found in the interior boreal and southcentral boreal forest regions of Alaska.

Source: Modified from Wolken et al. (2011, Table 3, p. 14) by authors of this report.

VIII. Implications for Mammals, Birds, Invertebrates, Lichens, & Mosses

Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations, sufficient information is available to discuss observed trends and future projections in the NPLCC region for the following terrestrial species groups:

1. Mammals
2. Birds
3. Invertebrates
4. Lichens & mosses

Chapter VII provides general information on implications for species, populations, and biological communities. The following structure will be used to present information on the implications of climate change for the NPLCC region's terrestrial species, populations, and communities:

- **Observed Trends** – observed changes for southcentral and southeast Alaska, western British Columbia, the Pacific Northwest, western Washington, western Oregon, and northwest California. One section includes information on changes observed in North America. For context, summary information on observed changes globally, for North America, or for western North America is also provided.
- **Future Projections** – projected direction and/or magnitude of change for southcentral and southeast Alaska, western British Columbia, the Pacific Northwest, western Washington, western Oregon, and northwest California. For context, summary information on future projections globally, for North America, or for western North America is also provided.
- **Information Gaps** – information and research needs identified by literature searches, as well as our summary of the sections missing information in this chapter.

Loss and deterioration of habitat seem to be the most likely impacts of climate change on vertebrates.²¹⁵⁶ Migrants (i.e., migratory species) may be affected disproportionately because of their reliance on high latitude, high altitude and wetland habitats as well as on particular stopover sites, which are vulnerable not only to habitat loss, but also to a reduction in seasonality (especially at high latitudes/altitudes) as winter temperatures are increasing faster than summer ones.²¹⁵⁷ Consequently, we may see either a reduction in migratory tendency – already apparent at mid-latitudes – or an expansion in the range of resident species.²¹⁵⁸

Unlike vertebrates, which have the capacity to cross hundreds or thousands of kilometres, yet still home in on specific breeding, stop-over or non-breeding sites, most insect species have much more diffuse

²¹⁵⁶ Verbatim from Robinson et al. (2008, p. 92). Robinson et al. refer the reader to Table 1 in the cited article for this information.

²¹⁵⁷ Verbatim from Robinson et al. (2008, p. 92-93). Robinson et al. cite Hassol (2004) and MEA (2005) for information on the vulnerability of stopover sites to habitat loss, and IPCC (2007) for information on reductions in seasonality.

²¹⁵⁸ Verbatim from Robinson et al. (2008, p. 93). Robinson et al. cite Fiedler (2003) for information on reduced migratory tendency at mid-latitudes.

migratory patterns, and are heavily dependent on appropriate weather conditions.²¹⁵⁹ Trends in herbivorous insect abundance have been found along climatic gradients and trends in biodiversity along altitudinal, latitudinal, and habitat gradients.²¹⁶⁰

The greatest risks to the vast biodiversity represented by moss and lichen communities are poor air quality and loss of critical habitats.²¹⁶¹

²¹⁵⁹ Verbatim from Robinson et al. (2008, p. 90)

²¹⁶⁰ Verbatim from Progar & Schowalter (2002, p. 129). *Canopy arthropod assemblages along a precipitation and latitudinal gradient among Douglas-fir Pseudotsuga menziesii forests in the Pacific Northwest of the United States*. Progar & Schowalter cite Landsberg & Gillieson (1995), Strathdee & Bale (1995), and Hysell et al. (1996) for information on trends in abundance along climatic gradients. Progar & Schowalter cite Stevens (1992) and Olsen (1994) for information on trends in biodiversity along altitudinal gradients, Gaston (1996) and Hodkinson (1997) for information on latitudinal gradients, and Kitching et al. (1993) for information on habitat gradients.

²¹⁶¹ Verbatim from USGS (2002, p. 4)

1. Mammals

Any major shift in precipitation (drier or wetter) would be expected to influence communities of small mammals by favoring either dry or wet-adapted species.²¹⁶² Reproductive success in many temperate bat species is linked to precipitation.²¹⁶³

Extensive studies of large mammals indicate that climatic extremes appear to influence juvenile survival, primarily during winter, although not independently of population density.²¹⁶⁴ The impact of such life history responses (i.e., changes in development and fecundity) responses on population dynamics can occur years later when cohorts have reached reproductive maturity and may, as in the case of Soay sheep, occur only above certain population densities.²¹⁶⁵

Observed Trends

Western North America

Confirmed northern hibernacula (i.e., winter hibernation sites) of little brown bats extend to mid-latitude regions of Canadian provinces and maritime-influenced areas of Alaska, where a model (i.e., of the relationship between ambient temperature and energy expenditure during hibernation) predicts successful hibernation by most individuals, but not into higher latitudes and continental regions, where the model predicts that successful hibernation is energetically impossible.²¹⁶⁶ Energetic constraints at higher latitudes should be especially severe for juveniles, owing to their limited capacity to grow and fatten during a short active season.²¹⁶⁷

A red squirrel population in the southwest Yukon, Canada, faced with increasing spring temperatures and food supply has advanced the timing of breeding by 18 days over the last 10 years (6 days per generation) (study period: 1989-2001, with a population of approximately 325 squirrels near Kluane Lake).²¹⁶⁸ Longitudinal analysis of females breeding in multiple years suggests that much of this change in parturition date (i.e., date of birth) can be explained by a plastic response to increased food abundance (3.7 days per generation).²¹⁶⁹ Significant changes in breeding values (0.8 days per generation), were in concordance with predictions from the breeder's equation (i.e., an equation used to predict evolutionary responses to selection; 0.6 days per generation), and indicated that an evolutionary response to strong

²¹⁶² Verbatim from Hixon et al. (2010, p. 283). Hixon et al. cite Grayson (2000) for this information.

²¹⁶³ Verbatim from Hixon et al. (2010, p. 284). Hixon et al. cite Frick et al. (2010) for this information.

²¹⁶⁴ Verbatim from Walther et al. (2002, p. 394). Walther et al. cite Post & Stenseth (1999) and Milner et al. (1999) for this information.

²¹⁶⁵ Nearly verbatim from Walther et al. (2002, p. 394). Walther et al. cite Post & Stenseth (1999) and Forchhammer et al. (2001) for information on the temporal lag of impacts to population dynamics, and Grenfell et al. (1998) for information on impacts taking place only above certain population densities.

²¹⁶⁶ Nearly verbatim from Humphries et al. (2002, p. 315). *Climate-mediated energetic constraints on the distribution of hibernating mammals*. Humphries et al. refer the reader to Figure 3 in the cited article for this information.

²¹⁶⁷ Nearly verbatim from Humphries et al. (2002, p. 315). Humphries et al. cite Kunz et al. (1998) for this information.

²¹⁶⁸ Nearly verbatim from Réale et al. (2003, p. 591). *Genetic and plastic responses of a northern mammal to climate change*.

²¹⁶⁹ Nearly verbatim from Réale et al. (2003, p. 591)

selection favoring earlier breeders also contributed to the observed advancement of this heritable trait.²¹⁷⁰ The timing of breeding in this population of squirrels, therefore, has advanced as a result of both phenotypic changes within generations, and genetic changes among generations in response to a rapidly changing environment.²¹⁷¹

Specific information on observed trends for several larger mammals, including wolverine, gray wolf, grizzly bear, mountain goat, mule deer, elk, and lynx, is available:

- **Wolverine:** Historically, wolverines were abundant in the forests of Canada, the Cascades, the Sierra Nevada, the Rocky Mountains, the Great Lakes area, and northeastern United States.²¹⁷² In southern portions of the wolverine's range in western North America, wolverine populations occupy peninsular extensions of boreal forests in montane regions.²¹⁷³ In a study of the wolverine's bioclimatic envelope worldwide, North America wolverines located their dens within the spring snow coverage, and most dens (45 of 65; 69%) were located in areas that were snow-covered for six to seven years (study period: 2000-2006; Figure 65).²¹⁷⁴ Globally, 95% of summer locations and 86% of winter locations fell within the spring snow coverage.²¹⁷⁵ In seven of eight North American study areas (i.e., includes all those in western North America) and in southern Norway, wolverines selected for areas within the spring snow coverage during winter, summer, and when seasons were pooled.²¹⁷⁶ Wolverine populations in the lower 48 states are increasingly fragmented and isolated from each other and from larger wolverine populations in British Columbia and Alberta.²¹⁷⁷
- **Gray wolf:** Before Europeans arrived, gray wolves roamed nearly all of North America from Alaska to Mexico and the Pacific to the Atlantic.²¹⁷⁸
- **Grizzly bear:** Grizzly bears thrived throughout western North America, as far south as Mexico.²¹⁷⁹
- **Mountain goat:** Mountain goats are native to Alaska, British Columbia, the Cascade Mountains, and a few other areas in the lower 48 states.²¹⁸⁰
- **Mule deer and elk:** Fossil records indicate that elk and mule deer reached western North America by the end of the Pleistocene Ice Age or earlier.²¹⁸¹ Mule deer occupy most regions from Alaska, in Canada west of Alberta, and south into northern Mexico.²¹⁸² Elk are distributed in

²¹⁷⁰ Nearly verbatim from Réale et al. (2003, p. 591)

²¹⁷¹ Verbatim from Réale et al. (2003, p. 591)

²¹⁷² Verbatim from North Cascades Conservation Council (2010, p. 23)

²¹⁷³ Verbatim from Copeland et al. (2010, p. 234). *The bioclimatic envelope of the wolverine (Gulo gulo): do climatic constraints limit its geographic distribution?*

²¹⁷⁴ Verbatim from Copeland et al. (2010, p. 239)

²¹⁷⁵ Nearly verbatim from Copeland et al. (2010, p. 239). Copeland et al. refer the reader to Table 1 in the cited article for this information.

²¹⁷⁶ Nearly verbatim from Copeland et al. (2010, p. 239)

²¹⁷⁷ Verbatim from North Cascades Conservation Council (2010, p. 23)

²¹⁷⁸ Verbatim from North Cascades Conservation Council (2010, p. 24)

²¹⁷⁹ Nearly verbatim from North Cascades Conservation Council (2010, p. 25)

²¹⁸⁰ Nearly verbatim from North Cascades Conservation Council (2010, p. 26)

²¹⁸¹ Nearly verbatim from DeVos, Jr. & McKinney (2007, p. 3). DeVos, Jr. & McKinney cite Dawson (1967), Kurtén & Anderson (1980), Bryant & Maser (1982), Harris (1987), and Geist (1998) for this information.

²¹⁸² Verbatim from DeVos, Jr. & McKinney (2007, p. 12). DeVos, Jr. & McKinney cite Mule Deer Working Group (2003) and Heffelfinger (2006) for this information.

many of the same regions as mule deer, but occur in a more patchy distribution.²¹⁸³ In the coastal rain forest ecoregion (i.e., most of the NPLCC region), productivity and recruitment of mule deer populations, which are non-migratory, has declined in this ecoregion during recent years.²¹⁸⁴ Recent studies in Oregon suggested mule deer avoided areas used by elk.²¹⁸⁵ Further, reductions in herbaceous and shrub productivity and senescence (i.e., deterioration with age) of browse are associated with declining abundance of mule deer in the American West during recent decades, whereas abundance of elk increased as these changes occurred.²¹⁸⁶

- **Lynx:** Habitat fragmentation and interspecific competition are two important forces that potentially affect lynx populations.²¹⁸⁷ Habitat fragmentation tends to facilitate competition by generalist predators, of which the most likely beneficiary is the coyote.²¹⁸⁸ Competition could take the form of exploitation by other predators of snowshoe hares, particularly the coyote, or involve interference competition, with larger-bodied carnivores acting aggressively toward lynx, even killing them.²¹⁸⁹ Overall, Buskirk et al. (2000) suspect that interference competition is more likely to be the critical form of competition that needs to be evaluated for lynx in the contiguous United States.²¹⁹⁰ Cougars, in particular, appear to be effective interference competitors with lynx.²¹⁹¹ Of these three carnivores (i.e., coyote, bobcat, cougar), all are more widespread and more abundant within the southern distribution of the lynx than 50 years ago.²¹⁹²

Southcentral and Southeast Alaska

The body size of masked shrews in Alaska increased significantly during the second half of the twentieth century.²¹⁹³ Specimens were collected between 1950 and 2003; 88% of them (i.e., 572 of 650 total specimens) were collected between May and August.²¹⁹⁴ Evidence indicates that warmer winter weather conditions increased the survival rate of shrew's prey (small invertebrates that are sensitive to the cold and whose availability decreases in cold winters), providing greater food availability for the shrew.²¹⁹⁵

In a modeling and connectivity study by Murphy et al. (2010), four species with very different connectivity issues were selected for evaluation.²¹⁹⁶ Caribou were selected to represent mammal species

²¹⁸³ Verbatim from DeVos, Jr. & McKinney (2007, p. 12)

²¹⁸⁴ Verbatim from DeVos, Jr. & McKinney (2007, p. 14)

²¹⁸⁵ Verbatim from DeVos, Jr. & McKinney (2007, p. 16)

²¹⁸⁶ Nearly verbatim from DeVos, Jr. & McKinney (2007, p. 17). DeVos, Jr. & McKinney cite Germaine et al. (2004) for information on declining abundance of mule deer in the American West in recent decades.

²¹⁸⁷ Verbatim from Buskirk et al. (2000, p. 83). *Habitat fragmentation and interspecific competition: implications for lynx conservation.*

²¹⁸⁸ Verbatim from Buskirk et al. (2000, p. 83)

²¹⁸⁹ Verbatim from Buskirk et al. (2000, p. 95)

²¹⁹⁰ Nearly verbatim from Buskirk et al. (2000, p. 95)

²¹⁹¹ Verbatim from Buskirk et al. (2000, p. 95)

²¹⁹² Nearly verbatim from Buskirk et al. (2000, p. 83)

²¹⁹³ Verbatim from Jezierski et al. (2010, p. 9). Jezierski et al. cite Yom-Tov & Yom-Tov (2005) for this information.

²¹⁹⁴ Nearly verbatim from Yom-Tov & Yom-Tov (2005, p. 804). *Global warming, Bergmann's rule and body size in the masked shrew *Sorex cinereus* Kerr in Alaska.*

²¹⁹⁵ Nearly verbatim from Jezierski et al. (2010, p. 9). Jezierski et al. cite Yom-Tov & Yom-Tov (2005) for this information. *Note: The information on reduced availability of invertebrates in cold winters is also obtained from Yom-Tov & Yom-Tov (2005, p. 807-808).*

²¹⁹⁶ Murphy et al. (August 2010, p. 32)

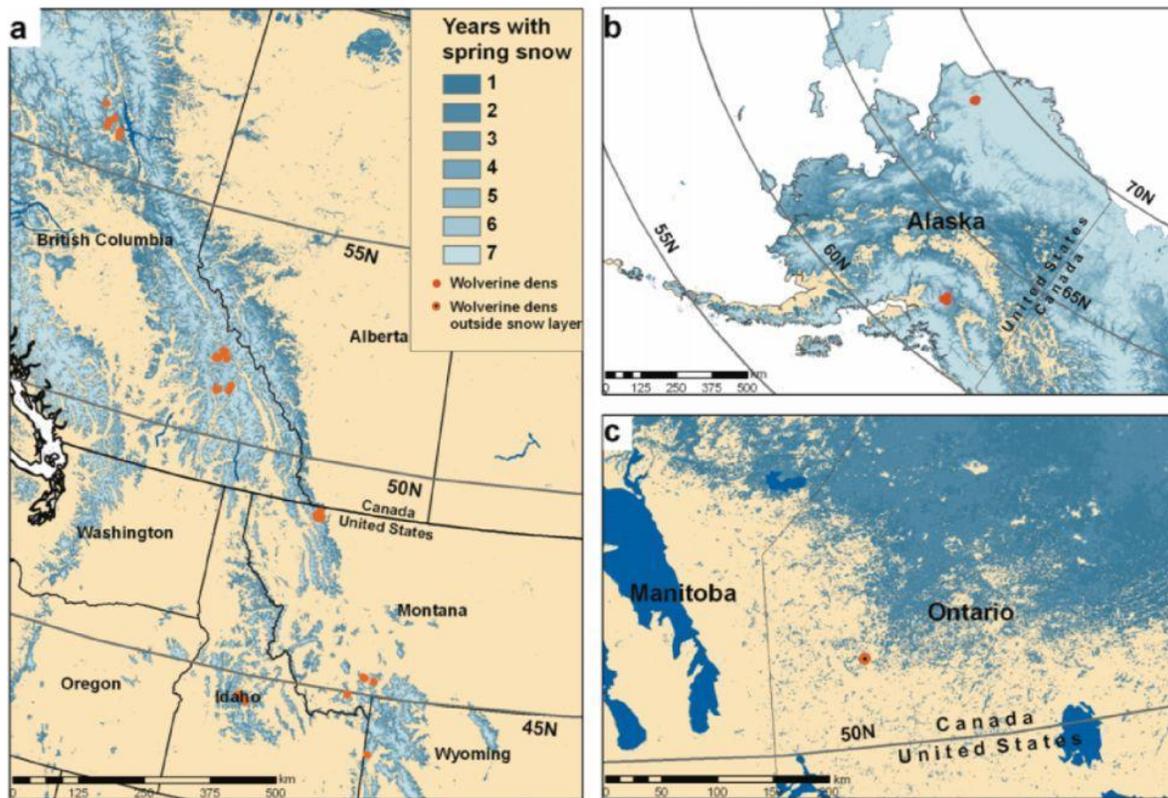


Figure 65. Distribution of wolverine dens in North America overlaid on the spring snow coverage in (a) the Rocky Mountains of British Columbia, Canada and the western U.S.; (b) Alaska, U.S.; and (c) Ontario, Canada. The gradient in the spring snow coverage represents the number of years out of seven (2000-2006) in which snow cover was present from 24 April to 15 May.

Source: Reproduced from Copeland et al. (2010, Figure 2, p. 236) by authors of this report.

with few migration constraints; Alaska marmot were selected to represent mammals with limited range and migration capability; trumpeter swans were selected to investigate how statewide landscape connectivity issues would apply to breeding bird populations; and reed canary grass was selected as an invasive plant species that uses the human footprint on the landscape for initial dispersal and may benefit from a warming climate.²¹⁹⁷ The latter three – Alaska marmot, trumpeter swan, and reed canary grass – are currently found in the NPLCC region. Alaska marmot is discussed in this section, trumpeter swan is discussed in Section 2 (Birds), and reed canary grass is discussed in a companion report to this one that focuses on freshwater ecosystems.²¹⁹⁸

The Alaska marmot, a relic species from the Beringia Ice Age, has limited adaptability and dispersal ability and thus makes an excellent case study for connectivity and habitat loss for endemics (native species) in arctic environments.²¹⁹⁹ Data for thirty-four known occurrences of Alaska marmots were provided by the Alaska National Heritage Program, based on various sources including the Gunderson

²¹⁹⁷ Verbatim from Murphy et al. (August 2010, p. 32)

²¹⁹⁸ For information on reed canarygrass, see Tillmann & Siemann (2011#), Chapters ## and ##.

²¹⁹⁹ Verbatim from Murphy et al. (August 2010, p. 35). The authors cite Gunderson et al. (2009) for information on adaptability and dispersal ability.

collections.²²⁰⁰ Murphy and colleagues used SNAP climate data for June and December mean temperature and precipitation for 2000–2009 to develop a climate envelope and current potential distribution based on known occurrence sites.²²⁰¹ However, terrain roughness was also added as a covariate.²²⁰² Rockiness, steepness, and associated biophysical features are of great importance to marmot habitat, since Alaska marmots use rock piles for cover.²²⁰³ It cannot be presumed that the species is absent from areas for which no data exist (Figure 66).²²⁰⁴

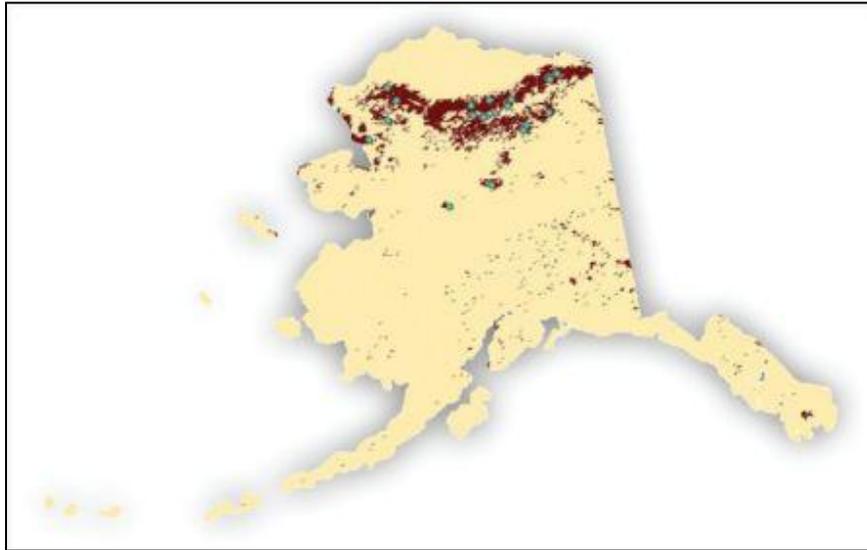


Figure 66. Known Alaska marmot distribution and modeled current distribution. Since no absence data exist, it cannot be assumed that marmots do not also inhabit similar habitat in which no confirmed presence data are available. *Source: Reproduced from Murphy et al. (2010, Fig. 19, p. 36) by authors of this report.*

Because of their high requirement for forage biomass, early stages of plant succession are important to moose.²²⁰⁵ Over years, quality of summer forages vary with respect to the intensity of solar radiation and winter forage abundance varies with the extent and duration of snowfall.²²⁰⁶ For example, moose select more mature spruce and deciduous habitats during deep snow.²²⁰⁷ In the western Copper River Delta from 1959 to 1986, during periods with less snow, moose occupied areas with a higher proportion of willow-sweetgale and closed alder-willow.²²⁰⁸ However, as snow depth increased, moose increased use of

²²⁰⁰ Verbatim from Murphy et al. (August 2010, p. 35). The authors cite Gunderson et al. (2009) for information on the Gunderson collections.

²²⁰¹ Nearly verbatim from Murphy et al. (August 2010, p. 36)

²²⁰² Nearly verbatim from Murphy et al. (August 2010, p. 36)

²²⁰³ Verbatim from Murphy et al. (August 2010, p. 36)

²²⁰⁴ Verbatim from Murphy et al. (August 2010, p. 35)

²²⁰⁵ Verbatim from Stephenson et al. (2006, p. 360). *Spatio-temporal constraints on moose habitat and carrying capacity in coastal Alaska: vegetation succession and climate*. Stephenson et al. cite Oldemeyer & Regelin (1987), Regelin et al. (1987), and Saether & Anderson (1990) for this information.

²²⁰⁶ Verbatim from Stephenson et al. (2006, p. 360). Stephenson et al. cite Bo & Hjeljord (1991) for information on summer forage and Coady (1974) for information on winter forage.

²²⁰⁷ Verbatim from Stephenson et al. (2006, p. 369). Stephenson et al. cite Peek et al. (1976), Hundertmark et al. (1990), Ballard et al. (1991), Miquelle et al. (1992), and MacCracken et al. (1997) for this information.

²²⁰⁸ Verbatim from Stephenson et al. (2006, p. 369)

relatively open canopy cottonwood and spruce types.²²⁰⁹ Further, moose responded to deep snow by concentrating in outwash plain community types within the primary winter range (i.e., in glacial outwash plain instead of uplifted marsh).²²¹⁰ Typically, this meant migrating farther (> 1.2 miles, 2 km) from early winter transitional ranges in outlying areas of the uplifted marsh.²²¹¹ Overall, there was a significant northerly and westerly shift in the core area with increasing winter severity.²²¹²

Successional modeling suggests a decline in the availability of vegetation types important to moose during severe winters with deep snow.²²¹³ Low willow communities are expanding in the uplifted marsh, a landform used primarily during summer and mild winters.²²¹⁴ However, tall willow communities that provide winter forage are declining and are being replaced by Sitka spruce forest in the glacial outwash plain.²²¹⁵ Consequently, nutritional carrying capacity of moose on the outwash plain during winter will decline by 42% during 1959-2013.²²¹⁶

Western British Columbia

British Columbia has intact large-mammal predator-prey systems with continentally important populations of grizzly bear, Stone's sheep, mountain goat, woodland mountain caribou, grey wolf, cougar, wolverine, lynx, and fisher marten.²²¹⁷ Ten to twenty grizzly bears are present in the British Columbia North Cascades.²²¹⁸ Among widespread species, caribou, moose, elk, grizzly bear, and cougar have locally varying population trends (Figure 67). Some local populations are increasing or have expanding ranges; others are stable, declining, or at risk, and a few have been extirpated (for example, the Dawson caribou, last observed on the Queen Charlotte Islands in 1908).²²¹⁹ Among rare species with limited ranges, both Vancouver Island marmot and spotted owl are endangered.²²²⁰ While spotted owl populations are decreasing, Vancouver Island marmot populations are increasing as a result of captive breeding and reintroduction efforts.²²²¹ Although few or no population trend data exist for many species (e.g., Pacific water shrew, marbled murrelet), their habitat is known to be declining in quantity and quality due to logging, urbanization, and agriculture.²²²²

Pacific Northwest

Western gray squirrel distribution in Oregon and Washington is mostly in conifer-hardwood forests with a strong component of Oregon white oak, and the forests they inhabit usually have some species of oak

²²⁰⁹ Verbatim from Stephenson et al. (2006, p. 369)

²²¹⁰ Nearly verbatim from Stephenson et al. (2006, p. 369)

²²¹¹ Verbatim from Stephenson et al. (2006, p. 369)

²²¹² Nearly verbatim from Stephenson et al. (2006, p. 368). *Stephenson et al. report statistics for the northerly ($r = 1.0$, $P < 0.001$) and westerly ($r = -0.9$, $P = 0.03$) shifts in the core area with increasing winter severity.*

²²¹³ Verbatim from Stephenson et al. (2006, p. 359)

²²¹⁴ Verbatim from Stephenson et al. (2006, p. 359)

²²¹⁵ Verbatim from Stephenson et al. (2006, p. 359)

²²¹⁶ Verbatim from Stephenson et al. (2006, p. 359)

²²¹⁷ Nearly verbatim from Pojar (2010, p. 10)

²²¹⁸ Nearly verbatim from North Cascades Conservation Council (2010, p. 25)

²²¹⁹ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 67)

²²²⁰ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 68)

²²²¹ Verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 68)

²²²² Nearly verbatim from B.C. Ministry of Forests, Mines and Lands. (2010, p. 68)

present.²²²³ Western gray squirrels have been positively associated with food-producing shrubs including snowberry, California hazel, bigleaf maple, vine maple, salal, and blackberries, and negatively associated with Scotch broom.²²²⁴ As noted in Chiller et al. (2000), Ryan and Carey (1995a) suggested two of the most limiting factors of western gray squirrel abundance are the availability of oak-dominated habitats and the availability of mast, and they suggested that management for western gray squirrels include a minimum of 18 square feet (~1.7 square meters) basal area of oaks.²²²⁵ Chiller et al. (2000) further note that Ryan and Carey predicted that the minimum size required for oak stands to support western gray squirrels was two to three acres (~0.8-1.2 hectares) for short-term usage and greater than five acres (~2 hectares) to support long-term requirements.²²²⁶

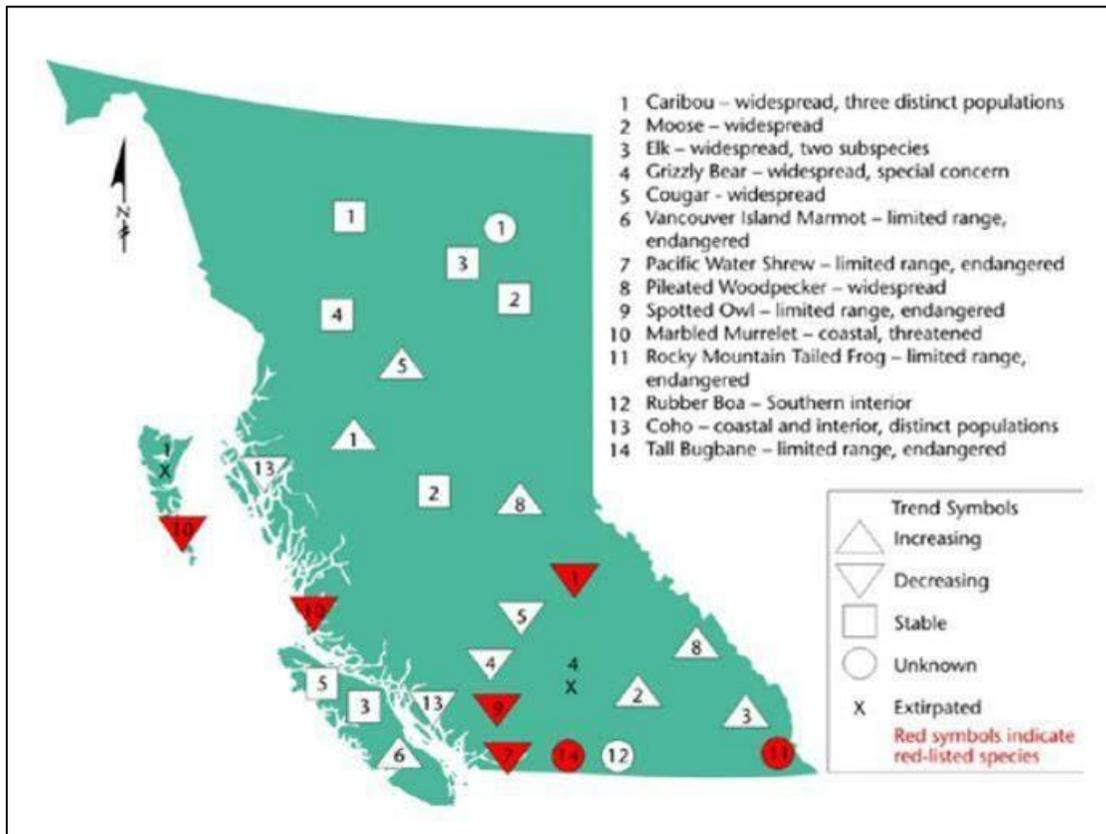


Figure 67. Population trends of some forest-associated species.

Source: Reproduced from B.C. Ministry of Forests, Mines, and Lands (2010, Figure 4-3, p. 67) by authors of this report.

²²²³ Verbatim from Chiller et al. (2000, p. 31-32). Chiller et al. cite Cross (1969) for information on Oregon white oak and Asserson (1974), Cross (1969), Foster (1992), and Gilman (1986) for information on oak species in general.

²²²⁴ Nearly verbatim from Chiller et al. (2000, p. 32). Chiller et al. cite Ryan and Carey (1995b) for this information.

²²²⁵ Verbatim from Chiller et al. (2000, p. 32). Chiller et al. cite Ryan & Carey (1995a) for this information. The secondary source is a Gen. Tech. Rep. 348 from the Pacific Northwest Research Station of the U.S. Forest Service and is titled “Biology and management of the western gray squirrel and Oregon white oak woodlands: with emphasis on Puget Trough.”

²²²⁶ Nearly verbatim from Chiller et al. (2000, p. 32). Chiller et al. cite Ryan and Carey (1995a) for this information.

Western Washington

Wildlife is abundant in the North Cascades, with many widespread species and others that are more limited by habitat characteristics.²²²⁷ Black bears, bobcats, coyotes, marten, deer, raccoons, and small mammals are common.²²²⁸ Other species, such as grizzly bears, mountain lions, lynx, wolverines, wolves, elk, mountain goats, western gray squirrels, river otters, golden eagles, marbled murrelets, and northern spotted owls are much less common.²²²⁹ Alpine and subalpine habitat areas provide important habitat for wolverines, grizzly bears, wolves, and mountain goats.²²³⁰ Low elevation forests also provide winter and spring habitat for migratory species like elk, deer, and their predators (e.g., wolves, cougars, coyotes).²²³¹

Specific information on observed trends for wolverine, gray wolf, grizzly bear, mountain goat, and fisher is available:

- **Wolverine:** The current range of wolverines in the lower 48 states has declined dramatically, with fewer than 1,000 individuals distributed widely in the more remote regions of the Cascades and Rocky Mountains.²²³² Wolverines all but disappeared from Washington in the early 1900s.²²³³ During the past two decades, wolverines have been sighted in the Mt. Baker-Snoqualmie and Okanogan-Wenatchee National Forests.²²³⁴ Only about 30% of the most suitable habitat for wolverines in Washington State is protected as national park or wilderness.²²³⁵
- **Gray wolf and grizzly bear:** Only about 50% of the most suitable habitat for gray wolves and grizzly bears is protected by park or wilderness status.²²³⁶ By 1930, wolves were thought to be extirpated from the North Cascades of Washington and were rarely seen in the North Cascades of British Columbia.²²³⁷ The current North Cascades grizzly bear population has fallen to an unsustainable level.²²³⁸ The population in Washington is estimated to be only five to ten bears.²²³⁹
- **Mountain goat:** There are multiple mountain goat herds in and around the North Cascades National Park.²²⁴⁰ However, mountain goats are more vulnerable to population declines than most other ungulate species.²²⁴¹
- **Fisher:** Fishers have only 19% of their most suitable habitat protected in national parks or wilderness.²²⁴²

²²²⁷ Verbatim from North Cascades Conservation Council (2010, p. 8). *Biodiversity conservation in the North Cascades*.

²²²⁸ Nearly verbatim from North Cascades Conservation Council (2010, p. 8)

²²²⁹ Verbatim from North Cascades Conservation Council (2010, p. 8)

²²³⁰ Verbatim from North Cascades Conservation Council (2010, p. 4)

²²³¹ Nearly verbatim from North Cascades Conservation Council (2010, p. 20)

²²³² Verbatim from North Cascades Conservation Council (2010, p. 23)

²²³³ Verbatim from North Cascades Conservation Council (2010, p. 24)

²²³⁴ Verbatim from North Cascades Conservation Council (2010, p. 24)

²²³⁵ Verbatim from North Cascades Conservation Council (2010, p. 19). North Cascades Conservation Council cites Cassidy et al. (1997) for this information.

²²³⁶ Verbatim from North Cascades Conservation Council (2010, p. 19)

²²³⁷ Verbatim from North Cascades Conservation Council (2010, p. 24)

²²³⁸ Verbatim from North Cascades Conservation Council (2010, p. 25)

²²³⁹ Verbatim from North Cascades Conservation Council (2010, p. 25)

²²⁴⁰ Verbatim from North Cascades Conservation Council (2010, p. 26)

²²⁴¹ Nearly verbatim from North Cascades Conservation Council (2010, p. 26)

²²⁴² Nearly verbatim from North Cascades Conservation Council (2010, p. 20)

Western Oregon

Mammal species found only in (i.e., endemic to) Oregon include two species of shrew (Baird's shrew, Pacific shrew) and the Camas pocket gopher.²²⁴³ The red tree vole is endemic to Oregon and extreme northeastern California, and the gray vole is endemic to Oregon and Clark County of Washington.²²⁴⁴

Four species are reported to be closely associated with grasslands in the Willamette Valley: the deer mouse, camas pocket gopher, gray-tailed vole, and red fox.²²⁴⁵ The Camas pocket gopher and gray-tailed vole are both endemic to the Willamette Valley, including into Clark County, Washington in the case of the gray-tailed vole.²²⁴⁶ Numerous mammals in the Willamette Valley take opportunistic advantage of mast crops, tree cavities, and other special attributes of oak stands, but only three species demonstrate a close affinity for pure oak stands or the oak component within mixed stands: the California vole, western gray squirrel, and Columbia white-tailed deer.²²⁴⁷ The Columbia white-tailed deer was reportedly common on prairies and savannas at the time of European settlement, but only relict populations currently exist in Clatsop, Columbia, and Douglas Counties.²²⁴⁸ The species is believed to have been extirpated from the Willamette Valley.²²⁴⁹

Species listed under the Endangered Species Act include the endangered Columbian subspecies of the white-tailed deer, gray wolves, and the threatened Canada lynx, although lynx are not known to breed in Oregon.²²⁵⁰ Wolverine, possibly extirpated from Oregon but still occasionally reported, require persistent winter snows for successful reproduction and, thus, have been negatively affected by declining snowpack across North America.²²⁵¹

In the Willamette Valley, 48 percent of the stomach contents of four black-tailed deer were comprised of acorns.²²⁵²

Northwest California

Information needed.

²²⁴³ Nearly verbatim from Hixon et al. (2010, p. 282)

²²⁴⁴ Nearly verbatim from Hixon et al. (2010, p. 282)

²²⁴⁵ Nearly verbatim from Vesely & Rosenberg (2010, p. 15). Vesely & Rosenberg cite O'Neil et al. (2001) for information on the red fox.

²²⁴⁶ Verbatim from Vesely & Rosenberg (2010, p. 15)

²²⁴⁷ Verbatim from Vesely & Rosenberg (2010, p. 15). Vesely & Rosenberg cite O'Neil et al. (2001) for information on Columbia white-tailed deer.

²²⁴⁸ Verbatim from Vesely & Rosenberg (2010, p. 16). Vesely & Rosenberg cite Verts & Carraway (1998) for this information.

²²⁴⁹ Verbatim from Vesely & Rosenberg (2010, p. 16). Vesely & Rosenberg cite O'Neil et al. (2001) for this information.

²²⁵⁰ Nearly verbatim from Hixon et al. (2010, p. 282)

²²⁵¹ Nearly verbatim from Hixon et al. (2010, p. 284). Hixon et al. cite Brodie & Post (2010) for this information.

²²⁵² Nearly verbatim from Chiller et al. (2000, p. 30). Chiller et al. cite Coblenz (1980) for this information.

Future Projections

Western North America

An analysis of potential climate change impacts on mammalian species in eight U.S. national parks indicates that if atmospheric CO₂ doubles over baseline levels used in current assessments, U.S. national parks stand to lose between 0% and 20% of current mammalian species diversity in any one park (the majority of parks stand to lose between 0% and 10%), with an average loss for all parks of 8.3% (under CGCM2 coupled to MAPSS).²²⁵³ Table 31 shows results for western North America. The greatest losses across all parks occurred in rodent species (44%), bats (22%), and carnivores (19%).²²⁵⁴ Species are projected to decline in direct proportion to their current relative representation within parks.²²⁵⁵ However, species gains to the parks should outweigh species losses.²²⁵⁶ Burns et al. (2003) estimated that parks will gain between 11.6% and 92.5% more species relative to current numbers, with an average gain across all parks of 48.1%.²²⁵⁷ Results suggest that the effects of global climate change on wildlife communities may be most noticeable not as a drastic loss of species from their current ranges, but instead as a fundamental change in community structure as species associations shift due to influxes of new species.²²⁵⁸

There is little research on the effects of climate change on bats in the western United States, although Adams and Hayes (2008) determined that the fringed bat had high water requirements during lactation and would have less successful reproduction if the climate becomes more arid.²²⁵⁹ In a study of little brown bats, integrating projections of climate change into a model (i.e., of the relationship between ambient temperature and energy expenditure during hibernation) predicts a pronounced northward range expansion of hibernating little brown bats within the next 80 years (by 2080 under HadCM2-GAX; baseline not provided).²²⁶⁰ The correspondence between predicted and observed hibernaculum (i.e., winter hibernation sites) microclimates and between predicted and observed northern hibernaculum localities provides strong evidence that the distribution of little brown bat is constrained by thermal effects on hibernation energetics.²²⁶¹

²²⁵³ Nearly verbatim from Burns et al. (2003, p. 11475). Burns et al. refer the reader to Table 1 in the cited article for this information.

²²⁵⁴ Verbatim from Jezierski et al. (2010, p. 11). Jezierski et al. cite Burns et al. (2003) for this information.

²²⁵⁵ Verbatim from Jezierski et al. (2010, p. 11). Jezierski et al. cite Burns et al. (2003) for this information.

²²⁵⁶ Nearly verbatim from Burns et al. (2003, p. 11476). *Global climate change and mammalian species diversity in U.S. national parks*. Burns et al. refer the reader to Table 1 in the cited article for this information.

²²⁵⁷ Verbatim from Burns et al. (2003, p. 11476). Burns et al. refer the reader to Table 2 in the cited article for this information.

²²⁵⁸ Verbatim from Burns et al. (2003, p. 11476)

²²⁵⁹ Nearly verbatim from Hixon et al. (2010, p. 284)

²²⁶⁰ Nearly verbatim from Humphries et al. (2002, p. 313)

²²⁶¹ Nearly verbatim from Humphries et al. (2002, p. 315). In the cited article, Humphries et al. refer the reader to Figure 2 for information on hibernaculum microclimates and to Figure 3 for information hibernaculum localities.

Contiguous areas of snow cover >386 square miles (>1000 square kilometers) in size, which are large enough to support small breeding populations of wolverines and presumably large enough for short-term population persistence, are retained in both the Ensemble 2085 and 29 May MODIS projections (i.e., an ensemble of 10 GCMs under the A1B scenario for 2070-2099; baseline period unclear, and for MODIS, a comparison of persistent snow cover on May 29 vs. May 15).²²⁶² In particular, British Columbia contains extensive areas of spring snow cover that are connected to snow-covered areas in northwestern Montana.²²⁶³ Additionally, large snow-covered areas exist in northern Washington, along the Montana–Idaho border, and in the Greater Yellowstone Area.²²⁶⁴ States in the contiguous U.S. where wolverines currently occur (Washington, Idaho, Montana, and Wyoming) retain 75.3% of their spring snow cover based on Ensemble 2045 (i.e., an ensemble of 10 GCMs run with the A1B scenario for 2030-2059; baseline period unclear).²²⁶⁵ However, by the late 21st century, dispersal modeling indicates that habitat

Table 31. Current species found in four western U.S. national parks and predicted species losses, gains, and net turnover under a doubling of atmospheric CO₂.

National Park	Current species richness ¹	Species lost	Species gained	Turnover ²	Species gained by taxonomic order ³						
					Bats	Carnivores	Insectivores	Hares, rabbits, & pikas	Rodents	Hoofed mammals	Other
Glacier	52	2	45	43	7 (15.6)	2 (4.4)	7 (15.6)	5 (11.1)	22 (48.9)	1 (2.2)	1 (2.2)
Yellowstone	53	0	49	49	6 (12.2)	4 (8.2)	10 (20.4)	4 (8.2)	23 (26.9)	1 (2.0)	1 (2.0)
Yosemite	64	6	25	19	2 (8.0)	3 (12.0)	5 (20.0)	1 (4.0)	13 (52.0)	1 (4.0)	0 (0.0)
Zion	53	1	41	40	3 (7.3)	5 (12.2)	7 (17.1)	3 (7.3)	19 (40.1)	2 (4.9)	2 (4.9)

1. Based on park species lists and Faunmap data for mammal species available.

2. Turnover calculated as species gained minus species lost.

3. Values are numbers and percentages (in parentheses) of species gained.

Source: Modified from Burns et al. (2003, Tables 1-2, p. 11475-11476) by authors of this report.

²²⁶² Nearly verbatim from McKelvey et al. (2011, p. 2894). *Climate change predicted to shift wolverine distributions, connectivity, and dispersal corridors.* Note: McKelvey et al. follow the methods of Hamlet & Lettenmaier (2005) and Elsner et al. (2010). The former method begins with data from 1915-2003, and reports results for several time periods within that range. The latter uses a 1917-2006 baseline.

²²⁶³ Verbatim from McKelvey et al. (2011, p. 2894)

²²⁶⁴ Verbatim from McKelvey et al. (2011, p. 2894). McKelvey et al. refer the reader to Figure 13 in the cited article for this information.

²²⁶⁵ Nearly verbatim from McKelvey et al. (2011, p. 2894). Note: McKelvey et al. follow the methods of Hamlet & Lettenmaier (2005) and Elsner et al. (2010). The former method begins with data from 1915-2003, and reports results for several time periods within that range. The latter method uses a 1917-2006 baseline.

isolation at or above levels associated with genetic isolation of wolverine populations becomes widespread.²²⁶⁶ Overall, wolverine habitat is expected to persist throughout the species range at least for the first half of the 21st century, but populations will likely become smaller and more isolated.²²⁶⁷

deVos Jr. & McKinney (2007) expect the abundance and distribution of mule deer and elk in hotter and drier ecoregions to be adversely affected most as climate change progresses.²²⁶⁸ Conversely, in ecoregions where extreme winters presently limit these populations in some years (i.e., generally outside the NPLCC region), short-term effects on abundance and distribution may be positive, but long-term effects are uncertain.²²⁶⁹ Further, deVos Jr. & McKinney (2007) suggest abundance of elk may increase at least locally in many areas of western North America due to their ability to utilize a wide array of low to moderate quality forage to meet their metabolic demands.²²⁷⁰ Throughout elk and mule deer range in western North America, if elevated levels of atmospheric CO₂ increase concentrations of secondary plant compounds that potentially inhibit digestion, forage digestion by mule deer likely would be inhibited more than elk.²²⁷¹

A parasite of concern as global warming continues is the mule deer muscleworm, a common parasite of black-tailed deer and mule deer in western North America.²²⁷² The muscleworm has the potential to for population-level impacts to mule deer and other native cervids and bovids.²²⁷³ Northern distribution of this parasite is likely limited by cold temperatures suitable for larval development, but climate warming may soon eliminate such constraints.²²⁷⁴

Southcentral and Southeast Alaska

Climate change effects on wildlife in coastal temperate forests will be driven primarily by changes in snowpack and growing season length.²²⁷⁵ Snow depth and duration exert major effects on habitat for animals, burying forage for herbivores such as black-tailed deer, moose, and mountain goat, and providing protective cover for subnivean mammals such as the Northwestern deer mouse, long-tailed vole, and common shrew, and insulation to denning black and brown bears.²²⁷⁶

Rapid climate change will likely have significant negative effects to endemic species living in southeastern Alaska in part due to their isolation on islands.²²⁷⁷ Young managed rainforests of southeastern Alaska provide marginal habitat for Wrangell Island red-backed voles, but continued warming could increase fragmentation of red-backed vole populations by rendering clearcuts and young

²²⁶⁶ Nearly verbatim from McKelvey et al. (2011, p. 2882)

²²⁶⁷ Nearly verbatim from McKelvey et al. (2011, p. 2882)

²²⁶⁸ Nearly verbatim from DeVos, Jr. & McKinney (2007, p. 2)

²²⁶⁹ Nearly verbatim from DeVos, Jr. & McKinney (2007, p. 2)

²²⁷⁰ Nearly verbatim from DeVos, Jr. & McKinney (2007, p. 23)

²²⁷¹ Nearly verbatim from DeVos, Jr. & McKinney (2007, p. 17). DeVos, Jr. & McKinney cite Baker & Hansen (1985), Lindzey et al. (1997), and Keegan & Wakeling (2003) for this information.

²²⁷² Nearly verbatim from DeVos, Jr. & McKinney (2007, p. 18)

²²⁷³ Verbatim from DeVos, Jr. & McKinney (2007, p. 18). DeVos, Jr. & McKinney cite Lankester (2001) for this information.

²²⁷⁴ Verbatim from DeVos, Jr. & McKinney (2007, p. 18)

²²⁷⁵ Verbatim from Wolken et al. (2011, p. 17)

²²⁷⁶ Verbatim from Wolken et al. (2011, p. 17)

²²⁷⁷ Verbatim from Kelly et al. (2007, p. 64)

second-growth stands unsuitable.²²⁷⁸ Red-backed voles have high water requirements and are ordinarily excluded from clearcuts and young second-growth stands of western coniferous forest, because conditions are too dry in the exposed ground vegetation.²²⁷⁹ The extent to which other mesic forest specialists will be impacted remains unclear, but continued warming and drying will likely reduce the abundance and diversity of fungal communities, a potentially important food item of several endemic small mammals, including flying squirrels.²²⁸⁰

Models suggest that the distribution of the little brown bat will expand northward in Alaska in the next century in response to warming temperatures and shorter winters in its current range.²²⁸¹

Using the covariates mentioned above (see “Observed trends: Southcentral and Southeast Alaska”), results from Random Forests™ modeling showed shrinking range size for the Alaska marmot (A1B scenario; Figure 68).²²⁸² Statewide, total range area shrank by 27% by 2039, 81% by 2069, and 87% by 2099, as compared with present estimated range size (2000-2099).²²⁸³ In addition, previously contiguous habitat areas became disconnected.²²⁸⁴

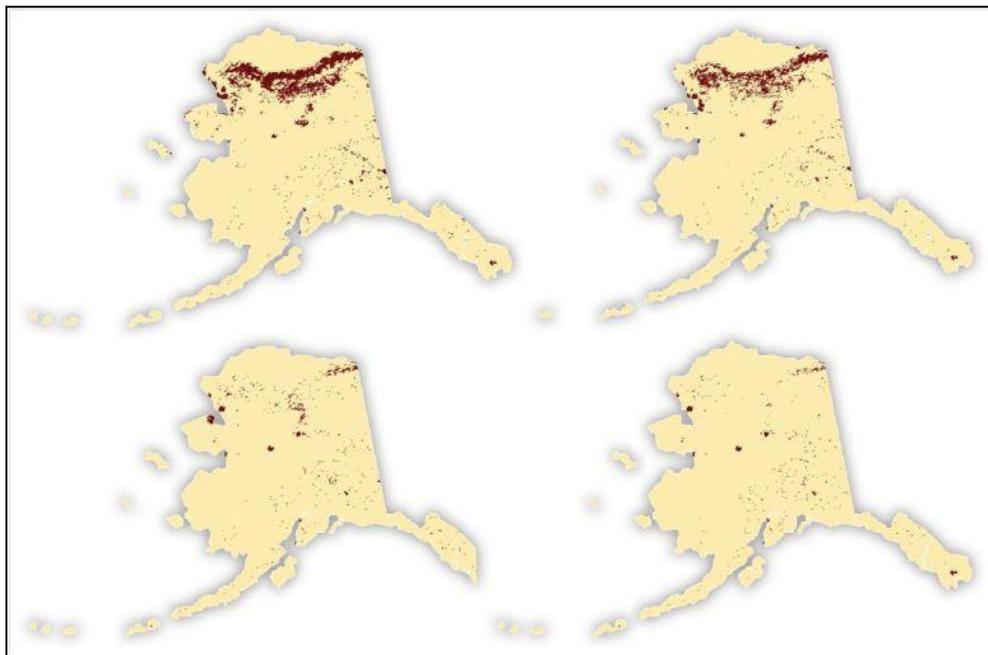


Figure 68. Projected Alaska marmot distribution. Marmot range is expected to diminish sharply as climate warms and alpine habitat shrinks. Clockwise from top left: 2000-2099, 2030-2039, 2060-2069, 2090-2099. *Source: Reproduced from Murphy et al. (2010, Fig. 20, p. 37) by authors of this report.*

²²⁷⁸ Nearly verbatim from Kelly et al. (2007, p. 63). Kelly et al. cite Smith & Nichols (2004) for information on marginal habitat for red-backed voles.

²²⁷⁹ Verbatim from Kelly et al. (2007, p. 63). Kelly et al. cite Smith & Nichols (2004) for this information.

²²⁸⁰ Verbatim from Kelly et al. (2007, p. 63-64). Kelly et al. cite Meyer & North (2005) for information on fungal communities and Smith (2007) for information on endemic small mammals, including flying squirrels.

²²⁸¹ Verbatim from Jezierski et al. (2010, p. 10). Jezierski et al. cite Humphries et al. (2002) for this information.

²²⁸² Nearly verbatim from Murphy et al. (August 2010, p. 36)

²²⁸³ Verbatim from Murphy et al. (August 2010, p. 36)

²²⁸⁴ Verbatim from Murphy et al. (August 2010, p. 36)

Longer growing seasons could benefit wildlife species such as black-tailed deer by increasing the total area of snow-free winter range, increasing winter energy availability, decreasing winter energy expenditures, and increasing the availability of high quality foods in spring at a critical time of the annual nutritional cycle, thereby decreasing winter mortality.²²⁸⁵ Increasing populations of deer, on the other hand, are likely to exert significant browsing pressure on the vegetation of their habitat, changing vegetation composition and structure.²²⁸⁶ Deer, vegetation, and wolves are likely to interact in complex patterns in relation to a changing climate, principally mediated through snow regime; populations may grow during successive mild winters but crash more severely during periodic cold winters.²²⁸⁷

Winter range availability, especially during periodic severe winters, will ultimately dictate the upper limit of the Copper River Delta moose population.²²⁸⁸ The decline in early successional communities such as gravel and open alder-willow and the increase in more mature types foretells a future decline in the forage base in the glacial outwash plain.²²⁸⁹ By 2040, closed alder-willow also will begin to decline and subsequently the cottonwood communities follow.²²⁹⁰ Estimates of the nutritional carrying capacity for moose in the glacial outwash plain winter range are shown in Table 32.

Table 32. Estimates of the nutritional carrying capacity for moose in the glacial outwash plain winter range of the west Copper River Delta, Alaska, during 1959-2040 under very mild (no snow) and severe winter conditions.				
Burial of browse by snow	Nutritional Carrying Capacity, by Year			
	<i>Absolute change (% change vs. 1959)</i>			
	1959	1986	2013	2040
None	1,110 (N/A)	1,126 (+1.4%)	950 (-14%)	871 (22%)
Severe (~50%)	453 (N/A)	310 (-32%)	261 (-42%)	239 (-47%)
<i>Source: Modified from Stephenson et al. (2006, Table 8, p. 368) by authors of this report.</i>				

High-elevation snowpack will affect some animals directly, such as mountain goats.²²⁹¹ However, it will affect a wide range of low-elevation animals indirectly through effects on streamflow and the production and availability of salmon, which are a major summer food resource for a diverse group of mammals, birds, and insects.²²⁹² Salmon play a critical role in body size, population density, and productivity of brown bear, nesting success and productivity of bald eagle, timing and success of reproduction in mink, and body condition and survival of American marten.²²⁹³ In the coastal temperate forest, as in other regions, the responses of anadromous salmonids to climate change differs among fish species and depends on their life cycle in freshwater and at sea.²²⁹⁴ For additional

²²⁸⁵ Verbatim from Wolken et al. (2011, p. 17). Wolken et al. cite Parker et al. (199) for this information, with the exception of information on decreasing winter mortality.

²²⁸⁶ Verbatim from Wolken et al. (2011, p. 17). Wolken et al. cite Hanley (1987) for this information.

²²⁸⁷ Verbatim from Wolken et al. (2011, p. 17-18)

²²⁸⁸ Verbatim from Stephenson et al. (2006, p. 370)

²²⁸⁹ Nearly verbatim from Stephenson et al. (2006, p. 369)

²²⁹⁰ Verbatim from Stephenson et al. (2006, p. 369)

²²⁹¹ Verbatim from Wolken et al. (2011, p. 18)

²²⁹² Verbatim from Wolken et al. (2011, p. 18). Wolken et al. cite Gende et al. (2002) for this information.

²²⁹³ Verbatim from Wolken et al. (2011, p. 18). Wolken et al. cite Hilderbrand et al. (1999) for information on brown bear, Hansen (1987) for information on bald eagle, Ben-David (1997) and Ben-David et al. (1997a) for information on mink, and Ben-David et al. (1997b) for information on American marten.

²²⁹⁴ Verbatim from Wolken et al. (2011, p. 18). Wolken et al. cite Bryant (2009) for this information.

information on the implications of climate change for Pacific salmon, please see the cited companion report.²²⁹⁵

Western British Columbia

Herbivores (including large ungulates) currently may base their reproductive cycles or seasonal migrations on day-length, while vegetation emerges in the spring more as a consequence of local temperatures.²²⁹⁶ As local temperatures increase and vegetation leafs out earlier in the season, successful herbivore reproduction might decline—as it evidently has in Arctic caribou.²²⁹⁷ However, some species that have been transplanted to southern latitudes have adapted quickly.²²⁹⁸

Western Washington

Wolverine habitat is being directly threatened by climate change.²²⁹⁹ As temperatures rise, more and more of the wolverine's high mountain habitat will probably be lost.²³⁰⁰ Snow is an important, even critical, component of the wolverine's seasonal habitat requirements and is considered an obligate component of reproductive denning habitat through thermal benefits and protection from predators.²³⁰¹ The distribution of spring snow cover has been shown to be concordant with year-round wolverine habitat associations as well as specific movement paths.²³⁰² As such, the distribution of spring snow cover appears to define a bioclimatic niche for the wolverine, the distribution and productivity of which may be adversely impacted by global warming.²³⁰³ For example, wolverines need deep snow cover from February to early May to provide insulation for kits in their dens.²³⁰⁴ Reduced snow cover will impact the availability of denning sites.²³⁰⁵ Ideal denning sites are becoming more scarce as the snow in high mountain areas melts out more quickly in the spring.²³⁰⁶

Western Oregon

Canada lynx are associated with winter snow cover and could be affected by changes in snowpack.²³⁰⁷ In addition, snowshoe hares are a key prey item in northern North America food webs and an essential prey for the Canada lynx, making it an appropriate focal species for understanding functional mismatches among interacting species under climate change.²³⁰⁸ In a study from the northern Rocky Mountains,

²²⁹⁵ Tillmann & Siemann (2011a)

²²⁹⁶ Nearly verbatim from Pojar (2010, p. 20)

²²⁹⁷ Nearly verbatim from Pojar (2010, p. 20). Pojar cites Post & Forchhammer (2008) for this information.

²²⁹⁸ Nearly verbatim from Pojar (2010, p. 20). Pojar cites Demarchi & Mitchell (1973) for this information.

²²⁹⁹ Verbatim from North Cascades Conservation Council (2010, p. 24)

²³⁰⁰ Verbatim from North Cascades Conservation Council (2010, p. 24)

²³⁰¹ Nearly verbatim from Running & Mills (2009, p. 20). Running & Mills cite Magoun & Copeland (1998) for this information.

²³⁰² Verbatim from Running & Mills (2009, p. 20). Running & Mills cite Schwartz et al. (in press) for this information.

²³⁰³ Verbatim from Running & Mills (2009, p. 20)

²³⁰⁴ Nearly verbatim from North Cascades Conservation Council (2010, p. 24)

²³⁰⁵ Verbatim from North Cascades Conservation Council (2010, p. 24)

²³⁰⁶ Verbatim from North Cascades Conservation Council (2010, p. 24)

²³⁰⁷ Nearly verbatim from Hixon et al. (2010, p. 284). Hixon et al. cite Verts & Carraway (1998) for information on the association of Canada lynx with snow cover.

²³⁰⁸ Nearly verbatim from Mills et al. (2013, p. 7360). *Camouflage mismatch in seasonal coat color due to decreased snow duration*. Mills et al. cite Traill et al. (2010) for this information.

without evolution in coat color phenology (i.e., from brown to white in winter and from white to brown in spring), reduced snow duration will increase the number of days that white hares will be mismatched on a snowless background by four- to eightfold by the end of the century (2070-2099 vs. 1970-1999; 19 CMIP5 models run with RCP4.5 and RCP8.5; see Box 1).²³⁰⁹ *For additional information on lynx, please see the section in this chapter on observed trends in Western North America.*

Northwest California

Information needed.

Information Gaps

Additional information on observed trends and future projections for northwest California are needed, future projections for western Oregon, and specific projections throughout the NPLCC region are needed, as few to no studies are presented here.

Anticipating the impacts of future climate change on mammals requires:

1. Understanding how to accurately downscale global climate change models to regional scales
2. Understanding the effects of climate on habitat (in particular, vegetation and surface water)
3. Understanding the effects of changes in habitat, precipitation, and temperature on physiology, behavior, and population dynamics
4. Understanding complex interactions among species and with other factors, such as disease.²³¹⁰

The first two areas are being addressed in other arenas of climate change research, whereas the third often must be approached on a species-by-species basis.²³¹¹ Species inhabiting deserts, high elevations, and other ecosystems already identified as “high risk” are the most obvious candidates for future research.²³¹² Refining predictions for future precipitation and identifying basic relationships among mammalian population dynamics and climate variables may be the highest priorities for future research.²³¹³ In addition, physiological investigations into critical temperatures for the wolverine could be important for understanding and anticipating the potential impacts of climate change on wolverine distribution and population persistence.²³¹⁴

²³⁰⁹ Nearly verbatim from Mills et al. (2013, p. 7360). Mills et al. cite Traill et al. (2010) for this information.

²³¹⁰ Nearly verbatim from Hixon et al. (2010, p. 284)

²³¹¹ Verbatim from Hixon et al. (2010, p. 284)

²³¹² Verbatim from Hixon et al. (2010, p. 284). Hixon et al. cite Loarie et al. (2009) for information on desert species and Parmesan (2006) for information on high elevation species.

²³¹³ Verbatim from Hixon et al. (2010, p. 284)

²³¹⁴ Nearly verbatim from Copeland et al. (2010, p. 242)

2. Birds

The direct effects of climate change on birds include loss of critical habitat, behavior, distribution, population dynamics, and phenology; many of these effects are driven by changes in precipitation and temperature.²³¹⁵ For example, the response of insect phenology to temperature change (approximately 6 days per °C) is greater than that of birds (~2 d/°C), creating a mismatch between date of egg-laying and peak food abundance.²³¹⁶ Overall, climate change is expected to lead to significant range changes for many bird species.²³¹⁷ Indirect effects of climate change on birds include sea level rise, changes in fire regimes, vegetation changes, land use changes, altered competitive interactions among species, and ecosystem reordering.²³¹⁸ Birds most at risk from habitat loss are those that are specialized in their habitat needs – including those species that are restricted to islands, alpine zones, or coastal beaches for critical parts of their life history.²³¹⁹ This section focuses on observed trends and future projections for terrestrial birds in the NPLCC region.

Observed Trends

North America

The egg-laying date in tree swallows advanced by up to nine days during 1959-1991.²³²⁰ This advance in phenology was associated with increasing surface air temperatures at the time of breeding.²³²¹ There was a significant negative interaction between longitude and temperature, which indicates that the relationship between laying date and temperature was steeper (i.e., more negative), and thus the rate of change in laying date was greater, at more western locations (higher longitude).²³²² In contrast, there was a positive interaction between latitude and temperature, which indicates that the relationship between laying date and temperature was steeper, and thus the rate of change in laying date was greater, at more southern locations (lower latitude) within the range of swallows (northern U.S. and Canada).²³²³ The mechanism for earlier laying in tree swallows is probably an advancement in the date of emergence or peak abundance of aerial insects.²³²⁴ Tree swallows feed primarily on dipterans and other flying arthropods

²³¹⁵ Nearly verbatim from Audubon Washington (2009a, p. 1). *Birds & Climate Change: Washington's Birds at Risk*.

²³¹⁶ Nearly verbatim from Robinson et al. (2008, p. 92). Robinson et al. cite Sparks & Menzel (2002) and Root et al. (2003) for information on the response of insect and bird phenology to temperature change. Robinson et al. cite Both et al. (2004) for information on the mismatch between date of egg-laying and peak food abundance.

²³¹⁷ Nearly verbatim from Audubon Washington (2009a, p. 1)

²³¹⁸ Verbatim from Audubon Washington (2009a, p. 1)

²³¹⁹ Verbatim from Audubon Washington (2009a, p. 1). Washington Audubon cites Butler & Taylor (2005) for this information.

²³²⁰ Verbatim from Dunn & Winkler (1999, p. 2487). *Climate change has affected the breeding date of tree swallows throughout North America*.

²³²¹ Verbatim from Dunn & Winkler (1999, p. 2487). *Note: Dunn & Winkler report a strong negative relationship between laying date and spring temperatures, i.e., the mean of April and May temperatures: $p = 0.0001$ (p. 2489).*

²³²² Verbatim from Dunn & Winkler (1999, p. 2489). Dunn & Winkler refer the reader to Table 1 in the cited article for this information.

²³²³ Nearly verbatim from Dunn & Winkler (1999, p. 2489). Dunn & Winkler refer the reader to Table 1 in the cited article for this information.

²³²⁴ Verbatim from Dunn & Winkler (1999, p. 2489)

whose abundance is directly related to air temperature.²³²⁵ Alternatively, higher spring temperatures could advance laying directly by reducing the energy requirements of pre-reproductive females.²³²⁶

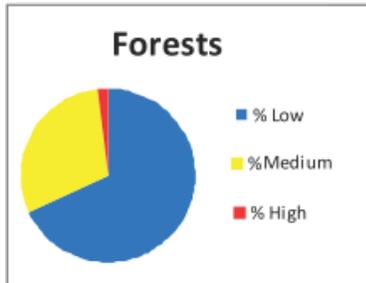


Figure 69. U.S. forest bird vulnerability to climate change. Overall, only 2% of forest bird species show high vulnerability to climate change, and another 30% show medium vulnerability. *Source: Reproduced from NABCI (2010, p. 20) by authors of this report.*

Across North America, tree swallows show extraordinarily little variation in the relationship between clutch size and timing of breeding.²³²⁷ As in other studies of tree-swallow breeding biology, the very strong effect of lay date on clutch size was negative: for every day later that a bird began laying, its final clutch size averaged 0.03 fewer eggs.²³²⁸ However, the distributions of egg-laying dates were more constricted in the warmest (and earliest) years, suggesting that changes in mean clutch size might be constrained by changes in the distribution of laying dates.²³²⁹

In the U.S., although only 2% of forest bird species show high vulnerability to climate change, more than half of the species with medium or high vulnerability were not previously considered species of conservation concern.²³³⁰ Among species that are restricted to a single forest type, a higher proportion of birds in eastern forests (75%) show medium or high vulnerability than birds in western (57%), boreal (49%), or subtropical (27%) forests.²³³¹

Southcentral and Southeast Alaska

A large tree die-off (of white spruce trees in the Copper River area due to a spruce beetle infestation) decreased the density of ruby-crowned kinglets as their habitat structure changed.²³³² The extensive tree mortality, however, opened the forest allowing shrubs to proliferate and concurrently greatly reduced the population of an important avian nest predator (red squirrel).²³³³ The opening of the forests and the reduction of nest predators overall appears to have benefitted breeding birds.²³³⁴

In a modeling and connectivity study, Murphy et al. (2010) selected the trumpeter swan as a species of interest because, like many other birds species in the state, it is migratory.²³³⁵ As such, statewide

²³²⁵ Verbatim from Dunn & Winkler (1999, p. 2489-2490). Dunn & Winkler cite Robertson et al. (1992) for information on feeding preferences for dipterans and flying arthropods, and Roeder (1953) for information on the relationship between abundance and air temperature.

²³²⁶ Verbatim from Dunn & Winkler (1999, p. 2490). Dunn & Winkler cite Winkler & Allan (1996) and D. W. Winkler & P. O. Dunn, unpublished data, for this information.

²³²⁷ Verbatim from Winkler et al. (2002, p. 13598). *Predicting the effects of climate change on avian life-history traits.*

²³²⁸ Verbatim from Winkler et al. (2002, p. 13597). Winkler et al. refer the reader to Table 1 in the cited article for this information. Winkler et al. cite Winkler & Allan (1996), Dunn et al. (2000), and Stutchbury & Robertson (1988) for information on other studies of tree-swallow breeding biology.

²³²⁹ Verbatim from Winkler et al. (2002, p. 13595)

²³³⁰ Nearly verbatim from North American Bird Conservation Initiative (2010, p. 20)

²³³¹ Verbatim from North American Bird Conservation Initiative (2010, p. 20)

²³³² Nearly verbatim from Kelly et al. (2007, p. 62)

²³³³ Verbatim from Kelly et al. (2007, p. 62). Kelly et al. cite Matsuoka et al. (2001) for this information.

²³³⁴ Verbatim from Kelly et al. (2007, p. 62). Kelly et al. cite Matsuoka et al. (2001) for this information.

²³³⁵ Nearly verbatim from Murphy et al. (2010, p. 38)

connectivity of habitat may not be an issue for them.²³³⁶ However, quantity and quality of habitat are pertinent to the survival of this species.²³³⁷ Swans are limited, in part, by summer season length to fledge their young.²³³⁸ Trumpeter swans in Alaska require 138 ice-free days to fledge their young successfully.²³³⁹ Trumpeter swans in Alaska have responded positively to a longer growing season by extending their breeding season.²³⁴⁰ In addition to the longer breeding season, habitats that were previously inhospitable to this species have become available as a result of an extended ice-free period.²³⁴¹ This range expansion, however, may result in competition with the tundra swan for breeding areas.²³⁴² Figure 71 shows the current and projected range for trumpeter swans.

Western British Columbia

Information on observed trends for birds on southeast Vancouver Island is available, and is presented following information on goshawks, Wilson's phalarope, Lewis's woodpecker, Swainson's thrush, and yellow warbler:

- **Goshawks:** Warmer, wetter springs in west central B.C. could be at least partly responsible for reduced nest area reoccupancy and breeding success of goshawks.²³⁴³ Increased precipitation is linked to a decrease in prey abundance, and warmer spring temperatures are associated with high rates of mortality as a result of attacks on nestlings by black flies.²³⁴⁴
- **Wilson's phalarope:** When all observations are considered, there is no apparent trend in timing of northward movements of Wilson's phalarope over the past 82 years (i.e., 1922-2003), although there are an increasing number of later observations with the passage of time.²³⁴⁵ When the observations are separated into two groups (coastal and interior) there again is no strong distinction, although more of the later observations appear among interior ecoprovinces.²³⁴⁶ However, examining only the earliest and latest dates of arrival produced unexpected results.²³⁴⁷ The smaller coastal population appears to be arriving significantly later, and departing significantly earlier, though the relationship is not strong.²³⁴⁸ Available data on clutch initiation for Wilson's phalarope indicate that birds in the Georgia Depression breed earliest (May 22nd on average, compared to the rest of the province), but there are no data after 1976 when the tendency

²³³⁶ Verbatim from Murphy et al. (August 2010, p. 38)

²³³⁷ Verbatim from Murphy et al. (August 2010, p. 38)

²³³⁸ Verbatim from Murphy et al. (August 2010, p. 38)

²³³⁹ Verbatim from Murphy et al. (August 2010, p. 38). The authors cite Mitchell (1994) for this information.

²³⁴⁰ Verbatim from Leicht-Young et al. (2013b, p. 2). *Observed changes in phenology across the United States – Alaska and the Arctic*.

²³⁴¹ Verbatim from Leicht-Young et al. (2013b, p. 2)

²³⁴² Verbatim from Leicht-Young et al. (2013b, p. 2). Leicht-Young et al. cite Schmidt et al. (2011) for this information.

²³⁴³ Nearly verbatim from Pojar (2010, p. 16)

²³⁴⁴ Nearly verbatim from Pojar (2010, p. 16). Pojar cites Doyle (2008) for this information.

²³⁴⁵ Nearly verbatim from Bunnell & Squires (2005, p. 21). *Evaluating potential influences of climate change on historical trends in bird species*. Bunnell & Squires refer the reader to Figure 17 in the cited report for this information.

²³⁴⁶ Verbatim from Bunnell & Squires (2005, p. 21)

²³⁴⁷ Nearly verbatim from Bunnell & Squires (2005, p. 21). Bunnell & Squires refer the reader to Figure 19 in the cited report for this information.

²³⁴⁸ Verbatim from Bunnell & Squires (2005, p. 21)

to arrive later begins.²³⁴⁹ However, from 1958 to 1987, there was no discernible trend in date of clutch initiation.²³⁵⁰ Maps of relative density between decades for Wilson's phalarope suggest both spatial extension of the range northward and an increase in relative density within northern regions.²³⁵¹ By the 1990s, the northward extension of the range had proceeded such that almost 30% of occupied cells were north of 52° N (vs. < 5% during the 1960s).²³⁵²

- **Lewis's woodpecker:** While there are no apparent trends in arrival and departure dates of migrants, there is an apparent increase in over-wintering birds.²³⁵³ Within the Georgia Depression over-wintering records increased from four during the period 1890 to 1950 to 40 during the period 1960 to 2003.²³⁵⁴ The maps of relative density between decades suggest that there has been relatively little tendency for Lewis's Woodpecker to move farther north in the province, but that there has been an increase in relative density in northern regions of its occupied range.²³⁵⁵
- **Swainson's thrush:** There is no evidence of over-wintering in the northeast, but an increase in over-wintering in both the coastal and interior ecoprovinces.²³⁵⁶ Moreover, there may be a tendency to arrive early in coastal ecoprovinces.²³⁵⁷ The tendency for earlier arrival is strongest in the southern coastal areas, becoming increasingly less so in more northern regions.²³⁵⁸ The regression analyses estimate 5.6 days earlier per decade on the coast, 4.2 days per decade for the interior, but only 2.0 days per decade in the northeast.²³⁵⁹ The earlier arrival in coastal areas is particularly pronounced, and combined with the later departure suggest that migratory individuals are extending their duration of stay in British Columbia by about 10 days per decade.²³⁶⁰ Maps suggest that by the 1990's the Swainson's thrush expanded its range in central and northern areas of the province, though the bulk of numbers remained concentrated in the south (vs. 1960s).²³⁶¹ The percent of total observations over the entire province that were north of 54° increased from 0.7% to 12% between the same two decades (i.e., 1990s vs. 1960s).²³⁶²
- **Yellow warbler:** Over the past century, the yellow warbler has shown a pronounced tendency to arrive earlier and depart later.²³⁶³ The tendency for early arrival is more apparent in southern and

²³⁴⁹ Nearly verbatim from Bunnell & Squires (2005, p. 21-22). Bunnell & Squires refer the reader to Figure 19 in the cited report for this information.

²³⁵⁰ Nearly verbatim from Bunnell & Squires (2005, p. 38). Bunnell & Squires refer the reader to Figure 36 in the cited report for this information.

²³⁵¹ Nearly verbatim from Bunnell & Squires (2005, p. 34). Bunnell & Squires refer the reader to Figure I.5 in the cited report for this information. *Note: Bunnell & Squires state both trends are statistically significant.*

²³⁵² Nearly verbatim from Bunnell & Squires (2005, p. 34). Bunnell & Squires refer the reader to Figure 32a in the cited report for this information. *Note: Bunnell & Squires state the extension is significant: K-S test, $p = 0.003$.*

²³⁵³ Nearly verbatim from Bunnell & Squires (2005, p. 25). Bunnell & Squires refer the reader to Figure 21 in the cited report for this information.

²³⁵⁴ Verbatim from Bunnell & Squires (2005, p. 25)

²³⁵⁵ Verbatim from Bunnell & Squires (2005, p. 35). Bunnell & Squires refer the reader to Figure I.6 in the cited report for this information.

²³⁵⁶ Nearly verbatim from Bunnell & Squires (2005, p. 26)

²³⁵⁷ Verbatim from Bunnell & Squires (2005, p. 26)

²³⁵⁸ Verbatim from Bunnell & Squires (2005, p. 26)

²³⁵⁹ Verbatim from Bunnell & Squires (2005, p. 26). *Note: Bunnell & Squires state these trends are significant ($p < 0.01$), but the r^2 value for the northeast is particularly weak ($p = 0.26$).*

²³⁶⁰ Verbatim from Bunnell & Squires (2005, p. 26)

²³⁶¹ Nearly verbatim from Bunnell & Squires (2005, p. 35). Bunnell & Squires refer the reader to Figure I.7 in the cited report for this information.

²³⁶² Nearly verbatim from Bunnell & Squires (2005, p. 36)

²³⁶³ Nearly verbatim from Bunnell & Squires (2005, p. 29)

the most northern populations.²³⁶⁴ The tendency for later departure and increasing incidence of over-wintering is apparent only in the south.²³⁶⁵ Maps suggest that by the 1990's the yellow warbler has clearly expanded its range into more northerly areas of the province, though the bulk of numbers remain concentrated in more southerly regions.²³⁶⁶

On southeast Vancouver Island, tests were conducted to determine whether bird abundance in remnant patches of Garry oak and adjacent Douglas-fir is related to Garry oak volume, patch size or urbanization.²³⁶⁷ Information on bird presence and abundance in Garry oak habitat, Douglas-fir communities, and in response to urbanization and human population density is available:

- **Bird presence and abundance in Garry oak habitat:** Only two species favor Garry oak habitat over Douglas-fir forest.²³⁶⁸ The brown-headed cowbird is avoiding the closed-canopy forest and selecting for oak habitat.²³⁶⁹ The chipping sparrow is also selecting for Garry oak habitat.²³⁷⁰ Unlike the cowbird, it is restricted to those oak patches surrounded by Douglas-fir forest, thus showing a response to surrounding habitat.²³⁷¹ The chipping sparrow may be the only species for which the Garry oak ecosystem is a vital component for its persistence in the region.²³⁷² Further studies on chipping sparrow use and productivity in other open-habitats are needed to test this claim.²³⁷³
- **Bird presence and abundance in Douglas-fir communities:** Although a community of oak associated species is not currently present, a small Douglas-fir forest community existed.²³⁷⁴ Three species (winter wren, brown creeper and golden-crowned kinglet) showed preference for Douglas-fir forest patches.²³⁷⁵ These species are associated with conifer forests in other Pacific Northwest landscapes.²³⁷⁶
- **Effects of urbanization and human population density on bird presence and abundance:** Urbanization factors, rather than patch type, were related to population size for the majority of the species analyzed.²³⁷⁷ Human population density—an indicator of urbanization in the landscape—was correlated to population size for five species (orange-crowned warbler, chestnut-backed chickadee, dark-eyed junco, Townsend's warbler, and Anna's hummingbird).²³⁷⁸

²³⁶⁴ Verbatim from Bunnell & Squires (2005, p. 29)

²³⁶⁵ Verbatim from Bunnell & Squires (2005, p. 29)

²³⁶⁶ Nearly verbatim from Bunnell & Squires (2005, p. 36). Bunnell & Squires refer the reader to Figure I.8 in the cited report for this information. *Note: Bunnell & Squires state the expansion in space is significant: K-S test, $p < 0.034$.*

²³⁶⁷ Nearly verbatim from Feldman & Krannitz (2002, p. 169)

²³⁶⁸ Verbatim from Feldman & Krannitz (2002, p. 175)

²³⁶⁹ Verbatim from Feldman & Krannitz (2002, p. 175)

²³⁷⁰ Verbatim from Feldman & Krannitz (2002, p. 175)

²³⁷¹ Verbatim from Feldman & Krannitz (2002, p. 175)

²³⁷² Verbatim from Feldman & Krannitz (2002, p. 175)

²³⁷³ Verbatim from Feldman & Krannitz (2002, p. 175)

²³⁷⁴ Verbatim from Feldman & Krannitz (2002, p. 175)

²³⁷⁵ Verbatim from Feldman & Krannitz (2002, p. 175)

²³⁷⁶ Verbatim from Feldman & Krannitz (2002, p. 175). Feldman & Krannitz cite Anderson (1972), McGarrigal and McComb (1995) and Schwab and Sinclair (1994) for this information.

²³⁷⁷ Verbatim from Feldman & Krannitz (2002, p. 175)

²³⁷⁸ Verbatim from Feldman & Krannitz (2002, p. 175)

Pacific Northwest

In a 12-year study of northern flickers, birds arrived earlier at breeding sites when temperatures along the migration route rose.²³⁷⁹ However, the strongest negative correlation between laying dates and ambient temperatures occurred after the arrival of most birds on the breeding site, which suggests that the ability of females to accumulate resources for egg laying on the breeding site was an important determinant of laying times.²³⁸⁰ At the population level, egg laying advanced by 1.15 days for every degree warmer on the breeding grounds.²³⁸¹ At the level of individuals, laying dates advanced as females aged from 1 to 3 years, and females in better body condition also laid earlier.²³⁸² However, there was no interaction between female age and ambient temperature, which suggests that the age classes had equal capacity to respond to environmental change.²³⁸³ Reproductive output declined seasonally as a result of declines in clutch size and not as a result of reduced fledgling success.²³⁸⁴ This suggests that there is no ecological mismatch linked to prey availability for northern flickers and that individuals could benefit by laying earlier if spring temperatures allow.²³⁸⁵

Among the 49 species highly associated with prairie-oak habitats, 21 have experienced extirpations, range contractions, and/or regional population declines.²³⁸⁶ Six species have expanded their range in prairie-oak habitats in the last fifty years.²³⁸⁷ Specific results for extirpations, range changes, and population trends are available:

- **Extirpations and range contractions:** Nine prairie-oak species have experienced local or ecoregional extirpations and/or range contractions.²³⁸⁸ These species include sandhill crane, which was extirpated from the Puget Lowlands shortly after Euro-American settlement, and streaked horned lark, which has been extirpated from two ecoregions, Georgia Depression and Klamath Mountains.²³⁸⁹ Three prairie-oak species have been extirpated as breeding species from the region since the 1940s.²³⁹⁰ Burrowing owl had a breeding population in the Rogue Valley and scattered breeding pairs elsewhere.²³⁹¹ Lewis's woodpecker formerly bred throughout the region.²³⁹² Say's phoebe had local breeding populations in the Willamette Valley and the Klamath

²³⁷⁹ Verbatim from Leicht-Young et al. (2013, p. 2)

²³⁸⁰ Verbatim from Wiebe & Gerstmar (2010, p. 917). *Influence of spring temperatures and individual traits on reproductive timing and success in a migratory woodpecker.*

²³⁸¹ Verbatim from Wiebe & Gerstmar (2010, p. 917)

²³⁸² Verbatim from Wiebe & Gerstmar (2010, p. 917)

²³⁸³ Verbatim from Wiebe & Gerstmar (2010, p. 917)

²³⁸⁴ Verbatim from Wiebe & Gerstmar (2010, p. 917)

²³⁸⁵ Verbatim from Wiebe & Gerstmar (2010, p. 917)

²³⁸⁶ Verbatim from Altman (2011, p. 194). *Historical and current distribution and populations of bird species in prairie-oak habitats in the Pacific Northwest.*

²³⁸⁷ Verbatim from Altman (2011, p. 194)

²³⁸⁸ Verbatim from Altman (2011, p. 199). Altman refers the reader to Table 1 in the cited article for this information.

²³⁸⁹ Verbatim from Altman (2011, p. 199)

²³⁹⁰ Verbatim from Altman (2011, p. 196). Altman refers the reader to Table 1 in the cited article for this information.

²³⁹¹ Verbatim from Altman (2011, p. 196-197)

²³⁹² Verbatim from Altman (2011, p. 197)

Mountains ecoregions.²³⁹³ The predominant pattern of range contraction starts at the northern end of a species range and moves southward.²³⁹⁴

- **Range expansions:** Six prairie-oak species have expanded their breeding range in the last fifty years.²³⁹⁵ Two of the six species, white-tailed kite and western scrub-jay, appear to be continuing to expand their range; one species, acorn woodpecker, seems to have stabilized; and three species, Anna's hummingbird, blue-gray gnatcatcher, and grasshopper sparrow, have only appeared in the region as breeding species in the last fifty years.²³⁹⁶ The predominant pattern of range expansion starts at the northern edge of a species range and moves northward.²³⁹⁷
- **Population trends:** Five species have a moderate or high degree of confidence in Christmas Bird Count trends from 1966-2006.²³⁹⁸ Two species are increasing – western bluebird (3.6% per year) and western scrub-jay (2.1% per year); two species are declining – slender-billed white-breasted nuthatch (2.2% per year) and western meadowlark (2.4% per year); and one has a stable population trend – acorn woodpecker.²³⁹⁹

Additional information is available on the range and population of two species endemic to prairie-oak habitats west of the Cascades in the Pacific Northwest (the streaked horned lark, Oregon vesper sparrow):

- **Historic range:** The historical breeding range of streaked horned lark included wet and dry prairie habitats and open coastal plains from the Georgia Depression ecoregion south through the Puget Lowlands and Willamette Valley ecoregions, and into the Rogue Valley, Oregon in the Klamath Mountains ecoregion.²⁴⁰⁰ The historical breeding range of Oregon vesper sparrow included dry prairie and oak savanna habitats from the Georgia Depression ecoregion south through the Puget Lowlands and Willamette Valley ecoregions, and into the Klamath Mountains ecoregion south to Del Norte County, California.²⁴⁰¹
- **Population declines and current population estimate:** Based on data from 544 roadside point counts in grassland habitats in the Willamette Valley in 1996 and repeated in 2008, the number of western meadowlark and Oregon vesper sparrow detections declined by 59% and 79% respectively.²⁴⁰² Streaked horned lark detections remained relatively stable during the same time period.²⁴⁰³ Estimates of lambda that include vital rates from all streaked horned lark nesting areas in Washington (i.e., south Puget Lowlands, coast, islands in the Columbia River) indicate that the population is declining by 40 percent per year between 2002-2005, apparently due to a combination of low survival and fecundity rates.²⁴⁰⁴ Estimates of regional population size for

²³⁹³ Verbatim from Altman (2011, p. 197)

²³⁹⁴ Verbatim from Altman (2011, p. 194)

²³⁹⁵ Verbatim from Altman (2011, p. 210)

²³⁹⁶ Verbatim from Altman (2011, p. 210)

²³⁹⁷ Verbatim from Altman (2011, p. 194)

²³⁹⁸ Nearly verbatim from Altman (2011, p. 212)

²³⁹⁹ Verbatim from Altman (2011, p. 212)

²⁴⁰⁰ Verbatim from Altman (2011, p. 196). Altman cites Beason (1995) and Pearson & Altman (2005) for this information.

²⁴⁰¹ Verbatim from Altman (2011, p. 196). Altman cites Jones & Cornely (2002) for this information.

²⁴⁰² Verbatim from Altman (2011, p. 211). Altman cites Altman (1999) for information on the 1996 study and Myers & Kreager (2010) for information on the 2008 study.

²⁴⁰³ Verbatim from Altman (2011, p. 211-212)

²⁴⁰⁴ Verbatim from Altman (2011, p. 212). Altman cites Camfield et al. (2010) for this information and reports lambda as follows: $\lambda = 0.61 \pm 0.10$ SD (SD = standard deviation).

these two subspecies is < 2,000 (i.e., 1170-1610) birds for streaked horned lark and < 3,000 (i.e., 1540-2770) birds for Oregon vesper sparrow.²⁴⁰⁵

In the maritime Pacific Northwest (i.e., west of the Cascade Mountains), bird communities and effects of fire are best known from the western hemlock vegetation type, which has a high-severity fire regime.²⁴⁰⁶ The post-fire stand-initiation stage in this type supports a reasonably distinct avifauna compared to other successional stages, a phenomenon that has been documented for high-severity fire regimes in other regions.²⁴⁰⁷ In general, there is a high turnover of species after high-severity fires, with a shift primarily from canopy-dwelling to ground-, shrub-, and snag-dwelling species that mostly are not associated with other successional stages.²⁴⁰⁸ The most likely bird communities vulnerable to these changes (i.e., changes in fire suppression) are in low-severity, high-frequency fire regimes that include the Douglas-fir type,



Figure 70. Washington's Important Bird Areas comprise diverse natural habitats from shrub-steppe to mountains, forests to shores, and the open Pacific Ocean.

Source: Reproduced from *Washington Audubon* (2009b, p. 2) by authors of this report.

State, only 33% of the most suitable habitat for spotted owls and 25% of the most suitable habitat for marbled murrelets are protected in national parks or wilderness.²⁴¹² Currently, the spotted owl population in Washington State continues to decline precipitously due to loss of habitat and possibly competition from barred owls.²⁴¹³ Recent surveys have found significantly fewer owls than were found in surveys performed only a decade ago.²⁴¹⁴ The marbled murrelet population in Washington, Oregon, and California

drier portions of the white fir type, Oregon-oak woodlands and savannas, native grasslands and sclerophyllous shrublands (i.e., shrublands composed of vegetation with hard leaves and a short distance between leaves along the stem).²⁴⁰⁹

Western Washington

Many of Washington's 74 Important Bird Areas are vital stops along the Pacific Flyway, one of the Western Hemisphere's biannual migration routes (Figure 70).²⁴¹⁰

In the North Cascades, low elevation forests provide winter and spring habitat for migratory wildlife and essential habitat for several endangered birds (e.g., spotted owls, marbled murrelets).²⁴¹¹ In Washington

²⁴⁰⁵ Nearly verbatim from Altman (2011, p. 213). Note: The specific estimates of breeding populations are found in Table 3 in the cited article.

²⁴⁰⁶ Nearly verbatim from Huff et al. (2005, p. 46). *Fire and birds in maritime Pacific Northwest*.

²⁴⁰⁷ Verbatim from Huff et al. (2005, p. 46)

²⁴⁰⁸ Verbatim from Huff et al. (2005, p. 46)

²⁴⁰⁹ Nearly verbatim from Huff et al. (2005, p. 46)

²⁴¹⁰ Audubon Washington (2009b, p. 2). *State of the Birds 2009: Summary Report*.

²⁴¹¹ Nearly verbatim from North Cascades Conservation Council (2010, p. 4)

²⁴¹² Verbatim from North Cascades Conservation Council (2010, p. 20). North Cascades Conservation Council cites Cassidy et al. (1997) for this information.

²⁴¹³ Verbatim from North Cascades Conservation Council (2010, p. 27)

²⁴¹⁴ Verbatim from North Cascades Conservation Council (2010, p. 27)

has been declining precipitously at four to seven percent per year.²⁴¹⁵ Only nine nests have been found in Washington State, although the breeding population is estimated at 1,800 birds.²⁴¹⁶

Western Oregon

In Oregon, 360 bird species regularly occur and an additional 135 are more occasional visitors.²⁴¹⁷ Among land birds breeding in Oregon, three are federally listed under the U.S. Endangered Species Act: Northern Spotted Owl, Western Snowy Plover, and the Marbled Murrelet.²⁴¹⁸ The largest urban areas in Oregon are located in the Willamette Valley, and common urban birds such as Vaux's swift and common nighthawks are declining.²⁴¹⁹ Resident urban birds appear to be holding their own, yet migrants such as the swifts and nighthawks are not.²⁴²⁰

Data from the Breeding Bird Survey indicate 15 species are experiencing significant population declines in western Oregon grasslands.²⁴²¹ Only two species, the common yellow-throat and red-winged blackbird, are increasing in numbers.²⁴²² At least six species once present on Willamette Valley grasslands no longer breed in the region or have been entirely extirpated: the sandhill crane, burrowing owl, Lewis' woodpecker, Say's phoebe, lark sparrow, and black-billed magpie.²⁴²³ Two subspecies endemic to western Oregon grasslands, the streaked horned lark and Oregon vesper sparrow were once common in the Willamette Valley, but now only occur in local populations.²⁴²⁴

Oak woodlands support avian communities that differ from conifer-dominated stands in the Willamette Valley and have a higher proportion of Neotropical migrants.²⁴²⁵ Species that are characteristic of oak woodlands and less common in conifer forests include the western wood-pewee, lazuli bunting, Cassin's vireo, and Bullock's oriole.²⁴²⁶ In a comparison of bird communities observed in oak woodlands during 1967-68 to observations made at the same sites 28 years later, three species (yellow warbler, common bushtit, and chipping sparrow) were common during the earlier period but were not detected at all during the later survey.²⁴²⁷ Species that had increased in abundance included the Swainson's thrush, Pacific slope

²⁴¹⁵ Verbatim from North Cascades Conservation Council (2010, p. 28). North Cascades Conservation Council cites McShane et al. (2004) for this information.

²⁴¹⁶ Verbatim from North Cascades Conservation Council (2010, p. 28)

²⁴¹⁷ Nearly verbatim from Hixon et al. (2010, p. 278). Hixon et al. cite Marshall et al. (2003) for this information.

²⁴¹⁸ Nearly verbatim from Hixon et al. (2010, p. 278)

²⁴¹⁹ Nearly verbatim from Hixon et al. (2010, p. 280). Hixon et al. cite NABCI (2009) for this information.

²⁴²⁰ Verbatim from Hixon et al. (2010, p. 280)

²⁴²¹ Nearly verbatim from Vesely & Rosenberg (2010, p. 18). Vesely & Rosenberg cite Altman et al. (2001) for this information.

²⁴²² Verbatim from Vesely & Rosenberg (2010, p. 18). Vesely & Rosenberg cite Altman et al. (2001) for this information.

²⁴²³ Verbatim from Vesely & Rosenberg (2010, p. 18). Vesely & Rosenberg cite Altman et al. (2001) for information on lark sparrow and O'Neil et al. (2001) for information on black-billed magpie.

²⁴²⁴ Verbatim from Vesely & Rosenberg (2010, p. 18). Vesely & Rosenberg cite Gabrielson & Jewett (1940) for information on past occurrence in the Willamette Valley and Altman (2003a), Altman (2003b), and Moore (2008a) for information on current occurrence in local populations.

²⁴²⁵ Verbatim from Vesely & Rosenberg (2010, p. 18). Vesely & Rosenberg cite Hagar & Stern (2001) for this information.

²⁴²⁶ Verbatim from Vesely & Rosenberg (2010, p. 18). Vesely & Rosenberg cite Hagar & Stern (2001) for information on Bullock's oriole.

²⁴²⁷ Nearly verbatim from Vesely & Rosenberg (2010, p. 18). Vesely & Rosenberg cite Anderson (1970) for information on the 1967-1968 time period and Hagar & Stern (2001) for information gathered 28 years later.

flycatcher, and purple finch.²⁴²⁸ The principle cause for differences in species composition at the woodland sites were successional changes in the plant community and a resulting increase in tree density and canopy closure.²⁴²⁹

Northwest California

Using combined sensitivity and exposure scores as an index, Gardali et al. (2012) ranked 358 avian taxa in California, and classified 128 as vulnerable to climate change.²⁴³⁰ Birds associated with wetlands had the largest representation on the list relative to other habitat groups.²⁴³¹ On the other end of the spectrum, grassland and oak woodland taxa were the least vulnerable to climate change.²⁴³² Of the 29 state or federally listed taxa, 21 were also classified as climate vulnerable, further raising their conservation concern.²⁴³³ Integrating climate vulnerability and California's Bird Species of Special Concern list resulted in the addition of five taxa and an increase in priority rank for ten.²⁴³⁴

In central and northern California, 13 of 21 species (62%) of Nearctic-Neotropical birds showed a change in arrival time, with eight species arriving earlier, two later, and three with a mixed response at different sites.²⁴³⁵ Of the 13 species, 10 (77%) are classified as likely or highly like climate associates.²⁴³⁶ The remaining three species are possible climate associates.²⁴³⁷ Specific results for birds in northern California are provided in Table 33.

Migrants tend to arrive earlier in association with warmer temperatures, positive NAO indices, and stronger ENSO indices.²⁴³⁸ Using correlation analysis, of the 13 species with a significant ($P < 0.10$) change in arrival, the arrival timing of 10 species (77%) is associated with both temperature and a large-scale climate oscillation index (El Niño Southern Oscillation, ENSO; North Atlantic Oscillation, NAO; and/or Pacific Decadal Oscillation, PDO) at least at one location.²⁴³⁹

²⁴²⁸ Verbatim from Vesely & Rosenberg (2010, p. 18)

²⁴²⁹ Nearly verbatim from Vesely & Rosenberg (2010, p. 18). Vesely & Rosenberg cite Hagar & Stern (2001) for this information

²⁴³⁰ Nearly verbatim from Gardali et al. (2012, p. 1). *A Climate Change Vulnerability Assessment of California's At-Risk Birds*. Note: Gardali et al. state that they judged adaptive capacity to be too difficult to score given how little information and guidance exists upon which to make objective assessments. They also state that several components of sensitivity may be considered indirect proxies of adaptive capacity, including dispersal ability and habitat specialization (p. 11).

²⁴³¹ Verbatim from Gardali et al. (2012, p. 1)

²⁴³² Verbatim from Gardali et al. (2012, p. 10-11)

²⁴³³ Verbatim from Gardali et al. (2012, p. 1)

²⁴³⁴ Verbatim from Gardali et al. (2012, p. 1)

²⁴³⁵ Nearly verbatim from Leicht-Young et al. (2013c, p. 2). *Observed changes in phenology across the United States – Southwest: California, Nevada, Utah, Colorado, Arizona, and New Mexico*.

²⁴³⁶ Verbatim from MacMynowski et al. (2007, p. 7). *Changes in spring arrival of Nearctic-Neotropical migrants attributed to multiscalar climate*.

²⁴³⁷ Verbatim from MacMynowski et al. (2007, p. 7)

²⁴³⁸ Verbatim from MacMynowski et al. (2007, p. 1)

²⁴³⁹ Verbatim from MacMynowski et al. (2007, p. 1)

Table 33. Arrival dates and climate associations of 13 northern California bird species.

Species	Climate*	Time Period	Median first arrival Julian [†] date	Median continuous arrival Julian date
Barn swallow	Very Likely	1980-2003	76	82.5
Black-headed grosbeak	Very Likely	1980-1992	107	110.5
Black-throated gray warbler	Likely	1979-1994	101	103
House wren	Possible	1982-1994	94.5	94.5
MacGillivray's warbler	Possible	1981-1992	110	111
Nashville warbler	Likely	1980-1994	92.5	108.5
Olive-sided flycatcher	Likely	1979-1992	118	127
Vaux's swift	Likely	1980-1994	102	106.5
Warbling vireo	Very Likely	1981-2003	90	92
Western kingbird	Very Likely	1979-2003	105	109
Western tanager	None	1979-2004	106	116
Western wood-pewee	Likely	1980-2003	121.5	127
Wilson's warbler	Very Likely	1981-1994	97	103

* Four categories of association between a species' phenology and climate are defined: (1) very likely (significant correlations ($P < 0.10$) of the same sign for both temperature and a climate index at two or more locations); (2) likely (significant correlations of the same sign for both temperature and a climate index at one location); (3) possible (significant correlation with only one climate variable or inconsistent signs for climate variables between locations); and (4) none (no significant correlations between arrival and climate variables). Trends in arrival over the study period were calculated with linear regression.

[†] Julian date is the number of days since the beginning of the year. For example, Julian day 32 is February 1.

Source: Modified from MacMynowski et al. (2007, Table 2, p. 5) by authors of this report.

Future Projections

Global

Jetz et al. (2007) used the four Millennium Ecosystem Assessment (MA) scenarios, which incorporate information on climate change and land use change, to estimate impacts on the breeding range of 8,750 land bird species (2050 and 2100 vs. 1985; IMAGE 2.2 model run with B1, B2, A1, and A2, one each for the four MA scenarios).²⁴⁴⁰ Based on scenarios of habitat change, between approximately 4.5% and 10% of species were projected to have more than half of their current range transformed to different habitats by 2050, and approximately 10% to 20% were projected to have their range transformed by 2100.²⁴⁴¹ Specifically, Jetz et al. (2007) found that 950-1,800 of the world's 8,750 species of land birds could be imperiled by climate change and land conversion by the year 2100.²⁴⁴² Even under environmentally benign scenarios, at least 400 species are projected to suffer greater than 50% range reductions by the year 2050 (over 900 by the year 2100).²⁴⁴³ Although expected climate change effects at high latitudes are significant, species most at risk are predominantly narrow-ranged and endemic to the tropics, where projected range contractions are driven by anthropogenic land conversions.²⁴⁴⁴ Most of these species are

²⁴⁴⁰ Nearly verbatim from Staudt et al. (2012, p. 5-13)

²⁴⁴¹ Nearly verbatim from Staudt et al. (2012, p. 5-13 to 5-14)

²⁴⁴² Nearly verbatim from Jetz et al. (2007, p. 1211). *Projected impacts of climate and land-use change on the global diversity of birds.*

²⁴⁴³ Verbatim from Jetz et al. (2007, p. 1211)

²⁴⁴⁴ Verbatim from Jetz et al. (2007, p. 1211)

currently not recognized as imperiled.²⁴⁴⁵ Climate change was the dominating effect driving range contractions in temperate regions, whereas land cover and land use change was the dominating effect in the tropics.²⁴⁴⁶

With a different set of assumptions that allowed species to change their elevational limits in response to climate change, Sekercioglu et al. (2008) used an intermediate estimate of warming of approximately 5.0 °F (2.8°C) combined with the Millennium Ecosystem Assessment land cover change scenarios to project that by 2100, 4.5% to 6% of species would go extinct and an additional 20% to 30% of species would be at risk of extinction (2100 vs. 2000 under six emissions scenarios).²⁴⁴⁷ Sekercioglu et al. (2008) specifically considered the extinction risk of landbirds, 87% of all bird species.²⁴⁴⁸ Worldwide, every degree of warming projected a nonlinear increase in bird extinctions of about 100–500 species.²⁴⁴⁹ Only 21% of the species predicted to become extinct in Sekercioglu et al.'s (2008) scenarios are currently considered threatened with extinction.²⁴⁵⁰

For migratory birds, the effects of climate change will not be uniform across regions, so for long-distance migrants, in particular, the use of local climatic cues that historically have been used to identify the best time to migrate from the non-breeding areas may mean populations no longer arrive at breeding sites at the appropriate time.²⁴⁵¹ This may partly explain why population declines in a wide range of temperate migrant birds are most pronounced for those that migrate the greatest distances.²⁴⁵² Furthermore, delays in spring arrival by migratory birds may lead to increased competition for nest sites with species arriving earlier.²⁴⁵³

Western North America

In general, because of their large ranges and high reproductive potential, forest birds are predicted to fare better in a changing climate than birds in other habitats.²⁴⁵⁴ Important exceptions include species that are specialized on highly seasonal resources, such as aerial insects or nectar, or that are dependent on high-elevation, extremely humid, or riparian forests.²⁴⁵⁵ For example, forest birds showing medium vulnerability include large flycatchers that feed on aerial insects and bird species in riparian or humid forests, mostly in the West, that are at risk from increased drought conditions and more frequent fires.²⁴⁵⁶

²⁴⁴⁵ Verbatim from Jetz et al. (2007, p. 1211)

²⁴⁴⁶ Verbatim from Staudt et al. (2012, p. 5-14)

²⁴⁴⁷ Nearly verbatim from Staudt et al. (2012, p. 5-14). *Note: Sekercioglu et al. provide real numbers in their estimates: a best guess of 400-550 landbird extinctions, and an additional 2150 species at risk of extinction by 2100.*

²⁴⁴⁸ Sekercioglu et al. (2008, p. 140)

²⁴⁴⁹ Verbatim from Sekercioglu et al. (2008, p. 140). *Climate change, elevation range shifts, and bird extinctions.*

²⁴⁵⁰ Verbatim from Sekercioglu et al. (2008, p. 140)

²⁴⁵¹ Nearly verbatim from Robinson et al. (2008, p. 92). Robinson et al. cite Visser et al. (2004) for this information.

²⁴⁵² Nearly verbatim from Robinson et al. (2008, p. 92). Robinson et al. cite Sanderson et al. (2006) for this information.

²⁴⁵³ Nearly verbatim from Walther et al. (2002, p. 394). Walther et al. cite Both & Visser (2001) for this information.

²⁴⁵⁴ Verbatim from North American Bird Conservation Initiative (2010, p. 21). *The State of the Birds Report on Climate Change: United States of America.*

²⁴⁵⁵ Verbatim from North American Bird Conservation Initiative (2010, p. 21)

²⁴⁵⁶ Nearly verbatim from North American Bird Conservation Initiative (2010, p. 20-21)

White-tailed ptarmigan and rosy-finches may disappear from mountaintops as alpine tundra diminishes.²⁴⁵⁷

The ranges of many forest birds will probably shift as ranges of tree species shift, generally northward or to higher elevations.²⁴⁵⁸ Some species may become less common in the United States as their ranges increase in Canada.²⁴⁵⁹ Conversely, species currently occurring primarily in Mexico may become more common in the United States.²⁴⁶⁰ For Western Hemisphere landbirds, Sekercioglu et al.'s (2008) intermediate extinction estimates based on climate-induced changes in actual distributions ranged from 1.3% (~2.0 °F, 1.1 °C warming) to 30.0% (~11 °F, 6.4 °C warming) of these species (2100 vs. 2000 under six emissions scenarios).²⁴⁶¹

Increased drought and frequency of fire in western forests may also alter forest bird communities.²⁴⁶² More than a third of forest birds are Neotropical migrants.²⁴⁶³ These long-distance migrating birds may experience mismatches in the timing of breeding with the availability of seasonal food resources, causing ecological disruption of bird communities or reproductive failure.²⁴⁶⁴

Southcentral and Southeast Alaska

Resident birds of the Sitka spruce and western hemlock forest in southeastern Alaska, such as blue grouse, may benefit as that forest type moves upslope and expands in size as warming trends continue over this century.²⁴⁶⁵ Alpine habitat, for species such as ptarmigan, is predicted to be reduced, fragmented, or even eliminated as it is converted to spruce/hemlock forest.²⁴⁶⁶

Using the same methodology and climate data described for modeling biomes (see Chapter VI.2 in this report), Murphy and colleagues modeled potential shifts in swan climate-linked habitat, using SNAP temperature and precipitation data for summer and winter for the current decade and three future decades (2000–2009, 2030–2039, 2060–2069, and 2090–2099).²⁴⁶⁷ Model results showed distribution expanding west and north (Figure 71), but did not predict movement into the Arctic.²⁴⁶⁸ It should be noted that this shift might be happening already.²⁴⁶⁹ Since biologists cannot easily distinguish tundra versus trumpeter swans from the air, mixing is probably occurring already at the interface between habitats along the northern and western parts of the range.²⁴⁷⁰

²⁴⁵⁷ Verbatim from North American Bird Conservation Initiative (2010, p. 5)

²⁴⁵⁸ Verbatim from North American Bird Conservation Initiative (2010, p. 21)

²⁴⁵⁹ Verbatim from North American Bird Conservation Initiative (2010, p. 21)

²⁴⁶⁰ Verbatim from North American Bird Conservation Initiative (2010, p. 21)

²⁴⁶¹ Verbatim from Sekercioglu et al. (2008, p. 140)

²⁴⁶² Verbatim from North American Bird Conservation Initiative (2010, p. 21)

²⁴⁶³ Verbatim from North American Bird Conservation Initiative (2010, p. 21)

²⁴⁶⁴ Verbatim from North American Bird Conservation Initiative (2010, p. 21)

²⁴⁶⁵ Verbatim from Kelly et al. (2007, p. 62)

²⁴⁶⁶ Verbatim from Kelly et al. (2007, p. 62)

²⁴⁶⁷ Nearly verbatim from Murphy et al. (August 2010, p. 38)

²⁴⁶⁸ Verbatim from Murphy et al. (August 2010, p. 38)

²⁴⁶⁹ Verbatim from Murphy et al. (August 2010, p. 38)

²⁴⁷⁰ Verbatim from Murphy et al. (August 2010, p. 38)

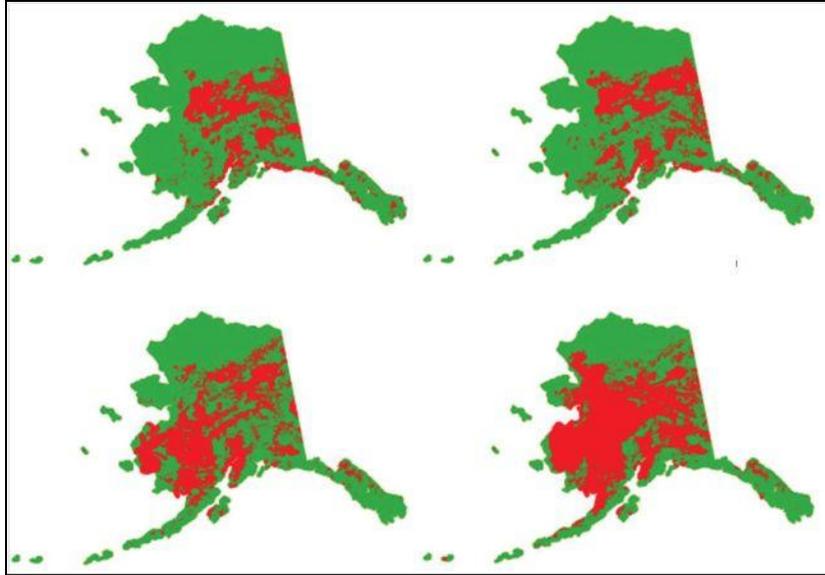


Figure 71. Potential expansion of trumpeter swan habitat. These predictions are based on 138-day ice-free season, summer and winter climate envelopes, as predicted by SNAP climate projections, and a competitive filter of non-forested biomes to represent tundra swans (not included in this figure). Trumpeter swans are predicted to shift their range northward and westward over the course of this century. Clockwise from top left: 2000-2009, 2030-2039, 2060-2069, 2090-2099. Red indicates trumpeters present. Green indicates trumpeters absent. *Source: Reproduced from Murphy et al. (2010, Fig. 21, p. 39) by authors of this report.*

Western British Columbia

Information needed.

Pacific Northwest

Model results for the northern spotted owl suggest that initial niche expansion may be followed by a contraction as climate change intensifies, but this prediction is uncertain due to variability in predicted changes in precipitation between climate projections (2011-2040 and 2061-2090 vs. 1961-1990 run with GISS-ER B1, ECHAM5 A2, and IPSL_CM4 A2 using Maxent).²⁴⁷¹ Winter precipitation was the most important climate variable identified, a finding consistent with previous demographic studies that suggest negative effects of winter and spring precipitation on survival, recruitment and dispersal.²⁴⁷² Specific results are available for changes in range size and location, predator-prey dynamics, and competition:

- **Change in range size and location:** Extrapolation of the best combination vegetation-climate model to future climates (assuming static vegetation) suggests northward expansion of high suitability northern spotted owl habitat.²⁴⁷³ Under the combination model, the range centroid moved 15.2 miles (24.4 km) north–northeast over the current to distant-future (i.e., 1961-1990 to

²⁴⁷¹ Nearly verbatim from Carroll (2010, p. 1432). *Role of climatic niche models in focal-species-based conservation planning: Assessing potential effects of climate change on northern spotted owl in the Pacific Northwest, USA.*

²⁴⁷² Verbatim from Carroll (2010, p. 1435). Carroll cites Franklin et al. (2000) for this information.

²⁴⁷³ Verbatim from Carroll (2010, p. 1436)

2061-2090) period.²⁴⁷⁴ Range size under the combination model was 4.60% and 2.52% larger than current range size for mean near-future and distant-future predictions, respectively (i.e., 2011-2040 and 2061-2090).²⁴⁷⁵ However, model results suggest that an initial expansion in the suitable climatic niche may be followed by a contraction as climate change intensifies.²⁴⁷⁶ Habitat suitability was reduced under projected future climates primarily in coastal Oregon (Figure 72).²⁴⁷⁷

- **Altered predator-prey dynamics and competition with barred owl:** Reduced winter precipitation and increased winter temperature under future climates might be expected to increase winter survival and nesting success and allow range expansion of prey species such as woodrat that currently occur at high densities only in the southern portions of the range.²⁴⁷⁸ Further, climate change could enhance the northern spotted owl's resiliency to barred owl competition, or alternately, such competition could make the northern spotted owl's northern range unavailable before it becomes more climatically favorable.²⁴⁷⁹

The projected northward expansion of prairie-oak habitat with climate change could result in further species range expansions, in particular for migratory species occurring in the Klamath Mountains such as ash-throated flycatcher and blue-gray gnatcatcher.²⁴⁸⁰ The northward expansion of habitat also may support the continued spread of species with expanding ranges such as white-tailed kite and western scrub jay.²⁴⁸¹ Further, it may enhance opportunities for species such as slender-billed white-breasted nuthatch, lark sparrow, and western meadowlark to repopulate areas to the north and beyond where their range has retracted from.²⁴⁸²

²⁴⁷⁴ Nearly verbatim from Carroll (2010, p. 1434)

²⁴⁷⁵ Nearly verbatim from Carroll (2010, p. 1434)

²⁴⁷⁶ Verbatim from Carroll (2010, p. 1436)

²⁴⁷⁷ Nearly verbatim from Carroll (2010, p. 1434). Carroll refers the reader to Figure 1c in the cited article for this information.

²⁴⁷⁸ Verbatim from Carroll (2010, p. 1436). Carroll cites Noon & Blakesley (2006) for this information.

²⁴⁷⁹ Nearly verbatim from Carroll (2010, p. 1437)

²⁴⁸⁰ Verbatim from Altman (2011, p. 215)

²⁴⁸¹ Verbatim from Altman (2011, p. 215)

²⁴⁸² Verbatim from Altman (2011, p. 215)

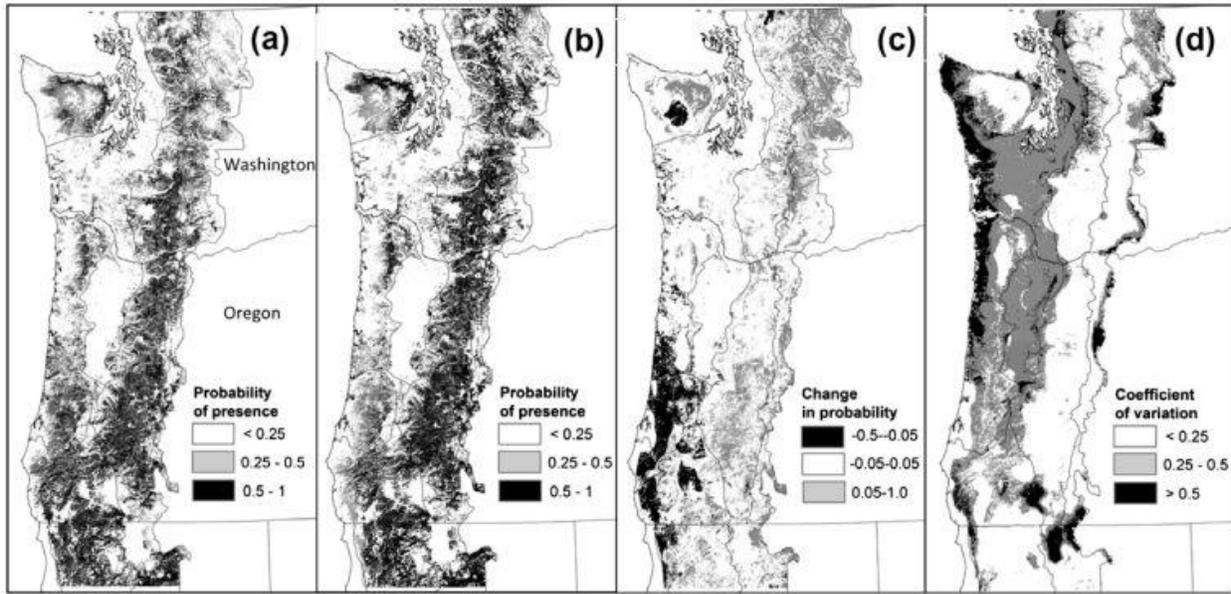


Figure 72. Results of analysis of habitat suitability for Northern Spotted Owl in the Pacific Northwest, USA, based on maximum entropy (Maxent) models using both climate and vegetation data. Figures show (a) predicted probability under current (1961–1990) climate, (b) mean predicted probability under three representative projections of future (2061–2090) climate, (c) change in probability between current and mean future predictions, and (d) coefficient of variation of future predictions.

Source: Reproduced from Carroll (2010, Figure 1, p. 1433) by authors of this report.

Western Washington

For Washington’s birds, temperature change is most likely to directly affect those species with limited ability to seek new ranges.²⁴⁸³ This includes species that are already near the southern or altitudinal limit of their ranges.²⁴⁸⁴ White-tailed ptarmigan, a species of alpine zones, could be pushed from its mountain top ranges.²⁴⁸⁵ This includes a population of ptarmigan near Mount Rainier, which is isolated from other Washington populations and may be genetically unique.²⁴⁸⁶ Ptarmigans are not migrants and typically move only short distances during the year, so the likelihood that individuals would migrate northward is remote.²⁴⁸⁷

Gray-crowned rosy-finch, another summer denizen of the alpine zone, would likely see its habitat shrink.²⁴⁸⁸ These finches are strong fliers and do range widely.²⁴⁸⁹ In response to increased temperatures they may simply move their range northward, with their numbers in Washington much reduced.²⁴⁹⁰ The

²⁴⁸³ Verbatim from Audubon Washington (2009a, p. 9)

²⁴⁸⁴ Verbatim from Audubon Washington (2009a, p. 9)

²⁴⁸⁵ Verbatim from Audubon Washington (2009a, p. 9)

²⁴⁸⁶ Verbatim from Audubon Washington (2009a, p. 9)

²⁴⁸⁷ Verbatim from Audubon Washington (2009a, p. 9)

²⁴⁸⁸ Verbatim from Audubon Washington (2009a, p. 9)

²⁴⁸⁹ Verbatim from Audubon Washington (2009a, p. 9)

²⁴⁹⁰ Verbatim from Audubon Washington (2009a, p. 9)

American pipit, another alpine breeding bird, barely has a range toehold in Washington.²⁴⁹¹ This species would likely shift northward as its mountain top habitat shrinks.²⁴⁹²

The three examples above all refer to birds that breed in Washington.²⁴⁹³ Also potentially affected are birds that traditionally winter in Washington.²⁴⁹⁴ Birds such as the northern shrike, snowy owl, and common redpoll that now descend from the northern boreal forests and subarctic may find Washington too warm in winter to meet their life history needs, or may find themselves competing with species that once migrated out of the state for winter, but no longer migrate under milder winter conditions.²⁴⁹⁵

Additional species potentially impacted by climate change are listed in Table 34.

Table 34. Washington Important Bird Area (Figure 70) species potentially impacted by increased forest fire intensity and changes in temperature and precipitation driven by climate change.

Forest Fire Intensity			
Beneficial	Low Risk	Moderate Risk	High Risk
Black-backed woodpecker Olive-sided flycatcher	Sooty grouse Williamson’s sapsucker	Northern goshawk Dusky grouse White-headed woodpecker Hermit warbler	Flammulated owl
Changes in temperature and precipitation			
	Black-crowned night-heron Cinnamon teal Common goldeneye Hooded merganser Osprey Lewis’s woodpecker	American bittern Canvasback Ring-necked duck Lesser scaup Ruddy duck Virginia rail Sora Sandhill crane Long-billed dowitcher Wilson’s snipe Wilson’s phalarope Forster’s tern Willow flycatcher	Western grebe Clark’s grebe Black-necked stilt American avocet Long-billed curlew Black tern

Source: Reproduced from Audubon Washington (2009, Tables shown on p. 7 and p. 10) by authors of this report.

Western Oregon

The Willamette Valley provides refuge for hundreds of thousands of Canada geese, dunlin, and other water birds in the winter.²⁴⁹⁶ The predicted warmer, wetter winters could enhance this wetland/savanna habitat.²⁴⁹⁷ However, the more ephemeral wetlands are created by rain, the more they are drained for

²⁴⁹¹ Verbatim from Audubon Washington (2009a, p. 10)
²⁴⁹² Verbatim from Audubon Washington (2009a, p. 10)
²⁴⁹³ Verbatim from Audubon Washington (2009a, p. 10)
²⁴⁹⁴ Verbatim from Audubon Washington (2009a, p. 10)
²⁴⁹⁵ Verbatim from Audubon Washington (2009a, p. 10)
²⁴⁹⁶ Nearly verbatim from Hixon et al. (2010, p. 280). Hixon et al. cite Taft & Haig (2003) for this information.
²⁴⁹⁷ Verbatim from Hixon et al. (2010, p. 280)

agricultural reasons.²⁴⁹⁸ Thus, summer residents such as Oregon's state bird, the western meadowlark, may not fare as well as warmer temperatures dry up water resources and invertebrates.²⁴⁹⁹

Impacts will probably be high for mountainous wetlands where temperature-sensitive birds will be unable to move upslope.²⁵⁰⁰ Lack of water or declining water levels in permanent and ephemeral Cascade Mountain lakes may most affect nearby cavity-nesting ducks such as the mergansers, common goldeneye, and bufflehead.²⁵⁰¹ Other Pacific forest birds of similar concern include marbled murrelet, spotted owl, olive-sided flycatcher, varied thrush, band-tailed pigeon, Rufous hummingbird, white-headed woodpecker, and chestnut-barked chickadee.²⁵⁰²

Warmer, wetter winters and hotter, drier summers may prove to be an additional challenge for the threatened northern spotted owl in the Coast Range and Cascade Mountains.²⁵⁰³ Glenn (2009) and Carroll (2010) both found changing climate, particularly wetter winters, accounted for moderate to high amounts of variation in owl survival and population growth rates.²⁵⁰⁴

McRae et al. (2008) similarly found that small changes in vital rates resulting from climate change or other stressors can have large consequences for population trajectories in winter wrens in mature conifer forests in the Cascades (i.e., in the Upper South Santiam Watershed in the Willamette National Forest), as well as song sparrows, which prefer more open, shrubby Cascade habitats:²⁵⁰⁵

- With minor warming (i.e., +2.7 °F, +1.5 °C in 2045 vs. 20th century) and reduced fecundity (i.e., 5% over 50 years), winter wren populations declined an average of 47% and 61% by 2060 and 2100, respectively, and song sparrows declined an average of 30% and 27%, respectively (vs. 1990).²⁵⁰⁶
- For both species, maximum declines resulted from the combination of the reduced fecundity climate scenario and the development scenario, with winter wrens declining by 55% and 71% in 2060 and 2100, respectively, and song sparrows declining by 39% and 32%, respectively.²⁵⁰⁷
- When combined with the conservation land-use scenario, the fourth climate scenario (i.e., 5% decline in fecundity over 50 years) resulted in winter wren populations that were an average of 41% smaller in 2060 than those in which fecundity remained unchanged; by 2100, the reduced fecundity populations were an average of 53% smaller.²⁵⁰⁸ Here, modest improvements in average

²⁴⁹⁸ Verbatim from Hixon et al. (2010, p. 280). Hixon et al. cite Taft et al. (2008) for this information.

²⁴⁹⁹ Nearly verbatim from Hixon et al. (2010, p. 280)

²⁵⁰⁰ Verbatim from Hixon et al. (2010, p. 280). Hixon et al. cite NABCI (2010) for this information.

²⁵⁰¹ Nearly verbatim from Hixon et al. (2010, p. 280)

²⁵⁰² Nearly verbatim from Hixon et al. (2010, p. 280). Hixon et al. cite NABCI (2009) for this information.

²⁵⁰³ Verbatim from Hixon et al. (2010, p. 280). Hixon et al. cite Johnson (1994), Glenn (2009), and Carroll (2010) for this information.

²⁵⁰⁴ Verbatim from Hixon et al. (2010, p. 280)

²⁵⁰⁵ Nearly verbatim from Hixon et al. (2010, p. 280-281)

²⁵⁰⁶ Verbatim from McRae et al. (2008, p. 85). *A multi-model framework for simulating wildlife population response to land-use and climate change.*

²⁵⁰⁷ Verbatim from McRae et al. (2008, p. 85-86). McRae et al. refer the reader to Figures 5g-j in the cited article for this information.

²⁵⁰⁸ Nearly verbatim McRae et al. (2008, p. 87). McRae et al. refer the reader to Figure 5 in the cited article for this information.

habitat suitability index scores across the landscape did little to offset even small effects on vital rates that could result from climate change or other stressors.²⁵⁰⁹

Changes in habitat suitability for winter wrens and song sparrows given changes in land use and climate change were also projected:

- **Winter wrens:** For winter wrens, mean habitat suitability index values based on FORCLIM predictions for 2050 increased a maximum of 4.1% (Conservation scenario, major climate change: +5.8 °F, +3.2 °C with 22% increase in winter precipitation and 9% increase in summer precipitation in 2045 vs. 20th century) and decreased a maximum of 1.9% (Plan Trend, no climate change) relative to 1990 values.²⁵¹⁰
- **Song sparrows:** Mean habitat suitability index values for song sparrows increased a maximum of 3.4% (Plan Trend, major climate change) and decreased a maximum of 11% (Development, no climate change) relative to 1990.²⁵¹¹

Habitat changes were primarily driven by conversion of coniferous stands to early seral stages by forest harvest, or conversion to older seral stages through stand growth.²⁵¹² In contrast to considerable habitat impacts of different land-use scenarios, climate change had little effect on habitat quality for either species.²⁵¹³ More specifically, with regard to impacts on habitat quality, simulations for 1990-2050 indicate that climate change slightly improved habitat suitability index scores across the Upper South Santiam Watershed for both winter wrens and song sparrows.²⁵¹⁴ Yet this result is tempered by the additional finding that consequences of more direct (and less predictable) impacts of climate change on species' demographic rates may be much larger still.²⁵¹⁵

Northwest California

Analysis suggests that, by 2070, individualistic shifts in species' distribution may lead to dramatic changes in the composition of California's avian communities, such that as much as 57% of the state (based on the scales of communities that Stralberg et al. 2009 examined) may be occupied by novel species assemblages (Figure 73; RegCM3 under A2 and run under two boundary conditions: NCAR CCSM3.0 for 2038-2069 vs. 1968-1999 and GFDL CM2.1 for 2038-2070 vs. 1968-2000).²⁵¹⁶ An even greater area would be considered no-analog if finer community delineations were considered.²⁵¹⁷ Thus, although net changes in the distributions of common species may be relatively small due to the combination of local decreases and increases, the cumulative effect on community composition is likely

²⁵⁰⁹ Verbatim McRae et al. (2008, p. 87)

²⁵¹⁰ Nearly verbatim McRae et al. (2008, p. 82)

²⁵¹¹ Verbatim McRae et al. (2008, p. 82)

²⁵¹² Verbatim McRae et al. (2008, p. 82). McRae et al. refer the reader to Figures 2 and 3 in the cited article for examples of habitat changes for selected scenarios.

²⁵¹³ Verbatim McRae et al. (2008, p. 82). McRae et al. refer the reader to Figures 2, 3, 4, 5a, and 5b in the cited article for this information.

²⁵¹⁴ Nearly verbatim McRae et al. (2008, p. 86)

²⁵¹⁵ Nearly verbatim McRae et al. (2008, p. 88)

²⁵¹⁶ Nearly verbatim from Stralberg et al. (2009, p. 3). *Re-shuffling of species with climate disruption: a no-analog future for California birds?*

²⁵¹⁷ Verbatim from Stralberg et al. (2009, p. 3)

to be great due to variation in individual species' responses to climate disruption and resulting differences in geographic shifts.²⁵¹⁸

The expected percentage of no-analog bird communities was dependent on the community scale examined, but consistent geographic patterns indicated several locations that are particularly likely to host novel bird communities in the future.²⁵¹⁹ For example, regions of high geologic diversity such as the Klamath Mountains in northern California, which represent the convergence of three mountain ranges, may have high bird community heterogeneity and thus greater potential for the re-shuffling of species.²⁵²⁰

Information Gaps

Additional information is needed on future projections for western British Columbia, as no studies were available. Additional information is also needed on future projections for southcentral and southeast Alaska and northwest California, as results from only one or two studies are presented here.

Since most of Oregon's birds are migrants, there is a need to understand how their world is changing in each phase of their annual cycle and how carryover of changes in one phase of the annual cycle is affecting the next.²⁵²¹ In many cases, migrant pathways to winter sites or locations of these winter sites are unknown.²⁵²² Closer to home, there is a need to better document basic information on distribution, abundance, elevation, and habitats used by birds now and as they change in the future.²⁵²³

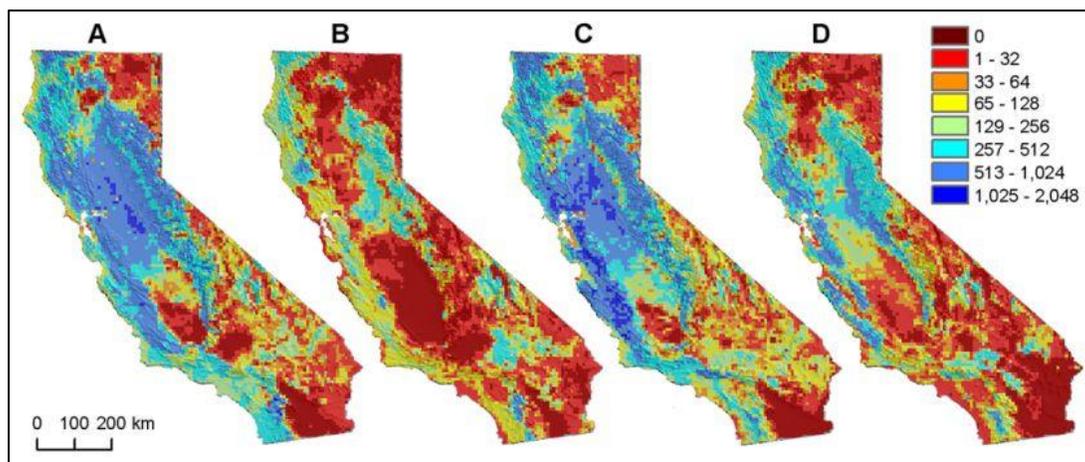


Figure 73. Number of modern analogs for predicted future bird communities across climate models and distribution-model algorithms. “Analog” communities are those for which Bray-Curtis dissimilarity was less than an ROC-determined (i.e., Receiver Operating Characteristic-determined) optimal threshold, based on a 60-group level of community aggregation. Predictions of future bird communities are based on: **(A)** GFDL CM2.1, Scenario A2, 2038–2070, generalized additive models. **(B)** GFDL CM2.1, Scenario A2, 2038–2070, maximum entropy models. **(C)** NCAR CCSM3.0, Scenario A2, 2038–2069, generalized additive models. **(D)** NCAR CCSM3.0, Scenario A2, 2038–2069, maximum entropy models.

Source: Reproduced from Stralberg et al. (2009, Figure 2, p. 4) by authors of this report.

²⁵¹⁸ Verbatim from Stralberg et al. (2009, p. 3)

²⁵¹⁹ Verbatim from Stralberg et al. (2009, p. 1)

²⁵²⁰ Nearly verbatim from Stralberg et al. (2009, p. 4). Stralberg et al. cite Whittaker (1960) for information on the convergence of three mountain ranges in the Klamath Mountains.

²⁵²¹ Nearly verbatim from Hixon et al. (2010, p. 281). Hixon et al. cite Webster et al. (2002) for this information.

²⁵²² Nearly verbatim from Hixon et al. (2010, p. 281)

²⁵²³ Nearly verbatim from Hixon et al. (2010, p. 281)

3. Invertebrates

Unlike vertebrates, which have the capacity to cross hundreds or thousands of kilometres, yet still home in on specific breeding, stop-over or non-breeding sites, most insect species have much more diffuse migratory patterns, and are heavily dependent on appropriate weather conditions.²⁵²⁴ In addition, return migrants are normally not the same individuals (or even of the same generation) that migrated originally and, with the notable exception of winter roost sites of the monarch butterfly they do not seek specific sites.²⁵²⁵ Changes in regional climate, whether caused by human or natural factors, can benefit some butterfly species while increasing the likelihood of extinction for others.²⁵²⁶ Climate change may impact butterfly populations in several ways, including affecting the nutrient content and palatability of host plants, the timing of host plant availability, and the vulnerability of butterflies to predators and parasites.²⁵²⁷

A trend in changing climate (e.g., rising temperatures) will have the following possible consequences for arthropods (i.e., insects and their relatives, such as spiders, mites, and centipedes) and other species:

1. Dying out locally or regionally,
2. Moving to a place where suitable conditions do exist (assuming such a place is available), or
3. Adapting and remaining in the same area.²⁵²⁸

The faster the rate of climate change, the more likely that scenarios (1) and (2) will occur and the less likely that scenario (3) will occur.²⁵²⁹ The critical issue with arthropods and climate change is a potential shift in seasonal timing (i.e., phenology) of critical life-history events, such as egg deposition, growth rates of immature stages, and timing of maturation of adults.²⁵³⁰ The sequence of development through life-history stages (egg, larva, pupa, adult) is intimately timed to occur in synchrony with other biological events.²⁵³¹

Observed Trends

Global

Introduced exotic earthworms now occur in every biogeographic region in all but the driest or coldest habitat types on Earth.²⁵³² The global distribution of a few species (e.g., *Pontoscolex corethrurus*) was noted by early naturalists, but now approximately 120 such peregrine (i.e., ability to become widespread

²⁵²⁴ Verbatim from Robinson et al. (2008, p. 90)

²⁵²⁵ Verbatim from Robinson et al. (2008, p. 90)

²⁵²⁶ Verbatim from Stinson (2005, p. 103). *Washington State status report for the Mazama pocket gopher, streaked horned lark, and Taylor's checkerspot.*

²⁵²⁷ Verbatim from Stinson (2005, p. 103). Stinson cites Hellmann (2002b) for this information.

²⁵²⁸ Nearly verbatim from Hixon et al. (2010, p. 272)

²⁵²⁹ Verbatim from Hixon et al. (2010, p. 272)

²⁵³⁰ Nearly verbatim from Hixon et al. (2010, p. 271)

²⁵³¹ Nearly verbatim from Hixon et al. (2010, p. 271)

²⁵³² Verbatim from Hendrix et al. (2008, p. 593). *Pandora's Box contained bait: the global problem of introduced earthworms.*

when introduced to new environments, which may be far from a species' native habitat) species are recognized to be widespread from regional to global scales, mainly via human activities.²⁵³³

Western North America

Two well-known western butterflies, the Edith's checkerspot and sagem skipper, have shifted their ranges northward and/or upward.²⁵³⁴ Information on sagem skipper is provided in the section on the Pacific Northwest. Parmesan (1996) censused populations of Edith's checkerspot butterfly throughout its range, and found significant latitudinal and altitudinal clines in population extinctions at sites undegraded by human activities, producing a northwards and upwards shift in the species' range.²⁵³⁵ Sites where previously recorded populations still existed were on average 2° farther north than sites where populations were extinct.²⁵³⁶ Populations in Mexico were four times more likely to be extinct than those in Canada.²⁵³⁷ Net extinctions also significantly decreased with altitude.²⁵³⁸ Populations above 7,874 feet (2,400 meters) were significantly more persistent than those at all lower elevations.²⁵³⁹ Although a predicted result of climate warming is an increased extinction rate at the very lowest elevations, no such trend appears in the data.²⁵⁴⁰

Earthworms are keystone detritivores that can influence primary producers by changing seedbed conditions, soil characteristics, flow of water, nutrients and carbon, and plant-herbivore interactions.²⁵⁴¹ The invasion of European earthworms into previously earthworm-free temperate and boreal forests of North America dominated by maple, oak, birch, pine and poplar has provided ample opportunity to observe how earthworms engineer ecosystems.²⁵⁴² Impacts vary with soil parent material, land use history, and assemblage of invading earthworm species.²⁵⁴³ Impacts include:

- Earthworms reduce the thickness of organic layers, increase the bulk density of soils and incorporate litter and humus materials into deeper horizons of the soil profile, thereby affecting the whole soil food web and the above ground plant community.²⁵⁴⁴ In some forests earthworm invasion leads to reduced availability and increased leaching of nitrogen and phosphorus in soil horizons where most fine roots are concentrated.²⁵⁴⁵

²⁵³³ Verbatim from Hendrix et al. (2008, p. 593)

²⁵³⁴ Nearly verbatim from Running & Mills (2009, p. 15). Running & Mills cite Parmesan & Galbraith (2004) and Crozier (2003) for this information.

²⁵³⁵ Nearly verbatim from Parmesan (1996, p. 765). *Climate and species' range*.

²⁵³⁶ Verbatim from Parmesan (1996, p. 765)

²⁵³⁷ Verbatim from Parmesan (1996, p. 765)

²⁵³⁸ Verbatim from Parmesan (1996, p. 765). Parmesan refers the reader to Figures 1 and 2b in the cited article for this information. Parmesan reports statistics for this finding as $P = 0.04$.

²⁵³⁹ Verbatim from Parmesan (1996, p. 765). Parmesan reports statistics for this finding as $P = 0.016$.

²⁵⁴⁰ Verbatim from Parmesan (1996, p. 765)

²⁵⁴¹ Verbatim from Frelich et al. (2006, p. 1235). *Earthworm invasion into previously earthworm-free temperate and boreal forests*.

²⁵⁴² Verbatim from Frelich et al. (2006, p. 1235)

²⁵⁴³ Verbatim from Frelich et al. (2006, p. 1235)

²⁵⁴⁴ Verbatim from Frelich et al. (2006, p. 1235)

²⁵⁴⁵ Verbatim from Frelich et al. (2006, p. 1235)

- Mixing of organic and mineral materials turns mor into mull humus which significantly changes the distribution and community composition of the soil microflora and seedbed conditions for vascular plants.²⁵⁴⁶
- Recent studies on the foraging behavior of salamanders (*Plethodon* spp.) suggest that introduced earthworms may play an important role in salamander diets, especially in lowland forests and during rainy seasons.²⁵⁴⁷ Earthworms apparently increase the fecundity of adult salamanders by providing a high protein food source, but decrease the survival rates of young salamanders, presumably by reducing populations of smaller invertebrate food sources, or by altering the habitat in other ways.²⁵⁴⁸

Southcentral and Southeast Alaska

Information needed.

Western British Columbia

Information needed.

Pacific Northwest

The sagem skipper has expanded its range up the west coast of the United States over the past 40 years, recently colonizing areas where winter minimum temperature has risen 5.4 °F (3 °C) since 1950 (Figure 74).²⁵⁴⁹ In chronic cold stress experiments, survivorship declined sharply in diurnally fluctuating thermal regimes typical of the current range edge.²⁵⁵⁰ High mortality occurred under constant 32 °F (0 °C) conditions as well as in fluctuating regimes, implying that thermal insulation from snow would not protect sagem skipper.²⁵⁵¹ There was no evidence of evolution in cold tolerance at the range margin, despite strong selection.²⁵⁵² Thus, winter warming was apparently a prerequisite for the range expansion.²⁵⁵³

Historical records indicate that at least 24 butterfly species were associated with upland prairies in the Willamette Valley, of which 13 species are extinct or exist only as isolated populations on relict patches of native upland prairie.²⁵⁵⁴ Characteristic upland species include the checkered skipper, Sonora skipper, and anise swallowtail.²⁵⁵⁵ Common Lepidoptera of wet prairies include the sheep moth and field crescent

²⁵⁴⁶ Verbatim from Frelich et al. (2006, p. 1235)

²⁵⁴⁷ Verbatim from Bohlen et al. (2004, p. 431). *Non-native invasive earthworms as agents of change in northern temperate forests*. Bohlen et al. cite Maerz et al. (in press) for this information.

²⁵⁴⁸ Verbatim from Bohlen et al. (2004, p. 431-432)

²⁵⁴⁹ Verbatim from Crozier (2003, p. 649). *Winter warming facilitates range expansion: cold tolerance of the butterfly *Atalopedes campestris**. Crozier refers the reader to Figure 1 in the cited article for this information.

²⁵⁵⁰ Verbatim from Crozier (2003, p. 648)

²⁵⁵¹ Verbatim from Crozier (2003, p. 648)

²⁵⁵² Verbatim from Crozier (2003, p. 648)

²⁵⁵³ Verbatim from Crozier (2003, p. 648)

²⁵⁵⁴ Verbatim from Vesely & Rosenberg (2010, p. 19). Vesely & Rosenberg cite Wilson et al. (1998a) for this information.

²⁵⁵⁵ Verbatim from Vesely & Rosenberg (2010, p. 19)

butterfly.²⁵⁵⁶ Two of the butterflies most closely associated with prairies of western Oregon are Fenders blue butterfly and Taylor's checkerspot butterfly.²⁵⁵⁷ The former species is federally listed as endangered and the latter species is a candidate for federal listing, and both are listed under the Interagency Special Status Sensitive Species Program.²⁵⁵⁸ Thirty-two species of Lepidoptera are closely associated with oak woodland habitats; many of these species are wholly dependent on oaks or related genera (family Fagaceae).²⁵⁵⁹

In a study of canopy arthropod assemblages in nine Douglas-fir forests in south Puget Sound and the Oregon and Washington Cascades, on average, estimates of richness and Shannon-Wiener diversity were higher in the northern forests than the southern forests.²⁵⁶⁰ The canopy invertebrate communities of the nine forests can be distinguished along a latitudinal gradient, a precipitation gradient and between old-growth and mature Douglas-fir trees.²⁵⁶¹ Of 91 taxa collected, 15 (16%) showed significant association with forest, 12 (13%) with subregion, 8 (9%) with precipitation level, and 4 (5%) with stand age at the Andrews Forest.²⁵⁶² Fungivorous arthropods, especially *Camisia carrolli* (Acari: Camiisidae, oribatid mite), were the most abundant feeding group in all forests and exhibited the expected higher association with cooler, moister forests.²⁵⁶³

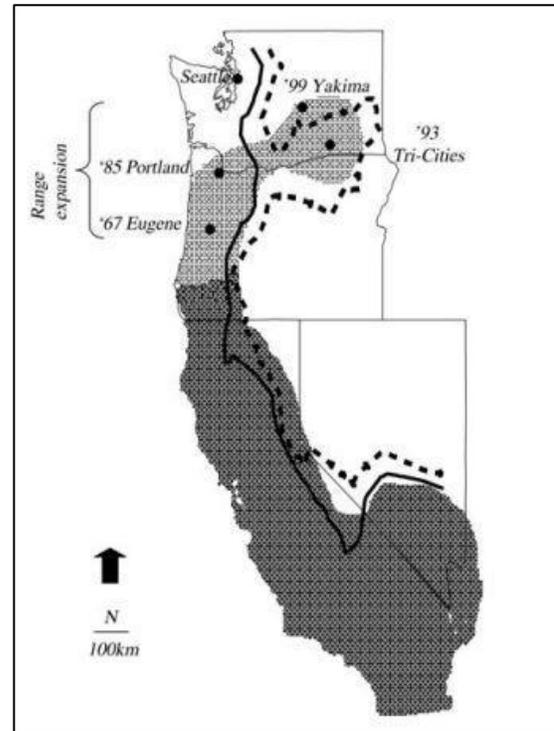


Figure 74. Overwintering range of sache skipper (shaded) in Washington, Oregon, California, and Nevada from Opler (1999), modified to include the western range expansion (lighter shading). Colonization dates of sache skipper by four cities in Oregon and Washington show the chronology of the range expansion. Contour lines represent the January average minimum 24.8 °F (-4 °C) isotherm from 1950–1959 (solid) and 1990–1998 (dotted) (NCDC 2000).
 Source: Reproduced from Crozier (2003, Figure 1, p. 649) by authors of this report.

²⁵⁵⁶ Verbatim from Vesely & Rosenberg (2010, p. 19). Vesely & Rosenberg cite Wilson et al. (1998a) for information on field crescent butterfly.

²⁵⁵⁷ Verbatim from Vesely & Rosenberg (2010, p. 19)

²⁵⁵⁸ Nearly verbatim from Vesely & Rosenberg (2010, p. 19). Vesely & Rosenberg refer the reader to Table 1 in the cited report.

²⁵⁵⁹ Nearly verbatim from Vesely & Rosenberg (2010, p. 19-20). Vesely & Rosenberg cite Miller & Hammond (2007) for this information.

²⁵⁶⁰ Nearly verbatim from Progar & Schowalter (2002, p. 132). Progar & Schowalter refer the reader to Table 2 in the cited article for this information.

²⁵⁶¹ Verbatim from Progar & Schowalter (2002, p. 133). In the cited article, Progar & Schowalter refer the reader to Figure 2A for information on the latitudinal gradient, Figure 2B for information on the precipitation gradient, and Figure 3 for information on the distinction between old-growth and mature Douglas-fir trees.

²⁵⁶² Verbatim from Progar & Schowalter (2002, p. 133). In the cited article, Progar & Schowalter refer the reader to Tables 3, 4, 5, and 6 for information on significant association with forest, subregion, precipitation level, and stand age, respectively.

²⁵⁶³ Verbatim from Progar & Schowalter (2002, p. 135). Progar & Schowalter refer the reader to Table 3 in the cited article for this information.

Additional results for association with regional forests, precipitation, and stand age are available:

- **Regional forests:** Shannon-Wiener diversity increased with latitude.²⁵⁶⁴ Herbivore abundance generally decreased with increasing latitude, but most of the Lepidoptera larvae were found at the Andrews Forest (Oregon).²⁵⁶⁵ Sap-feeding insects were abundant across all forests.²⁵⁶⁶ However, aphid abundance (giant conifer aphids and *Elatobium* spp.) was much higher in the Washington forests.²⁵⁶⁷ Fungus-feeding arthropods also had higher abundance in the Washington forests, although two of the predominant taxa (large *Jugatala* spp. and *Eremaeus* spp.) increased in abundance with decreasing latitude and were significant indicator taxa of the southern forests.²⁵⁶⁸ Predators were significantly more abundant in the northern forests.²⁵⁶⁹ Gall midge (Diptera: Cecidomyiidae), an aphid-feeding predator, erythraeid mites, and parasitic Hymenoptera (i.e., a large order of insects comprising sawflies, wasps, bees, and ants) showed strong association with the northern, Washington forests.²⁵⁷⁰
- **Precipitation gradient:** Herbivores, as a functional group, showed significantly higher association with the drier forests.²⁵⁷¹ Although not significant, sap-feeding arthropods showed a higher association with drier forests.²⁵⁷² Mealybugs, however, were significantly associated with moderate levels of precipitation.²⁵⁷³ Fungus-feeding arthropods were widespread in the canopy communities among the forests, and represented a large portion of the total taxa.²⁵⁷⁴ The distribution of individual taxa varied with the level of precipitation.²⁵⁷⁵ *Camisia carrolli* (i.e., an oribatid mite) and hypogasturid Collembola (i.e., a family of springtails, hexapods related to insects) showed strong association with wetter forests, whereas the large *Jugatala* spp. was associated with drier forests.²⁵⁷⁶ Predators, as a functional group, showed strong association with wetter forests.²⁵⁷⁷ In particular, gall midges exhibited a significant decrease in abundance as precipitation declined.²⁵⁷⁸ In contrast, therid spiders and net-winged insects (e.g., lacewings) were associated with drier forests.²⁵⁷⁹
- **Stand age:** Six stands of old-growth and six stands of mature Douglas-fir were randomly interspersed at the Andrews Forest.²⁵⁸⁰ Several taxa showed significant differences in association between old-growth and mature stands, suggesting that arthropod communities change with

²⁵⁶⁴ Verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁶⁵ Nearly verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁶⁶ Verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁶⁷ Verbatim from Progar & Schowalter (2002, p. 133). Progar & Schowalter refer the reader to Table 4 in the cited article for this information.

²⁵⁶⁸ Verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁶⁹ Verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁷⁰ Nearly verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁷¹ Verbatim from Progar & Schowalter (2002, p. 133). Progar & Schowalter refer the reader to Table 5 in the cited article for this information.

²⁵⁷² Verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁷³ Verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁷⁴ Verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁷⁵ Verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁷⁶ Nearly verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁷⁷ Verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁷⁸ Verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁷⁹ Nearly verbatim from Progar & Schowalter (2002, p. 133)

²⁵⁸⁰ Verbatim from Progar & Schowalter (2002, p. 134)

increasing tree age or stand development.²⁵⁸¹ Sap-feeders were strongly associated, and fungivorous arthropods approached significant association, with old-growth Douglas-fir.²⁵⁸² The pine needle scale and Cooley spruce gall adelgid showed a high association with older trees.²⁵⁸³ Two fungivorous oribatid mites, *Camisia carrolli* (i.e., an oribatid mite) and *Scapheremaeus* spp. (i.e., a genus of oribatid mites) were significantly associated with old-growth Douglas-fir.²⁵⁸⁴

Native earthworms were likely an important component of Willamette Valley plant communities prior to invasion by European species.²⁵⁸⁵ The Oregon giant earthworm was early described as occupying native prairies, and its rarity is often attributed to the loss of this plant community.²⁵⁸⁶ However, most of the locations where the Oregon giant earthworm has been found (only 15 reported specimens, <http://www.xerces.org/oregon-giant-earthworm/>) were found in gallery hardwood forests in the Willamette floodplain, and the most recent observation was in a mixed hardwood-conifer floodplain forest.²⁵⁸⁷

Northwest California

Drought resulted in the extinction of some Edith's checkerspot butterfly populations in California.²⁵⁸⁸ McLaughlin et al. (2002) reported an increase in the variability of growing-season rainfall after 1971, which likely caused the extinction of two populations of Bay checkerspot (endemic to the San Francisco Bay area).²⁵⁸⁹ They suggested that extremes in annual precipitation reduced the development overlap of larvae and host plants leading to wide population fluctuations.²⁵⁹⁰ The butterfly populations were unable to survive the climate change because habitat loss had reduced them to small insular populations.²⁵⁹¹

Future Projections

Global

Migration is only likely to be a successful strategy for insects that are associated with widespread, albeit still seasonal, habitats, and such species are doing well, as migratory journeys may be becoming easier.²⁵⁹² The disruption of phenological synchrony (appropriately timed occurrence of critical life

²⁵⁸¹ Verbatim from Progar & Schowalter (2002, p. 135-136). Progar & Schowalter refer the reader to Table 5 in the cited article for information on significant differences in association between old-growth and mature stands.

²⁵⁸² Verbatim from Progar & Schowalter (2002, p. 134). Progar & Schowalter refer the reader to Table 6 in the cited article for this information.

²⁵⁸³ Verbatim from Progar & Schowalter (2002, p. 136)

²⁵⁸⁴ Nearly verbatim from Progar & Schowalter (2002, p. 136)

²⁵⁸⁵ Verbatim from Vesely & Rosenberg (2010, p. 20). Vesely & Rosenberg cite Bailey et al. (2002) for this information.

²⁵⁸⁶ Verbatim from Vesely & Rosenberg (2010, p. 20)

²⁵⁸⁷ Verbatim from Vesely & Rosenberg (2010, p. 20). Vesely & Rosenberg cite a personal communication with J. Gervais of Oregon State University for information on the most recent observation of native earthworm.

²⁵⁸⁸ Verbatim from Stinson (2005, p. 103). Stinson cites Singer & Ehrlich (1979) for this information.

²⁵⁸⁹ Nearly verbatim from Stinson (2005, p. 103)

²⁵⁹⁰ Verbatim from Stinson (2005, p. 103)

²⁵⁹¹ Verbatim from Stinson (2005, p. 103). Stinson cites McLaughlin et al. (2002) for this information.

²⁵⁹² Nearly verbatim from Robinson et al. (2008, p. 90). Robinson et al. cite Warren et al. (2001) for information on species that are doing well.

stages) between herbivores and their host plants, or between predators and their prey, may be a key pathway for climate change to impact insect ecology.²⁵⁹³

With a warming climate, the demarcation lines of earthworm distributions might advance poleward and to higher elevations, where few or no earthworms occur owing to continental and alpine glaciations.²⁵⁹⁴ In the short term, especially in areas previously devoid of earthworms, invasive earthworms may increase the decomposition of soil organic matter and release more CO₂ into the atmosphere, and in some cases also more nitrous oxide.²⁵⁹⁵ In the longer term, earthworm activities may increase sequestration of organic carbon in soil via protection from decomposition within water-stable aggregates resulting from earthworm castings.²⁵⁹⁶ In addition to the possible expansion of regional peregrines, rapid adaptations (phenotypic and genetic) among known invasive species should be considered as possible mechanisms that could accelerate their spread into new habitats.²⁵⁹⁷ Conversely, introduced species with narrower temperature or moisture tolerances may become more restricted in distribution under warmer or drier conditions induced by climate change.²⁵⁹⁸

North America

Earthworm invasions may have important interactions with other rapid changes predicted for northern forests in the coming decades, including climate and land-use change, increased nutrient deposition, and other biological invasions.²⁵⁹⁹ Positive or negative interactions may occur, such as an acceleration of carbon loss (climate warming and earthworm invasion), increased gaseous or hydrologic flux of nitrogen (atmospheric deposition and earthworm invasion), or nutrient stress (drought or pollution and earthworm invasion).²⁶⁰⁰ The increasing length of growing seasons and enhanced productivity currently occurring at northern latitudes are likely to contribute to a more rapid northward expansion of earthworm populations and introductions of exotic species formerly limited by colder temperatures.²⁶⁰¹

At this point it appears likely that warming climate will allow higher deer populations in northern forests as well as faster northward expansion of invading earthworm populations.²⁶⁰² Thus Frelich et al. (2006) hypothesize that warmer temperatures, deer, and earthworms will work synergistically to change temperate forest ecosystems much faster than any one of these factors would by itself.²⁶⁰³

²⁵⁹³ Verbatim from Logan et al. (2003, p. 131). Logan et al. cite Watt & MacFarlane (2002) for this information.

²⁵⁹⁴ Nearly verbatim from Hendrix et al. (2008, p. 605-606).

²⁵⁹⁵ Verbatim from Hendrix et al. (2008, p. 606). Hendrix et al. cite Potthoff et al. (2001) and Speratti & Whalen (2008) for information on CO₂ and Rizhiya et al. (2007) for information on nitrous oxide.

²⁵⁹⁶ Verbatim from Hendrix et al. (2008, p. 606). Hendrix et al. cite Bossuyt et al. (2005) and Martin (1991) for this information.

²⁵⁹⁷ Nearly verbatim from Hendrix et al. (2008, p. 606). Hendrix et al. cite Terhivuo & Saura (2006) for this information.

²⁵⁹⁸ Verbatim from Hendrix et al. (2008, p. 606)

²⁵⁹⁹ Verbatim from Bohlen et al. (2004, p. 427)

²⁶⁰⁰ Verbatim from Bohlen et al. (2004, p. 434)

²⁶⁰¹ Verbatim from Bohlen et al. (2004, p. 434). Bohlen et al. cite Papadopol (2000) and Zhou et al. (2001) for information on increased length of growing season and enhance productivity at northern latitudes.

²⁶⁰² Verbatim from Frelich et al. (2006, p. 1243)

²⁶⁰³ Nearly verbatim from Frelich et al. (2006, p. 1243)

Southcentral and Southeast Alaska

Information needed.

Western British Columbia

Information needed.

Pacific Northwest

The implication of sagem skippers' thermal constraint in the context of global warming is mixed.²⁶⁰⁴ Pacific Northwest regional climate models predict increasing winter precipitation over the next century.²⁶⁰⁵ Increased snowfall will decrease the probability of persistence.²⁶⁰⁶ However, warming temperatures at the northern range edge will generally enhance persistence in this species, especially where snow transforms into rain.²⁶⁰⁷

In a study of canopy arthropod assemblages in Douglas-fir forests in the Oregon and Washing Cascades and southe Puget Sound, Progar & Schowalter (2002) anticipate that species characterizing old-growth forests will decline overall as anthropogenic influences continue to reduce the expanse of remnant forests to areas that cannot sustain habitats associated with old-growth communities.²⁶⁰⁸ Climate change, in particular warming and drying, will exacerbate these impacts by taxing the buffering effect of forest area on local temperature and relative humidity.²⁶⁰⁹ Such impacts may especially affect the arboreal oribatid mites that are sensitive to changes in moisture and humidity, existing in micro-ecosystems that require several hundred years to develop.²⁶¹⁰ These changes should result in a northward shift of the arthropod communities distinguished by Progar & Schowalter (2002).²⁶¹¹

Northwest California

Larval growth and survival of an oak specialist butterfly (*Propertius Duskywing*) was examined in Oregon and California to determine if the insect could change tree hosts (to different oak species) after moving to a new area under climate change; findings suggest local adaptation of butterflies to specific oak species often precluded their populations from colonizing new areas under climate change.²⁶¹²

Greenhouse experiments suggested that increased temperature (5.9 °F, 3.3 °C) alone would not hurt Bay checkerspot butterfly (endemic to the San Francisco Bay area) populations if larvae still had access to

²⁶⁰⁴ Nearly verbatim from Crozier (2003, p. 653)

²⁶⁰⁵ Verbatim from Crozier (2003, p. 653). Crozier cites Leung & Ghan (1999) for this information.

²⁶⁰⁶ Verbatim from Crozier (2003, p. 653)

²⁶⁰⁷ Verbatim from Crozier (2003, p. 653)

²⁶⁰⁸ Nearly verbatim from Progar & Schowalter (2002, p. 137)

²⁶⁰⁹ Verbatim from Progar & Schowalter (2002, p. 137). Progar & Schowalter cite Chen et al. (1992) for this information.

²⁶¹⁰ Verbatim from Progar & Schowalter (2002, p. 137)

²⁶¹¹ Nearly verbatim from Progar & Schowalter (2002, p. 137)

²⁶¹² Nearly verbatim from Staudinger et al. (2012, p. 2-4). Staudinger et al. cite Pelini & others (2010) for this information.

Indian paintbrush, but might lead to extinctions of populations dependent on plantain, unless they were able to compensate by earlier emergence.²⁶¹³

Information Gaps

Additional information is needed on observed trends and future projections for southcentral and southeast Alaska and western British Columbia. Additional information is also needed on observed trends and future projections for northwest California, as the information presented here is limited or outside the NPLCC region.

Two components that are essential to a well-planned comprehensive study of arthropods and climate change are (1) landscape-scale monitoring of species assemblages involving permanent sites subjected to repeated intra-annual sampling efforts at a frequency of 7-10 day intervals, and (2) expertise in identification of various species groups.²⁶¹⁴ The scope of the project at a landscape scale is a critical issue because the expected shift in species ranges may occur across hundreds to thousands of miles.²⁶¹⁵

Therefore, a monitoring plan should encompass transects, founded on elevation or latitude, that represent gradients of climate conditions across a broad geographical region.²⁶¹⁶ A species complex, involving dozens to hundreds of species, should be monitored.²⁶¹⁷ A novel approach, yet to be conducted by any group of scientists, would be to integrate arthropods into climate studies in concert with other species, all of which are associated via ecological connections, such as food webs.²⁶¹⁸

²⁶¹³ Nearly verbatim from Stinson (2005, p. 103). Stinson cites Hellmann (2002a) for this information.

²⁶¹⁴ Verbatim from Hixon et al. (2010, p. 274)

²⁶¹⁵ Verbatim from Hixon et al. (2010, p. 274)

²⁶¹⁶ Verbatim from Hixon et al. (2010, p. 274)

²⁶¹⁷ Verbatim from Hixon et al. (2010, p. 274)

²⁶¹⁸ Verbatim from Hixon et al. (2010, p. 274)

4. Lichens & mosses

Bryophytes and lichens, collectively referred to as non-vascular cryptogams, are important components of forests and other ecosystems around the world.²⁶¹⁹ Many species are sensitive to air pollution and have been used as biological indicators of change.²⁶²⁰ The greatest risks to the vast biodiversity represented by moss and lichen communities are poor air quality and loss of critical habitats.²⁶²¹

Bryophytes and lichens affect hydrology, microclimate, nutrient cycling, and food web and community dynamics:

- **Hydrology:** Moisture from fog and rain is collected by cryptogams growing on branches in the canopy, tree trunks, and the ground.²⁶²² Consequently, cryptogams slow the rate at which water is lost from the forest ecosystem.²⁶²³ In addition, they reduce erosion, a process that can wash away soil nutrients, damage the forest floor, and adversely affect the integrity of streams.²⁶²⁴
- **Microclimate:** Water stored in bryophytes and lichens evaporates slowly, and helps to maintain a humid environment in forests long after rainfall has ceased.²⁶²⁵ In the humid conditions created by cryptogams, plant leaves lose less water so they can keep their pores open longer and continue photosynthesizing.²⁶²⁶
- **Nutrient cycling and productivity:** Lichens and bryophytes concentrate various nutrients deposited from the atmosphere, which in turn become available to other plants when they are leached by rainfall.²⁶²⁷ Lichens with

Lichens consist of a fungus and an alga or a cyanobacterium. The alga provides carbohydrates (via photosynthesis) to the fungus, while the fungus provides structure, nutrients, water, and protection to the alga. Lichens are grouped into three categories according to their shape: foliose (leaf-like), fruticose (shrub-like), and crustose (growing closely attached to a surface). Further, cyanolichens are capable of nitrogen fixation, while alectorioid lichens refer to pendulous species in the *Alectoria*, *Bryoria*, and *Usnea* genera, commonly called hair lichens.

Bryophytes include mosses, liverworts, and hornworts. Their tissues for transporting food and water are more primitive than plants, and most bryophytes obtain their water through direct surface contact with the environment. During dry conditions, bryophytes may dry out completely, but can return to normal function when moisture is restored.

Both *lichens* and *bryophytes* can reproduce sexually or asexually, for example by releasing spores or by breaking off to form new individuals. In lichens, if fungal spores are released, a partner alga must be present for a lichen to reform.

Source: McCune (1993), USGS (2002)

²⁶¹⁹ Verbatim from USGS (2002, p. 2). *Bryophytes and lichens: small but indispensable forest dwellers.*

²⁶²⁰ Verbatim from USGS (2002, p. 4)

²⁶²¹ Verbatim from USGS (2002, p. 4)

²⁶²² Verbatim from USGS (2002, p. 2)

²⁶²³ Verbatim from USGS (2002, p. 2)

²⁶²⁴ Verbatim from USGS (2002, p. 2)

²⁶²⁵ Verbatim from USGS (2002, p. 2)

²⁶²⁶ Verbatim from USGS (2002, p. 2)

²⁶²⁷ Verbatim from USGS (2002, p. 2)

cyanobacterial partners, such as seaside kidney and lettuce lung, are able to fix nitrogen (i.e., convert nitrogen gas into a usable form, which vascular plants cannot do).²⁶²⁸ Large trees with large branches provide a habitat substrate for lichens that fix atmospheric nitrogen and provide nutrient capture for the forest ecosystem.²⁶²⁹ When these lichens decompose (for example after being knocked to the ground), the nitrogen leaches into the soil and becomes readily available for other plants.²⁶³⁰ Site-to-site differences in lettuce lung abundance and local patterns of temperature and precipitation determine how much nitrogen is fixed in a given forest.²⁶³¹

- **Food web dynamics:** Rodents eat ground-dwelling lichens, whereas elk and deer are especially fond of nitrogen-rich lichens such as lettuce lung.²⁶³² Many invertebrate animals, such as some insects, make their homes in mats of bryophytes and lichens.²⁶³³ Invertebrates hiding amongst these cryptogams are a food source for various birds that may also take advantage of the natural nesting sites afforded by cryptogams or use them as a source of materials for nest building.²⁶³⁴ For example, many species such as the marbled murrelet, rufous hummingbird, and winter wren use mosses for nesting material.²⁶³⁵ Fremont's horsehair lichen plays an important role in Sierra Nevada forest ecology as the principal nesting material and a critical winter survival food for northern flying squirrels when hypogeous (i.e., below the soil surface) truffles are not available.²⁶³⁶

Observed Trends

Global

The British Isles contain approximately 1,900 lichen species (approximately 45% of European lichen diversity), making lichens one of Britain's most important contributions to international biodiversity and a key group in UK conservation strategy.²⁶³⁷

Western North America

Among the non-vascular flora, approximately 105 moss species and varieties are endemic to western North America, representing about 18% of the moss flora.²⁶³⁸ Of these, some 20 mosses are found west

²⁶²⁸ Nearly verbatim from USGS (2002, p. 2)

²⁶²⁹ Nearly verbatim from Franklin et al. (2006, p. 103-104)

²⁶³⁰ Nearly verbatim from USGS (2002, p. 2)

²⁶³¹ Verbatim from Antoine (2004, p. 86). *An ecophysiological approach to quantifying nitrogen fixation by Lobaria oregana*.

²⁶³² Verbatim from USGS (2002, p. 2)

²⁶³³ Verbatim from USGS (2002, p. 3)

²⁶³⁴ Verbatim from USGS (2002, p. 3)

²⁶³⁵ Nearly verbatim from USGS (2002, p. 3)

²⁶³⁶ Verbatim from Rambo (2010, p. 1034). *Habitat preferences of an arboreal forage lichen in a Sierra Nevada old-growth mixed-conifer forest*. Rambo cites Maser et al. (1986) and Hayward & Rosentreter (1994) for information on nesting material, and McKeever (1960) and Maser et al. (1986) for information on winter survival food.

²⁶³⁷ Verbatim from Ellis et al. (2007, p. 218). *Response of British lichens to climate change scenarios: Trends and uncertainties in the projected impact for contrasting biogeographic groups*. Ellis et al. cite Mackey et al. (2001) and Coppins (2002) for information on the number and diversity of the UK's lichens. Ellis et al. also cite UK BAP (1999), Coppins (2003), and Gibby (2003) for information on lichens as a key contribution from Britain to international biodiversity and for information on lichens as a key group in UK conservation strategy.

but not east of the Cascade Range.²⁶³⁹ The proportion of endemic liverworts is similar, about 16%.²⁶⁴⁰ Nine moss and three (monotypic) liverwort genera are endemic to Pacific North America.²⁶⁴¹ The proportion of the lichen flora that is endemic to western North America is high, but the number is unknown to Hutten et al. (2002).²⁶⁴²

Rates of lichen litterfall in north temperate ecosystems exhibit distinct annual and seasonal variation, with higher rates typically observed during the winter period, as a result of storms and ice accumulation.²⁶⁴³ Thus, lichen litter loading at the forest floor surface may be quite episodic, with significant deposition of organic matter on snowpack surfaces.²⁶⁴⁴

Southcentral and Southeast Alaska

Information needed.

Western British Columbia

Lichens form an important component of high elevation forested ecosystems in north-central British Columbia (Cariboo Mountains), with canopy lichen loading reaching 882 pounds per hectare (400 kilograms per ha; 1 hectare \approx 2.5 acres).²⁶⁴⁵ Snowmelt events, in particular, rather than vertical gradients in canopy microclimate, are a primary factor that directly controls lichen growth rates.²⁶⁴⁶ Hair lichen communities in Engelmann spruce – subalpine fir forests of the northern Cariboo Mountains (i.e., outside the NPLCC region) show distinct vertical zonation.²⁶⁴⁷ *Alectoria sarmentosa* reaches peak abundance in the lower canopy (over 77 kilograms per hectare, 35 kg/ha) whereas *Bryoria* spp. lichens reach peak abundance in the upper canopy (over 551 lbs/ha, 250 kg/ha).²⁶⁴⁸ These distribution patterns are accentuated by stand structure with trees growing in clumps retaining significantly higher lichen loading on a per branch basis compared to solitary trees.²⁶⁴⁹

The vertical zonation of lichen communities is accompanied by distinct trends in canopy microclimate.²⁶⁵⁰ Snowmelt events account for the largest proportion of observed thallus (i.e., the body of the lichen)

²⁶³⁸ Verbatim from Hutten et al. (2002, p. 56). *Inventory of the mosses, liverworts, hornworts, and lichens of Olympic National Park, Washington: species list*. Hutten et al. cite Lawton (1971) and Schofield (1985) for this information.

²⁶³⁹ Verbatim from Hutten et al. (2002, p. 56). Hutten et al. cite Lawton (1971) for this information.

²⁶⁴⁰ Verbatim from Hutten et al. (2002, p. 56). Hutten et al. cite Schofield (1985) for this information.

²⁶⁴¹ Verbatim from Hutten et al. (2002, p. 56). Hutten et al. cite Schofield (1985, 2002) for this information.

²⁶⁴² Nearly verbatim from Hutten et al. (2002, p. 56)

²⁶⁴³ Verbatim from Coxson & Curteanu (2002, p. 399). *Decomposition of hair lichens (Alectoria sarmentosa and Bryoria spp.) under snowpack in montane forest, Cariboo Mountains, British Columbia*. Coxson & Curteanu cite Esseen (1985), Grier (1988), and Waterhouse et al. (1991) for this information.

²⁶⁴⁴ Verbatim from Coxson & Curteanu (2002, p. 399)

²⁶⁴⁵ Nearly verbatim from Coxson & Curteanu (2002, p. 395). Coxson & Curteanu cite Campbell & Coxson (2001) for this information.

²⁶⁴⁶ Nearly verbatim from Campbell & Coxson (2002, p. 552). *Canopy microclimate and arboreal lichen loading in subalpine spruce-fir forest*.

²⁶⁴⁷ Verbatim from Campbell & Coxson (2002, p. 537)

²⁶⁴⁸ Verbatim from Campbell & Coxson (2002, p. 537)

²⁶⁴⁹ Verbatim from Campbell & Coxson (2002, p. 537)

²⁶⁵⁰ Verbatim from Campbell & Coxson (2002, p. 537)

hydration in both *Alectoria* and *Bryoria*.²⁶⁵¹ Upper canopy *Bryoria* rely more heavily on snowmelt events to sustain thallus hydration, whereas lower canopy *Alectoria* utilize summer rainfall events to a greater extent.²⁶⁵² An important exception to this pattern is seen under midwinter conditions, when solar insolation is insufficient to sustain prolonged lower canopy snowmelt.²⁶⁵³

In an experimental study of the decomposition of hair lichens (specifically, *Alectoria sarmentosa* and *Bryoria* spp.) under snowpack in north-central B.C. (i.e., the Cariboo Mountains in an area transitional between the Interior Cedar Hemlock and Engelmann Spruce-Subalpine Fir biogeoclimatic zones, outside of the NPLCC region), lichen samples that were buried in the lower snowpack all winter long (196 days) lost two-thirds (65%) of their original mass.²⁶⁵⁴ In contrast lichens placed on the snowpack in mid- (127 days) or late-winter (61 days) lost only 6–15% of their total mass, far less than would be predicted on the basis of time in snowpack alone.²⁶⁵⁵ Early-winter litterfall samples had a significantly higher mass loss than did mid-winter and late-winter litterfall samples.²⁶⁵⁶ There were no significant differences in mass loss between samples placed in snowpack in the mid-winter versus late-winter period.²⁶⁵⁷

A major result of placing lichen litter-bag samples under the snowpack was the decline in total nitrogen content, falling by near half in both *Alectoria* and *Bryoria*.²⁶⁵⁸ Percent carbon content, on the other hand, was relatively unchanged, compared to control samples, resulting in higher carbon to nitrogen ratios in lichen samples from under the snowpack.²⁶⁵⁹ Thus, all lichen samples placed within the snowpack showed much higher carbon to nitrogen ratios on removal, indicating rapid leaching of readily soluble cellular constituents in the snowpack environment.²⁶⁶⁰

Pacific Northwest

Bryophytes and lichens are especially conspicuous in forests of the Pacific Northwest.²⁶⁶¹ Common witch's hair is a sensitive species commonly found in Pacific Northwest forests.²⁶⁶² Cyanolichens dominate epiphyte assemblages in wet old-growth, mid-elevation Douglas-fir forests of Oregon and Washington.²⁶⁶³ The lettuce lung lichen is the most abundant nitrogen-fixing lichen in these forests, often accounting for 60-80% of the total epiphytic lichen biomass.²⁶⁶⁴ It has been estimated that lettuce lung

²⁶⁵¹ Verbatim from Campbell & Coxson (2002, p. 537)

²⁶⁵² Verbatim from Campbell & Coxson (2002, p. 537)

²⁶⁵³ Verbatim from Campbell & Coxson (2002, p. 537)

²⁶⁵⁴ Nearly verbatim from Coxson & Curteanu (2002, p. 395)

²⁶⁵⁵ Verbatim from Coxson & Curteanu (2002, p. 395)

²⁶⁵⁶ Verbatim from Coxson & Curteanu (2002, p. 398). *Coxson & Curteanu report statistics for this finding as ANOVA $P < 0.001$, $\alpha = 0.05$.*

²⁶⁵⁷ Verbatim from Coxson & Curteanu (2002, p. 398). *Coxson & Curteanu report statistics for this finding as ANOVA $P > 0.1$.*

²⁶⁵⁸ Verbatim from Coxson & Curteanu (2002, p. 398). Coxson & Curteanu refer the reader to Table 3 in the cited article for this information.

²⁶⁵⁹ Verbatim from Coxson & Curteanu (2002, p. 398)

²⁶⁶⁰ Verbatim from Coxson & Curteanu (2002, p. 395)

²⁶⁶¹ Nearly verbatim from USGS (2002, p. 2)

²⁶⁶² Verbatim from USGS (2002, p. 4)

²⁶⁶³ Verbatim from Antoine (2004, p. 82). Antoine cites Neitlich (1993), Pike et al. (1975), and Sillett (1995) for this information.

²⁶⁶⁴ Verbatim from Antoine (2004, p. 82). Antoine cites McCune (1994), Pike et al. (1977), and Sillett (1995) for this information.

provides an average of 7.1 pounds (3.2 kilograms) of nitrogen for each hectare of Pacific Northwest forest (1 hectare \approx 2.5 acres).²⁶⁶⁵ In areas where it reaches peak abundance, as in close proximity to major streams in old-growth Douglas-fir forests, the magnitude of its contribution to the forest nitrogen budget may be higher than has previously been acknowledged.²⁶⁶⁶

Epiphyte biomass on branches and trunks was estimated for 42 individual felled trees, distributed among three Douglas-fir/western hemlock stands aged 95, 145, and 400+ years, in the western Cascade Range of Oregon and Washington, then extrapolated to the whole stands by regression techniques.²⁶⁶⁷ In general the spatial sequence of dominance of the four groups studied, from upper canopy to forest floor, was: "other" lichens (i.e., predominantly tube lichens and ragged lichens), alectorioid lichens, cyanolichens, and bryophytes.²⁶⁶⁸ This pattern was consistent among all three stands, except that the series was truncated in the younger stands where cyanolichens were essentially absent and bryophytes were much less abundant.²⁶⁶⁹ Additional information on the variation in lichen biomass by stand age is available:

- **Overall:** Epiphyte biomass was greatest in the old-growth stand.²⁶⁷⁰ The zones of these functional groups of epiphytes apparently migrate upward in forests through time.²⁶⁷¹ For example, the tube lichens and ragged lichens that dominate throughout canopies in young forests are found primarily in the upper canopies of old forests.²⁶⁷²
- **“Other” lichens** (i.e., predominantly tube lichens and ragged lichens) dominated the upper canopy in the old growth and had highest biomass in the 95-year stand.²⁶⁷³
- **Alectorioid lichens** tended to peak at a height just below “other” lichens, and had only slightly higher biomass in the 400- than the 145-year stand which, in turn, had more alectorioid biomass than the 95-year stand.²⁶⁷⁴
- **Cyanolichens** peaked at a height below alectorioid lichens in the old growth and were virtually absent from the younger stands.²⁶⁷⁵
- **Bryophytes** dominated closest to the ground in the old growth and, although present on tree bases in all stands, were much more abundant in the 400-year stand.²⁶⁷⁶

²⁶⁶⁵ Nearly verbatim from USGS (2002, p. 3)

²⁶⁶⁶ Verbatim from Antoine (2004, p. 86). Antoine cites Howe (1978), McCune et al. (2002), and Sillett & Neitlich (1996) for information on the location of peak abundance in lettuce lung.

²⁶⁶⁷ Verbatim from McCune (1993, p. 405). *Gradients in epiphyte biomass in three Pseudotsuga-Tsuga forests of different ages in western Oregon and Washington.*

²⁶⁶⁸ Nearly verbatim from McCune (1993, p. 405)

²⁶⁶⁹ Verbatim from McCune (1993, p. 407)

²⁶⁷⁰ Nearly verbatim from McCune (1993, p. 408)

²⁶⁷¹ Verbatim from McCune (1993, p. 405)

²⁶⁷² Verbatim from McCune (1993, p. 405)

²⁶⁷³ Verbatim from McCune (1993, p. 408). McCune refers the reader to Figures 2 and 3 in the cited article for this information.

²⁶⁷⁴ Verbatim from McCune (1993, p. 408). McCune refers the reader to Figures 2 and 3 in the cited article for this information.

²⁶⁷⁵ Nearly verbatim from McCune (1993, p. 408)

²⁶⁷⁶ Verbatim from McCune (1993, p. 408). McCune refers the reader to Figures 2 and 3 in the cited article for this information.

Western Washington

More than 1,280 species of mosses, liverworts, hornworts, and lichens have been catalogued from the Olympic Peninsula, and species new to the area are still frequently discovered.²⁶⁷⁷ Within Olympic National Park, collections and locality data are available for some 900 species.²⁶⁷⁸ At present, no mosses, liverworts, or lichens are known to be endemic exclusively to the Olympic Mountains.²⁶⁷⁹

At the Wind River Canopy Crane Research Facility (i.e., an old-growth Douglas-fir forest located in the Gifford Pinchot National Forest), estimated annual nitrogen fixation by lettuce lung is 3.3 pounds per hectare (1.5 kilograms ha⁻¹; 1 ha ≈ 2.5 acres).²⁶⁸⁰ *For additional information on the study method, please see the following section on Western Oregon.*

Western Oregon

In the Willamette National Forest, Peck & McCune (1997) used a retrospective approach to compare canopy lichen litter in adjacent, paired stands of rotation age (55–120 yr): one with and one without old-growth (> 300 yr) remnant trees.²⁶⁸¹ They sampled three functional groups of lichens in 17 stands in western Oregon (i.e., 13 low-elevation and 4 mid-elevation stands): alectorioid lichens, cyanolichens, and green-algal foliose lichens.²⁶⁸² Biomass varied by elevation, the presence or absence of remnant (old-growth) trees, and the number and density of trees:

- **Elevation:** Alectorioid lichens were most abundant in mid-elevation stands, whereas cyanolichens and green-algal foliose lichens were most abundant in low-elevation stands.²⁶⁸³ The mean biomass of alectorioid lichen litter was 0.66 g/m² higher in the mid-elevation sites than in the low-elevation sites.²⁶⁸⁴ The mean biomass of cyanolichen litter and of green-algal foliose lichen litter was 0.06 g/m² and 0.29 g/m² higher in the low-elevation sites than in the mid-elevation sites, respectively.²⁶⁸⁵ Cyanolichens were absent from all mid-elevation sites and some low-elevation sites.²⁶⁸⁶
- **Presence or absence of remnant (old-growth) trees at low-elevation:** Alectorioid lichens and cyanolichens (i.e., lichens associated with old-growth) were most abundant in remnant plots,

²⁶⁷⁷ Verbatim from Hutten et al. (2005, p. 55). Hutten et al. cite Rhoades (1997), supplemented with data from Hutten et al.'s project, for this information. *Note: Table 1 in the cited report lists 1,283 as the total number of species documented from the Olympic Peninsula in 2004 (see p. 52 in the cited report).*

²⁶⁷⁸ Verbatim from Hutten et al. (2005, p. 55)

²⁶⁷⁹ Verbatim from Hutten et al. (2002, p. 56)

²⁶⁸⁰ Nearly verbatim from Antoine (2004, p. 82)

²⁶⁸¹ Nearly verbatim from Peck & McCune (1997, p. 1181). *Remnant trees and canopy lichen communities in western Oregon: a retrospective approach.*

²⁶⁸² Nearly verbatim from Peck & McCune (1997, p. 1181). *Note: The alectorioid lichens were composed of common witch's hair lichen, species in the beard lichen group, and several species of hair lichens. The cyanolichens consisted primarily of lettuce lung, with small amounts of kidney lichens, specklebelly lichens, and spotted lichens. The green-algal foliose lichens were primarily tube lichens, ragged lichens, and coral lichen.*

²⁶⁸³ Verbatim from Peck & McCune (1997, p. 1184)

²⁶⁸⁴ Nearly verbatim from Peck & McCune (1997, p. 1184). *Note: Peck & McCune report statistics for this finding as $df = 16, P < 0.001$.*

²⁶⁸⁵ Nearly verbatim from Peck & McCune (1997, p. 1184). *Note: Peck & McCune report statistics for these findings as $df = 16, P = 0.01$ for cyanolichen litter and $df = 16, P = 0.03$ for green-algal foliose litter.*

²⁶⁸⁶ Verbatim from Peck & McCune (1997, p. 1184)

whereas green-algal foliose lichens were most abundant in nonremnant plots.²⁶⁸⁷ Total lichen biomass was not significantly greater in the remnant plots than in the nonremnant plots.²⁶⁸⁸ The biomass of alectorioid lichens and cyanolichens was greater in the remnant plots, with a mean difference in biomass between the remnant and non-remnant plots (remnant – nonremnant) of 0.23 ± 0.03 grams per square meter (g/m^2) for alectorioid lichens and 0.08 ± 0.09 g/m^2 for cyanolichens.²⁶⁸⁹ Green-algal foliose lichen litter biomass was greater, on average, by 1.3 ± 0.40 g/m^2 in nonremnant plots than in remnant plots.²⁶⁹⁰

- **Elevation and presence or absence of remnant (old-growth) trees:** Biomass of alectorioid lichen and cyanolichen litter was greater in low-elevation sites with remnant trees than in those without remnant trees by 86% and 233%, respectively.²⁶⁹¹ The biomass of green-algal foliose lichen litter was 80% greater in mid-elevation sites without remnant trees than in those with remnant trees.²⁶⁹² Total lichen litter biomass was slightly, but not significantly, greater in stands with remnant trees at both low elevations (by 23%; ~816 pounds per hectare, 370 kilograms/ha standing biomass in remnant stands) and mid elevations (by 12%; ~1,036 lbs/ha, 470 kg/ha standing biomass).²⁶⁹³
- **Number and density of trees:** Cyanolichen litter biomass was positively related to the number of remnant trees present; alectorioid and green-algal lichen litter biomass were negatively correlated with the density of trees in the regeneration cohort.²⁶⁹⁴ Alectorioid lichen biomass was not correlated with any other stand characteristic or any of the current or historic context variables.²⁶⁹⁵

Studies undertaken in the H.J. Andrews Experimental Forest during the 1970's estimate that lettuce lung lichen may fix up to 9.9 pounds of nitrogen per hectare per year (4.5 kilograms N_2 ha^{-1} yr^{-1} ; 1 hectare \approx 2.5 acres), over 50% of the annual new nitrogen input to the forest's nutrient budget.²⁶⁹⁶ Using data from 2000-2001 (analyzed with a model based on physiological field measurements and laboratory experiments), Antoine (2004) estimated lettuce lung may fix 5.7-36.4 pounds of nitrogen per hectare per year (2.6 – 16.5 kg N_2 ha^{-1} yr^{-1}) depending on its stand-level canopy biomass.²⁶⁹⁷

- With 1213 pounds per hectare (550 kg ha^{-1}) standing biomass of lettuce lung, estimated annual nitrogen fixation was 5.7 pounds of nitrogen per hectare per year (2.6 kg ha^{-1}).²⁶⁹⁸

²⁶⁸⁷ Nearly verbatim from Peck & McCune (1997, p. 1184)

²⁶⁸⁸ Nearly verbatim from Peck & McCune (1997, p. 1184). Peck & McCune refer the reader to Table 2 in the cited article for this information. *Note: Peck & McCune report statistics for this finding as $df = 25$, $P = 0.34$.*

²⁶⁸⁹ Nearly verbatim from Peck & McCune (1997, p. 1184). *Note: Numbers reported as mean \pm 1 SD (standard deviation).*

²⁶⁹⁰ Nearly verbatim from Peck & McCune (1997, p. 1184). *Note: Peck & McCune report statistics for this finding as $df = 25$, $P < 0.001$.*

²⁶⁹¹ Verbatim from Peck & McCune (1997, p. 1181)

²⁶⁹² Verbatim from Peck & McCune (1997, p. 1181)

²⁶⁹³ Verbatim from Peck & McCune (1997, p. 1181)

²⁶⁹⁴ Verbatim from Peck & McCune (1997, p. 1181)

²⁶⁹⁵ Verbatim from Peck & McCune (1997, p. 1184)

²⁶⁹⁶ Nearly verbatim from Antoine (2004, p. 82). Antoine cites Denison (1979) and Pike (1978) for information on estimates of nitrogen fixation by lettuce lung, and Sollins et al. (1980) for information on the percent of the annual new nitrogen input from nitrogen fixation by lettuce lung.

²⁶⁹⁷ Nearly verbatim from Antoine (2004, p. 82)

²⁶⁹⁸ Antoine (2004, Table 2, p. 85)

- With 3499 pounds per hectare (1587 kg ha⁻¹) standing biomass of lettuce lung, estimated annual nitrogen fixation was 17 pounds of nitrogen per hectare per year (7.5 kg ha⁻¹).²⁶⁹⁹
- With 5776 pounds per hectare (2620 kg ha⁻¹) standing biomass of lettuce lung, estimated annual nitrogen fixation was 27.1 pounds of nitrogen per hectare per year (12.3 kg ha⁻¹).²⁷⁰⁰
- With 7767 pounds per hectare (3523 kg ha⁻¹) standing biomass of lettuce lung, estimated annual nitrogen fixation was 36.4 pounds of nitrogen per hectare per year (16.5 kg ha⁻¹).²⁷⁰¹
- *Note: Standing biomass is from five different old-growth Douglas-fir forests. Results for the fifth forest are provided in the section on Western Washington.*

Northwest California

In a study of habitat preferences for Fremont's horsehair lichen in the southern Sierra Nevada, the lichen had strong positive associations with red fir, proximity to streams, and decreasing vapor pressure deficit (VPD, the difference between the moisture content of air and the amount of moisture air can hold when fully saturated).²⁷⁰² Specific results for tree association and proximity to streams are available:

- **Tree association:** Biomass averaged across tree heights was estimated as 15.9, 0.60, 0.15, 0.25, and 0.19 grams per meter in red fir, white fir, incense cedar, Jeffrey pine, and sugar pine, respectively.²⁷⁰³ The amount of the lichen averaged across tree heights was significantly greater in red fir than in white fir, incense cedar, Jeffrey pine, or sugar pine.²⁷⁰⁴ The amount of the lichen in white fir was also significantly greater than in incense cedar or sugar pine, but not Jeffrey pine.²⁷⁰⁵
- **Proximity to streams:** Regressions showed strong positive correlations between lichen abundance and proximity to red fir, white fir, and sugar pine to perennial water.²⁷⁰⁶ To further study growth and proximity to water, 792 lichens were also transplanted to 18 trees in the study area.²⁷⁰⁷ Transplant growth was significantly greater in trees less than 82 feet (25 meters) from water (11.4%) than in trees greater than 82 feet (25 m) from water (9.7%).²⁷⁰⁸

²⁶⁹⁹ Antoine (2004, Table 2, p. 85)

²⁷⁰⁰ Antoine (2004, Table 2, p. 85)

²⁷⁰¹ Antoine (2004, Table 2, p. 85)

²⁷⁰² Nearly verbatim from Rambo (2010, p. 1034)

²⁷⁰³ Nearly verbatim from Rambo (2010, p. 1034)

²⁷⁰⁴ Nearly verbatim from Rambo (2010, p. 1037). Rambo refers the reader to Figure 1 in the cited article for this information. Rambo reports statistics for this finding as $P < 0.0001$.

²⁷⁰⁵ Nearly verbatim from Rambo (2010, p. 1037). Rambo reports statistics for these findings: $P = 0.0045$ for white fir compared to incense cedar, $P = 0.0196$ for white fir compared to sugar pine, and $P = 0.1484$ for white fir compared to Jeffrey pine.

²⁷⁰⁶ Nearly verbatim from Rambo (2010, p. 1037). Rambo refers the reader to Figure 3 in the cited article for information on red fir. Rambo reports statistics for these findings: $R^2 = 0.579$ for red fir, $R^2 = 0.392$ for white fir, $R^2 = 0.693$ for sugar pine, and $P < 0.05$ for each.

²⁷⁰⁷ Rambo (2010, p. 1036-1037)

²⁷⁰⁸ Verbatim from Rambo (2010, p. 1034)

Future Projections

Global

Lichen-rich terricolous (i.e., living on the ground or in soil) communities are maintained by the absence of strong interspecific competition, and may therefore be susceptible to vegetation change driven by climate warming.²⁷⁰⁹ Experimental research to simulate the effects of climate warming (increased temperature and improved soil nutrient status) has demonstrated an increase in canopy height and the dominance of more competitive tall-stature species, causing a decline in abundance of small-stature species, including terricolous lichens.²⁷¹⁰

In a study of 26 British lichen species, the projected bioclimatic response based on the UKCIP02 scenarios strongly indicates a loss of bioclimatic space for Northern species and an increase in bioclimatic space for Southern species (2050s vs. 1961-2000 under B2 and A1F1).²⁷¹¹ Results are also available for Oceanic species:

- **Northern species:** Ten species categorized as Northern-montane and Northern-boreal each show a consistent and strong decrease in projected range, compared between the modeled present-day climatic setting and the 2050s climate change scenarios, with significant loss of climate space compared to little or no gain.²⁷¹² Based upon the spatial trends in the UKCIP02 data, Northern-montane and Northern-Boreal species will be most susceptible to the effects of projected climate change towards their southern range margins (Wales, northern England and the Scottish borders) and towards the west of their range in Scotland.²⁷¹³ The climate is projected to remain relatively more suitable for this suite of species in the mountains and Straths of north-east Scotland (i.e. the Cairngorm region).²⁷¹⁴ Projections for Northern-montane species are consistent with experimental evidence demonstrating a decline in lichen occurrence following the simulated effects of climate change (e.g. increased temperature and nutrient cycling), which may shift the balance of arctic-alpine communities in favor of more competitive species.²⁷¹⁵
- **Southern species:** The present-day bioclimatic range occupied by the suite of Southern species is projected to shift northwards, into Wales, much of northern England, the Scottish borders and the

²⁷⁰⁹ Verbatim from Ellis & Yahr (2011, p. 467). *An interdisciplinary review of climate change trends and uncertainties: lichen biodiversity, arctic-alpine ecosystems and habitat loss.*

²⁷¹⁰ Verbatim from Ellis & Yahr (2011, p. 467). Ellis & Yahr cite Chapin et al. (1995), Press et al. (1998), Cornelissen et al. (2001), Graglia et al. (2001), Hollister et al. (2005), Klanderud & Totland (2005), Walker et al. (2006), and Klanderud (2008) for this information.

²⁷¹¹ Nearly verbatim from Ellis et al. (2007, p. 227). Ellis et al. refer the reader to Figures 6a and 6b in the cited article for information on northern species, and to Figure 6c for information on southern species.

²⁷¹² Verbatim from Ellis et al. (2007, p. 222). Ellis et al. refer the reader to Figures 6a in the cited article for information on Northern-montane species, to Figure 6b for information on Northern-boreal species, and to Figure 7 for the comparison between modeled present-day and 2050s conditions.

²⁷¹³ Verbatim from Ellis et al. (2007, p. 229)

²⁷¹⁴ Verbatim from Ellis et al. (2007, p. 229)

²⁷¹⁵ Verbatim from Ellis et al. (2007, p. 227). Ellis et al. cite Chapin et al. (1995), Press et al. (1998), and Cornelissen et al. (2001) for this information.

eastern coast of Scotland.²⁷¹⁶ The group of eight species categorized as Southern-widespread show a consistent increase in projected range northward.²⁷¹⁷

- **Oceanic species:** Species categorised as Oceanic-northern show a consistent loss in projected range between the modelled present-day climatic setting and the 2050s climate change scenarios, though the magnitude of this shift is less than for species comprising the Northern groups.²⁷¹⁸ Two species categorized as Oceanic-widespread show little or no change in the availability of bioclimatic space, while a third species (*Pyrenula macrospora*) shows an increase in projected range, compared between the modelled present-day climatic setting and the 2050s climate change scenarios.²⁷¹⁹

Southcentral and Southeast Alaska

Information needed.

Western British Columbia

Information needed.

Western Washington

The cascading effects of rapid climate change could have a major impact on an island-type flora (i.e., potentially those found on the Olympic Peninsula) where species may be more easily lost than replaced.²⁷²⁰

Western Oregon

Information needed.

Northwest California

As reported by McCune et al. (2007), where environmental conditions may already be marginal for *Bryoria* (i.e., *Bryoria* spp. of which Fremont's horsehair lichen is one species) in this more southerly extent of its range (i.e., southern Sierra Nevada), it could be especially vulnerable to increasing stresses from air pollution and changing climate.²⁷²¹ *Bryoria* has known sensitivity to air pollution, and vapor pressure deficits may increase with warming regional temperatures.²⁷²²

²⁷¹⁶ Nearly verbatim from Ellis et al. (2007, p. 229)

²⁷¹⁷ Verbatim from Ellis et al. (2007, p. 222)

²⁷¹⁸ Verbatim from Ellis et al. (2007, p. 225). Ellis et al. refer the reader to Figure 6d in the cited article for information on Oceanic-northern species and to Figure 7 for information on the comparison to Northern groups.

²⁷¹⁹ Verbatim from Ellis et al. (2007, p. 225). Ellis et al. refer the reader to Figure 6e in the cited article for information on the Oceanic-widespread species and to Figure 7 for information on the comparison between modeled present-day conditions and the 2050s climate change scenarios.

²⁷²⁰ Nearly verbatim from Hutten et al. (2002, p. 59)

²⁷²¹ Nearly verbatim from Rambo (2010, p. 1040)

²⁷²² Nearly verbatim from Rambo (2010, p. 1040)

Information Gaps

Information is needed on observed trends for southcentral and southeast Alaska, western British Columbia, and northwest California, as no information is available or is from outside the NPLCC region. Information is also needed on future projections throughout NPLCC region.

Research should examine in more detail the metapopulation response to climate change: i.e., the spatial arrangement of habitat patches of varying quality, with respect to likelihoods of dispersal and establishment, and spatially explicit changes in model parameters under climate change scenarios.²⁷²³ The metapopulation approach would benefit from targeted molecular research to examine population processes in lichens, also integrating studies on cryptic speciation and the potential for in-situ adaptation.²⁷²⁴

²⁷²³ Verbatim from Ellis & Yahr (2011, p. 477)

²⁷²⁴ Verbatim from Ellis & Yahr (2011, p. 477)

IX. Adapting to the Effects of Climate Change in Terrestrial Environments

Adaptation is one of two major ways in which climate-related risks can be managed (the other is mitigation, which includes strategies to reduce greenhouse gas sources and emissions, and enhance greenhouse gas sinks).²⁷²⁵ Even if global greenhouse gas emissions were to be stabilized near their current levels, atmospheric concentrations would increase throughout the 21st century, and might well continue to increase slowly for several hundred years after that.²⁷²⁶ Thus, mitigation can reduce climate-related risks only in the longer term.²⁷²⁷ Adaptation has emerged as a necessary response to and preparation for the unavoidable impacts of global climate change.²⁷²⁸

As an example for terrestrial systems, thinking about adaptation for forests is in many ways in its infancy, but examples might include stronger emphases on: reducing anthropogenic stresses on forest ecosystems, promoting resilience to likely impacts, landscape and biological diversity, planning for projected future conditions, and assessing the decision context in terms of barriers and opportunities that limit or facilitate local adaptation.²⁷²⁹ General and specific approaches to adaptation action are emerging.²⁷³⁰ Along with these, existing conservation activities are being applied to climate change adaptation, and new activities are also being developed.²⁷³¹

Adaptation is defined in this report as “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” (IPCC, 2007b, p. 6).

This chapter highlights possible adaptation actions in the context of conservation, restoration, protection and natural resource management, including actions that are underway or being considered in the NPLCC region. The actions described represent the range of ideas suggested by the literature on climate change adaptation. They are not intended as recommendations, as their relevance and effectiveness will depend on the context in which they are applied (e.g., the desired management goals, trade-offs with other socioeconomic and ecological goals, costs and benefits of implementation, etc.).

²⁷²⁵ Asian Development Bank (ADB). *Climate Proofing: A risk-based approach to adaptation*. (2005, p. 7); Information on mitigation available from Parry et al. (2007, p. 878)

²⁷²⁶ Nearly verbatim from ADB. (2005, p. 7)

²⁷²⁷ ADB. (2005, p. 7)

²⁷²⁸ Verbatim from Gregg et al. (2011, p. 29)

²⁷²⁹ Verbatim from Littell et al. (2010, p. 150). Littell et al. cite Millar et al. (2007) and Joyce et al. (2008) for this information.

²⁷³⁰ ADB (2005); Gregg et al. (2011); Heller and Zavaleta (2009); NOAA. *Adapting to Climate Change: A Planning Guide for State Coastal Managers*. (2010)

²⁷³¹ See, for example, Baron et al. (2009); Heller and Zavaleta (2009); Mawdsley et al. (2009); NOAA. (2010); U.S. EPA. (2009).

1. Adaptation options for terrestrial ecosystems

Recent assessments of forest management in light of climate change have consistently identified the principles of diversifying forest structure, maintaining complexity and microclimates, embracing environmental variability and uncertainty, decreasing fragmentation, extending rotation lengths, and addressing as wide a variety of ecosystem components (not just trees and vertebrates) and functions as possible.²⁷³² Managing forests as complex adaptive systems makes sense in light of changes in climate and other environmental conditions, changes in society's expectations of forests and foresters, and changes in the economics of forestry, forest conservation, and the evaluation of ecosystem services.²⁷³³ Mountain and valley systems provide the best opportunities for biodiversity conservation—beyond the typical north-south and east-west opportunities for species migration, mountains also offer up-down altitudinal and “contouring around the mountain” avenues for migration.²⁷³⁴

Support science-management partnerships

Partnerships between scientists and managers are needed to improve understanding of climate science and increase experience in developing adaptation strategies.²⁷³⁵ The experience and judgment of resource professionals are also important for evaluating potential future climate conditions and ecosystem responses.²⁷³⁶

These collaborations can develop in different forms.²⁷³⁷

For example, science information might reside with staff within an agency, but in different program areas than those traditionally involved with forest management.²⁷³⁸ University extension specialists have a long history of spanning boundaries between science and applications (e.g., providing genetic expertise in developing seed-transfer rules), and can be brought into partnerships.²⁷³⁹ Research scientists with universities and agencies increasingly participate in

Adaptation in Action

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, suggested options for the vegetation resource areas, include preserving tree genetic diversity, increasing disease resistance in western white pine and whitebark pine, and increasing capacity to restore forest lands after disturbance. A similar approach was taken by the North Cascadia Adaptation Partnership (see next box).

Source: Halofsky et al. (2011a, 2011b); Millar et al. (2012); Peterson et al. (2011)

²⁷³² Nearly verbatim from Pojar (2010, p. 48-49). Pojar cites Pojar (1999), Noss (2001), and Puettmann et al. (2009) for information on recent assessments of forest management.

²⁷³³ Verbatim from Pojar (2010, p. 49)

²⁷³⁴ Verbatim from Pojar (2010, p. 21)

²⁷³⁵ Verbatim from Millar et al. (2012, p. 126)

²⁷³⁶ Nearly verbatim from Millar et al. (2012, p. 128)

²⁷³⁷ Verbatim from Millar et al. (2012, p. 126)

²⁷³⁸ Verbatim from Millar et al. (2012, p. 126)

²⁷³⁹ Verbatim from Millar et al. (2012, p. 126)

resource management collaborations.²⁷⁴⁰ Further, managers have many years of experience, including experience with weather-related or climatically extreme events.²⁷⁴¹ Discussion about the type of event and about what could have improved the management response may help focus the conversation with scientists on the types of information that would be helpful now and in the future.²⁷⁴²

A key element in all collaborations is that they maintain interactive dialogue, with managers and scientists reciprocally learning from and informing each other about relevance.²⁷⁴³ Commitment to work together is also critical, because a year or more may be needed to complete workshops, individual dialogues, and writing.²⁷⁴⁴ For example, a commitment by a national forest or other organization to the process of adaptation will need to endure for decades, because of the long-term nature of climate change effects.²⁷⁴⁵ The science-management partnership must have good communication, a consensus on specific objectives, an established schedule, and a clearly identified written product to document the results.²⁷⁴⁶ Documenting all aspects of the workshops, scientific information, vulnerability assessments, and adaptation options in reports ensures a unified statement on adaptation for the participating units and interested stakeholders.²⁷⁴⁷

Among the genetic options to adapt national forests to climate change, six action items are suggested to support and expand internal and external partnerships to improve response to climate change:

- **Support and contribute to integrated gene conservation and monitoring program initiatives**, such as the Forest Health Protection (FHP) Gene Conservation Framework for at-risk forest tree species and Monitoring on the Margins, an integrated, enhanced FHP monitoring program for critical ecosystems threatened by insects, disease, and climate change.²⁷⁴⁸
- **Initiate and expand partnerships with other land owners** to broaden the portfolio of *ex situ* and *in situ* gene conservation resources.²⁷⁴⁹
- **Partner with other land managers** to create cooperative virtual seedbanks for germplasm (i.e., genetic variability of a population) exchange to facilitate reforestation and restoration after disturbances.²⁷⁵⁰ See “Preserve and restore genetic diversity” for more information.
- **Contribute to the development of databases** that will facilitate the sharing and exchange of data and seed among national forests, as well as with other Federal and State agencies.²⁷⁵¹
- **Partner with other land managers** to manage forest nurseries to facilitate reforestation and restoration activities.²⁷⁵²
- **Evaluate and modify, as needed, policies and practices** to simplify transfer of Forest Service-owned seed to other entities, including private landowners.²⁷⁵³

²⁷⁴⁰ Verbatim from Millar et al. (2012, p. 126)

²⁷⁴¹ Nearly verbatim from Peterson et al. (2011, p. 25)

²⁷⁴² Verbatim from Peterson et al. (2011, p. 25). Peterson et al. refer the reader to Box 2 in the cited report for this information.

²⁷⁴³ Verbatim from Millar et al. (2012, p. 126)

²⁷⁴⁴ Nearly verbatim from Peterson et al. (2011, p. 23)

²⁷⁴⁵ Nearly verbatim from Peterson et al. (2011, p. 23)

²⁷⁴⁶ Verbatim from Peterson et al. (2011, p. 23)

²⁷⁴⁷ Verbatim from Peterson et al. (2011, p. 46)

²⁷⁴⁸ Verbatim from Erickson et al. (2012, p. 14)

²⁷⁴⁹ Verbatim from Erickson et al. (2012, p. 14)

²⁷⁵⁰ Verbatim from Erickson et al. (2012, p. 14)

²⁷⁵¹ Verbatim from Erickson et al. (2012, p. 14)

²⁷⁵² Verbatim from Erickson et al. (2012, p. 14)

Facilitate dialogue on climate change adaptation

These questions are intended to establish the local management context, elicit overarching management responses to climate change, and promote mutual learning within the science-management partnership.²⁷⁵⁴ Questions can be designed to accommodate local interests and preferences:²⁷⁵⁵

- What are priorities for long-term resource management (e.g., 50 years)?;
- How can climate change be integrated in planning at this time scale?;
- What is the policy and regulatory environment in which management and planning are currently done?;
- What are the biggest concerns and ecological/social sensitivities in a changing climate?;
- Which management strategies can be used to adapt to potentially rapid change in climate and resource conditions?;
- Which information and tools are needed to adequately address the questions above?; and,
- Which aspects of the policy and regulatory environment affect (enable, inhibit) management that adapts to climate change?²⁷⁵⁶

Another important component of facilitated dialogue is capturing ideas and information that are relevant to preparing for a warmer climate but may not be explicit adaptation options.²⁷⁵⁷ For example, it is helpful to summarize opportunities and barriers to adaptation as a context related to administrative process, policy, and budgets that affect all management issues.²⁷⁵⁸ It is also helpful to compile a list of analytical tools and information needs that can assist the adaptation process.²⁷⁵⁹ This provides a heads-up for the science-

Adaptation in Action

Working with a broad range of scientists, managers, and stakeholders, the **North Cascadia Adaptation Partnership** (NCAP) process identified and assessed the vulnerability of four key resource sectors, namely hydrology and access, vegetation and ecological disturbance, wildlife, and fisheries, in Mt. Baker-Snoqualmie National Forest, Okanogan-Wenatchee National Forest, North Cascades National Park Complex, and Mount Rainier National Park. 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).

Source: Lawler et al. (2013); Littell et al. (2013); Millar et al. (2012); Raymond et al. (2013); Strauch et al. (2013)

²⁷⁵³ Verbatim from Erickson et al. (2012, p. 14)

²⁷⁵⁴ Verbatim from Peterson et al. (2011, Box 2, p. 26)

²⁷⁵⁵ Verbatim from Peterson et al. (2011, Box 2, p. 26)

²⁷⁵⁶ Verbatim from Peterson et al. (2011, Box 2, p. 26)

²⁷⁵⁷ Verbatim from Peterson et al. (2011, p. 46). Peterson et al. refer the reader to Box 6 in the cited report for this information.

²⁷⁵⁸ Verbatim from Peterson et al. (2011, p. 46). Peterson et al. refer the reader to Box 9 in the cited report for this information.

²⁷⁵⁹ Verbatim from Peterson et al. (2011, p. 46). Peterson et al. refer the reader to Box 10 in the cited report for this information.

management partnership on future steps that may be needed to facilitate adaptation and informs scientists about specific ways in which they can help.²⁷⁶⁰

Facilitate workshops to develop climate change adaptation options

Adaptation options are developed after the scientific information available and tools to identify vulnerabilities have been completed.²⁷⁶¹ Adaptation options are typically generated for individual resource disciplines (e.g., vegetation, wildlife, water), although it is also possible to focus on adaptation for individual biogeographic entities (e.g., watersheds, subalpine forests, coastal ecosystems) and projects (e.g., forest thinning at a specific location, bridge design).²⁷⁶² In general, scientists provide information on climate change and climate change effects, including vulnerability assessments, and resource managers provide strategic and tactical adaptation options and guidance on how they can be implemented.²⁷⁶³

Modify infrastructure

Alter road management

Roads can be designed to reduce the potential for landslides.²⁷⁶⁴

Support natural infrastructure in forested landscapes

While concrete-and-steel built infrastructure will continue to play a critical role in water storage and treatment, investing in natural infrastructure can reduce or avoid costs and enhance water services and security as part of an integrated system to cost-effectively deliver safe drinking water.²⁷⁶⁵ High source water quality and well-regulated flow can reduce the capital and variable costs of providing clean and abundant water.²⁷⁶⁶ Even where detailed scientific modeling has not been conducted, conservative assumptions and careful sensitivity analyses can produce actionable results.²⁷⁶⁷ Cultivating partnerships and large-scale sustained investment are two components of the design and implementation process:

- ***Cultivate partnerships:*** In each of the successful attempts to build robust programs for investment in natural infrastructure, essential components have been collaboration among a variety of stakeholders and experts, and the emergence of champions within stakeholder groups to push the program forward.²⁷⁶⁸ Landowner participation is essential in privately owned watersheds.²⁷⁶⁹

²⁷⁶⁰ Verbatim from Peterson et al. (2011, p. 46)

²⁷⁶¹ Verbatim from Peterson et al. (2011, p. 39)

²⁷⁶² Verbatim from Peterson et al. (2011, p. 39)

²⁷⁶³ Verbatim from Peterson et al. (2011, p. 39). Peterson et al. refer the reader to Table 5 in the cited report for information on vulnerability assessments and to Box 6 for information on the development of adaptation options.

²⁷⁶⁴ Verbatim from Dale et al. (2008, p. 730)

²⁷⁶⁵ Verbatim from Gartner et al. (2013, p. 1). *Natural infrastructure: Investing in forested landscapes for source water protection in the United States*. Gartner et al. refer the reader to Table ES-1 in the cited report for this information.

²⁷⁶⁶ Verbatim from Gartner et al. (2013, p. 3)

²⁷⁶⁷ Verbatim from Gartner et al. (2013, p. 3)

²⁷⁶⁸ Verbatim from Gartner et al. (2013, p. 4)

²⁷⁶⁹ Verbatim from Gartner et al. (2013, p. 5)

- **Large-scale, sustained investment:** A long list of public, private, and hybrid public/private finance mechanisms is available to get dollars on the ground to restore, enhance, protect, and manage natural infrastructure for water resources.²⁷⁷⁰ The primary challenge is to select a finance mechanism (or combination of mechanisms) that is capable of gaining the necessary political support for adoption, while also generating sufficient funds for meaningful and sustained investment in natural infrastructure.²⁷⁷¹

Implementation steps for water managers, conservationists, and other stakeholders at the local watershed level differ from those for the broader community of practitioners (Table 35).

Table 35. Implementation steps for natural infrastructure in forested landscapes.	
Steps for water managers, conservationists, and other stakeholders at the local watershed level	Steps for the broader community of practitioners
<ol style="list-style-type: none"> 1. Assess the watershed for ecological condition and trends causing water-related issues tied to substantial current or projected costs. 2. Engage with key stakeholders and decision makers early and often to articulate a vision of success, expand capacity for program development and implementation through strategic partnerships and consultation with experts, and build on the lessons of past successes and failures. 3. Conduct necessary economic analyses to determine if natural infrastructure is the best approach and to make the case for financial investment. 4. Assess a broad array of finance mechanisms with an eye toward securing large-scale “anchor funding” as well as a broader “funder quilt” to ensure meaningful and sustained investment over the long term. 5. Prioritize investments across parcels and interventions (i.e., reforestation or forest best management practices), monitor outcomes, and adapt investments accordingly. 	<ol style="list-style-type: none"> 1. Actively participate in the community of experts, facilitators, consultants, and “mobilizers” seeking to scale up integration of natural infrastructure into water management strategies, in order to leverage others’ efforts. 2. Assist in securing large-scale natural infrastructure funds such as bonds by ballot measure and natural infrastructure “set-asides” like the 20 percent green infrastructure requirement in the State Revolving Funds. 3. Expand research to quantify forest-to-water connections and improve the reliability and accessibility of watershed models. 4. Improve accounting standards to enable operations and maintenance spending on natural infrastructure by public entities as part of normal business practices. 5. Build awareness among the water resource management industry, the urban planning field, ratepayers, and taxpayers of the importance of natural infrastructure as a cost-effective and beneficial element of an integrated solution to emerging water issues.
<p><i>Table created by authors of this report.</i> <i>Source: Verbatim from Gartner et al. (2013, p. 6-7)</i></p>	

Modify forest water management

In broad terms, strategies to reduce forest vulnerability to increasing water stress will need to be tailored to specific management objectives and landscapes.²⁷⁷² The effectiveness of various approaches, trade-offs between forest and downstream water uses, and applications in specific locations need to be explored to develop viable and socially acceptable management strategies.²⁷⁷³ For example, discussion of the provision of water services by forests could be better informed by explicitly acknowledging any trade-offs

²⁷⁷⁰ Verbatim from Gartner et al. (2013, p. 5)

²⁷⁷¹ Verbatim from Gartner et al. (2013, p. 5)

²⁷⁷² Verbatim from Grant et al. (2013, p. 316). *Watering the forest for the trees: an emerging priority for managing water in forest landscapes.*

²⁷⁷³ Verbatim from Grant et al. (2013, p. 314)

between dispersed water available for on-site use by vegetation (e.g., transpiration and growth) and aggregated and concentrated water yield available downstream.²⁷⁷⁴ There may also be some places – for example, wet tropical forests with high cloud interception rates – where such strategies might not apply in the short term because water is not currently limiting nor is it projected to be in the near future.²⁷⁷⁵ Even in typically moist places, however, there are scenarios in which forests become water-limited.²⁷⁷⁶

Many of these strategies for addressing increased drought stress in forested landscapes are consistent with other forest management objectives, and are not necessarily new.²⁷⁷⁷

Forest thinning or prescribed burns

Developing managed burn or thinning strategies specifically directed at reducing fire severity, as well as increasing productivity and long-term forest resistance to drought-related dieback and disturbance across various projected climate scenarios, is relevant for both highly managed forests and as an adaptation strategy in natural reserves.²⁷⁷⁸ Initial findings from a U.S. network of long-term fire treatment studies suggest that fuels and thinning measures can be combined to reduce drought-stress vulnerability; however, these relationships are complex.²⁷⁷⁹ Recent advances in coupled models of climate and forest hydroecological processes could be combined with treatment studies to identify the most promising density, architecture, location, and orientation of stand manipulations.²⁷⁸⁰ *For additional information on adaptation options related to forest thinning, please see the section “Reduce fuel loads.”*

Consider drought tolerance during post-disturbance species selection

Selection of tree species for post-disturbance replanting could also explicitly consider the ability of particular species and genotypes to germinate and grow under conditions of water stress, particularly given that seedling establishment is closely tied to drought tolerance for a range of ecosystem types, from tropical to semi-arid.²⁷⁸¹

Alter stand structure and composition

Direct manipulation of stand structure and composition to increase water for on-site forest use – for example, by choosing species whose canopies intercept less water – has not been well-researched but may provide other options.²⁷⁸²

²⁷⁷⁴ Nearly verbatim from Grant et al. (2013, p. 319)

²⁷⁷⁵ Verbatim from Grant et al. (2013, p. 316)

²⁷⁷⁶ Nearly verbatim from Grant et al. (2013, p. 316). Grant et al. cite Choat et al. (2012) for this information.

²⁷⁷⁷ Verbatim from Grant et al. (2013, p. 319)

²⁷⁷⁸ Verbatim from Grant et al. (2013, p. 317)

²⁷⁷⁹ Verbatim from Grant et al. (2013, p. 317). Grant et al. cite McIver et al. (2009) for this information.

²⁷⁸⁰ Verbatim from Grant et al. (2013, p. 317). Grant et al. cite Tague & Band (2004) for information on recent advances in coupled models of climate and forest hydroecological processes.

²⁷⁸¹ Verbatim from Grant et al. (2013, p. 317). Grant et al. cite Engelbrecht et al. (2007) and Kursar et al. (2009) for this information.

²⁷⁸² Verbatim from Grant et al. (2013, p. 317)

Soil conservation

Contour felling, mulching, and fertilization may be effective in reducing soil loss; mulching may also reduce soil water evaporation but possibly at the expense of increasing litter interception and loss through evaporation.²⁷⁸³ Clearly, widespread mulching of forest lands would create a range of logistical and technical issues; however, for high-valued forests, for forests where thinning is performed to reduce fire risk, or for post-burn watershed treatments, strategies to reduce evaporative losses may be logistically feasible and cost-effective.²⁷⁸⁴ *For additional information on soil conservation, please see section “Increase carbon storage.”*

Measures to increase or sustain snowpack storage

Strategies would require evaluation within a local context and under different climate scenarios to determine whether approaches to marginally increasing soil water (such as by modifying snowpack storage) would be effective or counterproductive for increasing forest resilience.²⁷⁸⁵ For example, the placement of snow fences has been proposed to increase snow pack in areas where sensitive alpine plant communities are threatened by reduced snowpack.²⁷⁸⁶ Augmenting water availability for forests that are chronically drought-stressed may increase productivity and thereby actually increase the risks associated with drought-related disturbances in some situations.²⁷⁸⁷ However, manipulating the dimensions, orientations, spatial patterns, and densities of forest openings in the Rocky Mountains increased snow catch and reduced rates of snowmelt by over two weeks.²⁷⁸⁸ More radical snowpack storage treatments include deliberately mulching snow with wood chips, which has been shown to delay snowmelt by over three weeks.²⁷⁸⁹ Removing or re-engineering roads to deliver water back to the hillslope can increase local soil moisture levels considerably.²⁷⁹⁰

Hillslope capture or redistribution

The most direct manipulation of water availability for forests – namely, hillslope capture and redistribution, or even irrigation – has been used to support intensively managed forests.²⁷⁹¹ In many lightly managed forest areas, for instance in the western U.S., the concept of irrigating vegetation to enhance on-site forest resilience would be a marked departure from current water management practices but might ultimately be worth considering in highly valued landscapes.²⁷⁹²

²⁷⁸³ Verbatim from Grant et al. (2013, p. 317). Grant et al. cite Robichaud et al. (2000), Wagenbrenner et al. (2006), and Yanosek et al. (2006) for information on mulching, Dodson et al. (2010) for information on fertilization, and Helvey & Patric (1965) for information on the effects of mulching.

²⁷⁸⁴ Verbatim from Grant et al. (2013, p. 317)

²⁷⁸⁵ Verbatim from Grant et al. (2013, p. 317-318)

²⁷⁸⁶ Verbatim from Lawler (2009, p. 89). Lawler cites Hansen et al. (2003) for this information.

²⁷⁸⁷ Nearly verbatim from Grant et al. (2013, p. 317)

²⁷⁸⁸ Nearly verbatim from Grant et al. (2013, p. 317). Grant et al. cite Troendle (1983) for this information.

²⁷⁸⁹ Verbatim from Grant et al. (2013, p. 317). Grant et al. cite Osterhuber et al. (2007) for this information.

²⁷⁹⁰ Verbatim from Grant et al. (2013, p. 317). Grant et al. cite Kolka & Smidt (2004) for this information.

²⁷⁹¹ Verbatim from Grant et al. (2013, p. 318). Grant et al. cite Hillel (2008) and Tapia et al. (2008) for this information.

²⁷⁹² Verbatim from Grant et al. (2013, p. 318)

Reduce fuel loads

Fuel management options to reduce, convert, and/or isolate fuel can be a potential mechanism to reduce area burned.²⁷⁹³ For example, they can be used for small areas of the range of 100 kha, but are not realistic at the national scale of Canada.²⁷⁹⁴

Modify forestry practices

Forest harvest strategies may need to be adapted in the face of a changing climate.²⁷⁹⁵ Harvesting trees to create a diverse array of age structure and communities (for example, selective clear cutting, harvesting specific trees), target select ages of trees to harvest (harvest only trees that are sexually mature), or target species of trees to harvest (for example, harvest tree species that are not resilient to climate change) are all strategies that can be used to selectively harvest forest to increase the resiliency to climate change.²⁷⁹⁶ Other management techniques are also available:

- Short rotations to reduce the length of time that a tree is influenced by unfavorable climate conditions;
- Planting improved varieties developed through selection, breeding, or genetic engineering to reduce vulnerability; and,
- Thinning, weeding, managing pests, irrigating, improving drainage, and fertilizing to improve general vigor.²⁷⁹⁷ *For more information, please see the sections “Preserve and restore genetic diversity” and “Reduce fuel loads.”*

Such actions are likely to reduce the probability of moisture stress and secondary risks from fire, insects, and disease.²⁷⁹⁸

Increase biomass heating sources

The USDA Forest Service Fuel for Schools program is an example of an attempt to solve the problem of wildland fire fuel reduction with an opportunity to replace fossil fueled heating with biomass heating for local schools.²⁷⁹⁹ New estimates are that 5% of United States energy production could be sustainably produced by Advanced Wood Combustion facilities that already are operating in Austria.²⁸⁰⁰ If, in the future, any cellulosic material in a natural ecosystem has biofuel value, more carefully conducted thinning and restoration may be financially viable.²⁸⁰¹ Options like replacing oil- and gas-fueled heating systems in public buildings with wood-fueled boilers can be very viable in some places with ample local wood resources.²⁸⁰²

²⁷⁹³ Verbatim from Liu et al. (2013, p. 13)

²⁷⁹⁴ Nearly verbatim from Liu et al. (2013, p. 13)

²⁷⁹⁵ Verbatim from Staudt et al. (2012, p. 5-21)

²⁷⁹⁶ Verbatim from Staudt et al. (2012, p. 5-21). Staudt et al. cite Steenberg & others (2011) for this information.

²⁷⁹⁷ Verbatim from Kareiva et al. (2012, p. 4-26)

²⁷⁹⁸ Verbatim from Kareiva et al. (2012, p. 4-26)

²⁷⁹⁹ Verbatim from Running & Mills (2009, p. 24-25)

²⁸⁰⁰ Verbatim from Running & Mills (2009, p. 25). Running & Mills cite deb Richter Jr. et al. (2009) for this information.

²⁸⁰¹ Verbatim from Running & Mills (2009, p. 25)

²⁸⁰² Verbatim from Running & Mills (2009, p. 24)

Thinning and fuels reduction

Fuel reduction and restoration treatments can increase resiliency by reducing density-dependent tree mortality and excessive insect and/or disease problems and can increase spatial heterogeneity.²⁸⁰³

Landscape-scale thinning and fuel reduction treatments can be used to reduce the risk of anomalous crown fire, drought susceptibility and insect outbreaks.²⁸⁰⁴ Strategically placed firebreaks and other area treatments that reduce the continuity of forest floor debris will be especially important near residential areas, municipal watersheds and habitats that are designated as critical for the survival and recovery of threatened or endangered species.²⁸⁰⁵

Decisions about location and size of treatments can be explored with optimization models, expert knowledge of local landscapes, and examination of spatial patterns of forest structure and fuels over large landscapes over time.²⁸⁰⁶ In general, placement of treatments is designed to create landscape patterns that deter wildfire spread and modify fire behavior, while minimizing area needed for treatment.²⁸⁰⁷

Fuel treatments can have unintended consequences on other forest resources.²⁸⁰⁸ For example, thinning and surface fuel treatments can provide an avenue for propagation of exotic plant species.²⁸⁰⁹ Prescribed fire can scorch the crowns of live trees, which may increase stress or tree mortality.²⁸¹⁰ However, the biggest effect of fuel treatments is often on wildlife habitat, with animal species that depend on complex forest structure being negatively affected.²⁸¹¹ Alternatively, species that forage in open forest structure (e.g., ungulates) may benefit from fuel treatments.²⁸¹² Accounting for this interaction among resources will be a challenging consideration in fuel treatment planning in a warmer climate, because a warmer climate may directly affect those individual resources as well as the interactions.²⁸¹³

Prescribed burning

Prescribed burning can be used to reduce fuel loads, and hence the risk of catastrophic fire.²⁸¹⁴

²⁸⁰³ Verbatim from Stephens et al. (2013, p. 42). Stephens et al. cite Williams et al. (2013) for information on the role of fuel reduction and restoration treatments in reducing density-dependent tree mortality.

²⁸⁰⁴ Nearly verbatim from Blate et al. (2009, p. 60)

²⁸⁰⁵ Nearly verbatim from Blate et al. (2009, p. 60)

²⁸⁰⁶ Nearly verbatim from Peterson, Halofsky & Johnson (2011, p. 261). Peterson, Halofsky & Johnson cite Finney (2007) for information on optimization models, Peterson & Johnson (2007) for information on expert landscapes, and refer the reader to Figure 10.3 in the cited document for information on examining spatial patterns.

²⁸⁰⁷ Verbatim from Peterson, Halofsky & Johnson (2011, p. 261). Peterson, Halofsky & Johnson cite Finney (2001) and Hirsch et al. (2001) for this information.

²⁸⁰⁸ Verbatim from Peterson, Halofsky & Johnson (2011, p. 262)

²⁸⁰⁹ Verbatim from Peterson, Halofsky & Johnson (2011, p. 262). Peterson, Halofsky & Johnson cite Crawford et al. (2001) and Griffis et al. (2001) for this information.

²⁸¹⁰ Verbatim from Peterson, Halofsky & Johnson (2011, p. 262). Peterson, Halofsky & Johnson cite Graham et al. (2004) for this information.

²⁸¹¹ Verbatim from Peterson, Halofsky & Johnson (2011, p. 262). Peterson, Halofsky & Johnson cite Randall-Parker & Miller (2002) for information on wildlife habitat and Pilliod et al. (2006) for information on species dependent on complex forest structure.

²⁸¹² Verbatim from Peterson, Halofsky & Johnson (2011, p. 262)

²⁸¹³ Verbatim from Peterson, Halofsky & Johnson (2011, p. 262)

²⁸¹⁴ Verbatim from Lawler (2009, p. 88). Lawler cites Spittlehouse & Stewart (2003) and Scott et al. (2008) for this information.

Increase carbon storage

Mitigation, involving actions to reduce human influence on the climate system, is another fundamental approach for addressing climate challenges, and integrating mitigation activities with adaptation strategies is important.²⁸¹⁵ For this reason, options to increase carbon storage are presented here.

Because ecosystems both absorb and release CO₂, the relative balance between the two processes determines whether a particular ecosystem is a net carbon source or a sink.²⁸¹⁶ Depending on how they naturally function, and how they are managed, ecosystems can therefore either contribute to or reduce greenhouse gas emissions and climate change.²⁸¹⁷

Forests have the potential to mitigate global climate change by serving as net carbon sinks.²⁸¹⁸ Forestry activities that promote carbon storage include afforestation, reforestation, deforestation avoidance, replacing fossil fuels with biomass energy, wood products management, and improved forest management.²⁸¹⁹ Specific forest management techniques to improve carbon sequestration – thereby enhancing productivity, improving disease control, reducing decomposition and respiration, and managing wildfires – include the following: managing nutrients and water, performing residue management (e.g., the use of wood to offset fossil fuels), thinning and utilizing the products from thinning, low-impact harvesting, optimizing rotation length, administering species selection, and modifying genotype through biotechnology.²⁸²⁰ Further, protecting forests from wildfire increases carbon stocks in the short term but, combined with climate-change effects, may also increase the risk of large future releases of stored CO₂ during fire events, bark beetle or other defoliating insect outbreaks, hurricanes, ice storms, droughts, and other disturbances.²⁸²¹

Alter timber harvest patterns

Either an increase of the interval between harvests or a reduction in the amount of carbon removed each harvest would lead to an increase in average carbon stores in forests.²⁸²² For example, preservation of forests with the highest carbon stores, such as the moist mature and old-growth forests of the Pacific Northwest, would prevent vast amounts of carbon from reaching the atmosphere if these forests were logged.²⁸²³ Additionally, preservation of these forests provides habitat protection for the threatened and declining northern spotted owl and marbled murrelet.²⁸²⁴ *Alternative sentence:* Increasing carbon stores

²⁸¹⁵ Verbatim from Millar et al. (2012, p. 128). Millar et al. cites Metz et al. (2001) for information on mitigation as a fundamental approach for addressing climate challenges.

²⁸¹⁶ Verbatim from Pojar (2010, p. 57)

²⁸¹⁷ Verbatim from Pojar (2010, p. 57)

²⁸¹⁸ Verbatim from Sturrock et al. (2011, p. 133). Sturrock et al. cite IPCC (2007) for this information.

²⁸¹⁹ Verbatim from Post et al. (2012, p. 555). *Management opportunities for enhancing terrestrial carbon dioxide sinks.*

²⁸²⁰ Verbatim from Post et al. (2012, p. 556). Post et al. cite Stanturf et al. (2003) for information on wildfire.

²⁸²¹ Nearly verbatim from Post et al. (2012, p. 555). Post et al. cite Westerling et al. (2006) for information on wildfire.

²⁸²² Verbatim from Shafer et al. (2010, p. 188). Shafer et al. cite Harmon et al. (2009) for this information.

²⁸²³ Nearly verbatim from North American Bird Conservation Initiative (2010, p. 21)

²⁸²⁴ Verbatim from North American Bird Conservation Initiative (2010, p. 21)

would require increasing the interval between harvests and/or reducing harvest amounts, which may be unrealistic without having funds available to offset losses in traditional harvest-based revenues.²⁸²⁵

Store carbon in wood products

An alternative to increasing carbon stores within the forest is to harvest wood and store some of this carbon within wood products.²⁸²⁶ Under current manufacturing, use, and disposal practices this alternative is unlikely to increase the overall carbon store of the forest sector, which includes the forest and wood products derived from the forest.²⁸²⁷

Reduce soil degradation and continue soil conservation

Land-use change will have a large impact on carbon soil sequestration, with transitions from cropland to forest and urban areas having a positive impact on soil carbon storage.²⁸²⁸

Strategies to reduce or even reverse soil degradation include no-till farming, water conservation and harvest, cover cropping, woodland regeneration, agroforestry, improved grazing practices, more efficient irrigation, and erosion control.²⁸²⁹

- ***No-till and conservation tillage:*** No-till farmers plant their crops directly into the stubble left from the previous year's crop.²⁸³⁰ The stubble acts like a garden mulch and helps soil retain more moisture by trapping snow, decreasing evaporation from the top layer of soil, and improving water infiltration to plant root systems.²⁸³¹ However, the benefits of no till on soil organic carbon sequestration may be soil/site specific, and the improvement in soil organic carbon may be inconsistent in fine-textured and poorly drained soils.²⁸³² Some studies have also shown more nitrous oxide emissions in no till.²⁸³³
- ***Water conservation, harvest, and irrigation:*** Similar to the addition of fertilizers and manures in a nutrient-depleted soil, judicious application

Adaptation in Action

The **Conservation Biology Institute** (CBI) is creating a soil vulnerability index to identify drought-sensitive areas in the NPLCC region. CBI is also mapping where forest cover will be most affected by climate change. Combined, the vulnerability index and map will provide information on possible future changes in soil moisture and temperature, which could be used to improve vegetation models and inform resource management decisions.

Source: Conservation Biology Institute (2013)

²⁸²⁵ Verbatim from Shafer et al. (2010, p. 189). Shafer et al. cite Alig et al. (2002) for this information.

²⁸²⁶ Verbatim from Shafer et al. (2010, p. 189). Shafer et al. cite Perez-Garcia et al. (2005) for this information.

²⁸²⁷ Verbatim from Shafer et al. (2010, p. 189). Shafer et al. cite Harmon et al. (2009) for this information.

²⁸²⁸ Verbatim from Kareiva et al. (2012, Table 4-2). Kareiva et al. cite E. Nelson's analysis for this information.

²⁸²⁹ Verbatim from Peterman & Bachelet (2012, p. 172). Peterman & Bachelet cite Kaiser (2004) and Oldeman (1992) for this information.

²⁸³⁰ Verbatim from O'Connor (2013, p. 7). *Soil matters: how the Federal Crop Insurance Program should be reformed to encourage low-risk farming methods with high-reward environmental outcomes.*

²⁸³¹ Verbatim from O'Connor (2013, p. 7). O'Connor cites Osteen et al. (2012) for this information.

²⁸³² Verbatim from Lal (2004, p. 11). *Soil carbon sequestration to mitigate climate change.* Lal cites Wander et al. (1998) for this information.

²⁸³³ Verbatim from Lal (2004, p. 11). Lal cites Mackenzie et al. (1998) for this information.

of irrigation water in a drought prone soil can enhance biomass production, increase the amount of above-ground and the root biomass returned to the soil and improve soil organic carbon concentration.²⁸³⁴

- **Cover cropping:** Cover crops are non-commodity crops that are either planted with the primary purpose of improving the soil ecosystem.²⁸³⁵ Like no-till management, cover cropping increases water infiltration and storage, thereby helping to provide water to growing commodity crops and decreasing the need for irrigation.²⁸³⁶ For example, growing leguminous cover crops enhances biodiversity, the quality of residue input, and the soil organic carbon pool.²⁸³⁷ Although cover crops themselves require water to grow, when they are properly selected and managed, the net water available for commodity crops tends to increase due to cover crops' ability to increase infiltration and reduce surface evaporation.²⁸³⁸ However, the use of cover crops as a short-term green manure may not necessarily enhance the soil organic carbon pool.²⁸³⁹
- **Woodland regeneration, agroforestry, and afforestation:** Converting degraded soils under agriculture and other land uses into forests and perennial land use can enhance the soil organic carbon pool.²⁸⁴⁰ Afforestation, particularly on abandoned agricultural land, reclaimed mine sites, and other degraded lands, generally increases soil carbon in addition to producing wood.²⁸⁴¹ The magnitude and rate of soil organic carbon sequestration with afforestation depends on climate, soil type, species, and nutrient management.²⁸⁴² Afforestation, however, may not always enhance the soil organic carbon pool.²⁸⁴³ In such cases, agroforestry may be another option of conserving soil and improving the soil organic carbon pool.²⁸⁴⁴
- **Improved grazing practices:** Similar to cropland, management options for improving pastures include judicious use of fertilizers, controlled grazing, sowing legumes and grasses or other species adapted to the environment, improvement of soil fauna and irrigation.²⁸⁴⁵
- **Erosion control:** Increasing carbon and nitrogen sequestration with policies and practices such as applying conservation agriculture, using cover crops, keeping the soil covered with residue, using crop rotations, or returning crop residue, will improve soil quality and will help minimize soil erosion.²⁸⁴⁶

²⁸³⁴ Verbatim from Lal (2004, p. 12)

²⁸³⁵ Verbatim from O'Connor (2013, p. 8)

²⁸³⁶ Verbatim from O'Connor (2013, p. 8). O'Connor cites Blanco-Canqui (2011) for this information.

²⁸³⁷ Verbatim from Lal (2004, p. 12). Lal cites Singh et al. (1998), Fullen & Auerswald (1998), and Uhlen & Tveitnes (1995) for this information.

²⁸³⁸ Verbatim from O'Connor (2013, p. 8-9). O'Connor cites De Bruin et al. (2005) for information on water requirements for cover crops and Blanco-Canqui (2011) for information on the ability of cover crops to increase infiltration and surface evaporation.

²⁸³⁹ Verbatim from Lal (2004, p. 12)

²⁸⁴⁰ Verbatim from Lal (2004, p. 13)

²⁸⁴¹ Verbatim from Post et al. (2012, p. 555). Post et al. cites Guo & Giffor (2002) for this information.

²⁸⁴² Verbatim from Lal (2004, p. 13). Lal cites Lal (2001c) for this information.

²⁸⁴³ Verbatim from Lal (2004, p. 13)

²⁸⁴⁴ Verbatim from Lal (2004, p. 13)

²⁸⁴⁵ Verbatim from Lal (2004, p. 13). Lal cites Follett et al. (2001a) for this information.

²⁸⁴⁶ Nearly verbatim from Lal et al. (2011, p. 282). *Management to mitigate and adapt to climate change.*

Restore, create, or maintain climate-resilient habitats

One strategy for conserving species and their habitat under changing climate is to identify locations that may sustain suitable habitat conditions for a species as climate changes.²⁸⁴⁷ Resilience-enhancing adaptations include efforts to boost population sizes, increase the number (or diversity) of locations where individual populations, species and habitats are managed, and restore key ecosystem conditions and processes following disturbance.²⁸⁴⁸ Place-based approaches could also focus on microclimatic variations that provide refugia from large-scale changes in climate or involve planting trees and other vegetation to provide shade and reduce temperatures.²⁸⁴⁹

Identify potential refugia at regional and landscape levels

Mountainous terrain will experience spatially variable levels of climate change (Daly et al. 2009) and harbor climate refugia.²⁸⁵⁰ For example, some topographic positions subject to cold air drainages and topographic shading in the Oregon Cascades have old conifers that have persisted for more than 800 years with little fire.²⁸⁵¹

Adjust user fees

Innovative approaches to adjusting user fees to account for maintenance and protection costs of valuable, natural habitats are growing in popularity.²⁸⁵²

Maintain older forest

Large conifers are more resistant to drought and have lower mortality rates than smaller individuals, and may be found in moist parts of the landscape that may be buffered against the effects of climate change.²⁸⁵³ This resistance may result from deeper roots and greater water holding capacity than younger trees.²⁸⁵⁴ Although mortality rates in old-growth forests have increased over the last few decades, the very existence of centuries-old trees demonstrates that they can persist in the face of some level of climate variability.²⁸⁵⁵

²⁸⁴⁷ Verbatim from Shafer et al. (2011, p. 212). Shafer et al. refer the reader to Figures 4, 5, and 6 in the cited article.

²⁸⁴⁸ Verbatim from Blate et al. (2009, p. 60)

²⁸⁴⁹ Verbatim from Stein et al. (2012, p. 6-22). Stein et al. cite Mosblech & others (2011) for information on microclimatic variations that provide refugia from large-scale climatic changes. Stein et al. cite Wilby & others (1998) and Wilby & Perry (2006) for information on using vegetation to provide shade and reduce temperatures.

²⁸⁵⁰ Nearly verbatim from Spies et al. (2010, p. 1192). Spies et al. cite Daly et al. (2009) for information on spatially variable levels of climate change in mountainous terrain.

²⁸⁵¹ Nearly verbatim from Spies et al. (2010, p. 1192-1193). Spies et al. cite Giglia (2004) for this information.

²⁸⁵² Verbatim from Kareiva et al. (2012, p. 4-26)

²⁸⁵³ Verbatim from Spies et al. (2010, p. 1192). Spies et al. cite Phillips et al. (2003) for information on drought resistance and lower mortality rates in large conifers compared to smaller individuals.

²⁸⁵⁴ Verbatim from Spies et al. (2010, p. 1192)

²⁸⁵⁵ Verbatim from Spies et al. (2010, p. 1192). Spies et al. cite van Mantgem et al. (2009) for information on increased mortality rates in old-growth forests in the last few decades..

Restore old-growth forest

Restoring old-growth trees not only will help sequester carbon but will cool temperatures in the understory enough to mitigate higher wind speeds and drying of live and dead fuels in forest openings.²⁸⁵⁶ Moreover, long-established herbaceous species in these openings will contribute carbon to the soil through continual root decomposition.²⁸⁵⁷ Thinning in some forest types to reduce crown-to-crown and ground-to-crown contact will lower fire risk and therefore prevent carbon from being lost to stand-replacing wildfires.²⁸⁵⁸

Promote forest recovery

Management actions can enhance forest recovery.²⁸⁵⁹ Recovery efforts can focus either on managing the state of the system immediately after the disturbance (e.g., salvage logging) or managing the ongoing process of recovery (e.g., planting and reseeded).²⁸⁶⁰ Aggressive site preparation has been proposed to enhance regeneration after disturbances.²⁸⁶¹ Recovery can also be managed to reduce vulnerability to future disturbances.²⁸⁶² However, stands can recover naturally without any removal of the dead or damaged trees.²⁸⁶³ Recovery efforts need careful consideration of the long-term impacts because such actions can damage soils and residual trees.²⁸⁶⁴

Recovery actions can be designed to speed recovery.²⁸⁶⁵ For example:

- **Modify forest structure:** Forest structure can be modified to speed up the successional process in the event of a disturbance.²⁸⁶⁶ In the aftermath of a disturbance, recovery can be enhanced by adding structural elements that create shade or other safe sites necessary for reestablishing vegetation or that serve as perches for birds (and thus places where seeds would be dispersed).²⁸⁶⁷ Alternatively, late successional species can be planted to speed up succession.²⁸⁶⁸
- **Modify species composition:** Alternatively, species composition can be adjusted to promote recovery.²⁸⁶⁹ For example, in areas likely to experience a disturbance, trees with salvage value can be planted.²⁸⁷⁰
- **Modify water and nutrient cycling:** Additions of water or nutrients can reduce environmental stress and facilitate restoration.²⁸⁷¹

²⁸⁵⁶ Verbatim from Senos et al. (2006, p. 420)

²⁸⁵⁷ Verbatim from Senos et al. (2006, p. 420)

²⁸⁵⁸ Verbatim from Senos et al. (2006, p. 420)

²⁸⁵⁹ Verbatim from Dale et al. (2008, p. 730)

²⁸⁶⁰ Verbatim from Dale et al. (2008, p. 730)

²⁸⁶¹ Verbatim from Lawler (2009, p. 88-89). Lawler cites Spittlehouse & Stewart (2003) for this information.

²⁸⁶² Verbatim from Dale et al. (2008, p. 731)

²⁸⁶³ Nearly verbatim from Dale et al. (2008, p. 730)

²⁸⁶⁴ Verbatim from Dale et al. (2008, p. 730)

²⁸⁶⁵ Verbatim from Dale et al. (2008, p. 730)

²⁸⁶⁶ Verbatim from Dale et al. (2008, p. 730)

²⁸⁶⁷ Verbatim from Dale et al. (2008, p. 730-731)

²⁸⁶⁸ Verbatim from Dale et al. (2008, p. 731)

²⁸⁶⁹ Verbatim from Dale et al. (2008, p. 730)

²⁸⁷⁰ Verbatim from Dale et al. (2008, p. 730)

²⁸⁷¹ Verbatim from Dale et al. (2008, p. 731)

Targeted thinning to increase resilience to disturbance

Targeted thinning in drier forests in which fire suppression has led to fuel accumulations capable of sustaining a high severity fire (novel in those ecosystems) may increase the resilience of that forest to a fire.²⁸⁷² In wetter forests where twentieth century harvest practices have decreased age class diversity and altered patch structure, targeted thinning and cutting could simultaneously create appropriate fuel breaks and increase canopy and age-class diversity.²⁸⁷³ Furthermore, the removal of dead or dying trees and downed woody debris can reduce the risk of fire as well as alter insect and disease dynamics.²⁸⁷⁴

Spatially heterogeneous thinning of dense young stands has promoted the growth and survivorship of remaining individual trees and, more recently, been used to accelerate the development of structurally and ecologically diverse conditions.²⁸⁷⁵ Such thinning could, in theory, also promote growth and vigor of the tree layer under warming climate, but no studies have examined this question.²⁸⁷⁶ However, the duration of this effect and the degree to which it promotes undesirable understory growth is a major uncertainty.²⁸⁷⁷ In addition, thinning and associated management activities can increase occurrence of invasive plants.²⁸⁷⁸

In water-limited forests, it is possible that tailoring stand density to the expected water conditions of the future will increase resilience to insect attack and climate change in general by increasing stand water supply to counteract the projected increased atmospheric demand.²⁸⁷⁹ Thus, density management can reduce drought stress as well as alter insect population dynamics, but it could make forests more susceptible to wind.²⁸⁸⁰

However, thinning to reduce water stress would lower carbon stores in the short-term, but might assure more carbon is stored over the long-term if disturbance severity or frequency greatly increase or if forests disturbed in the future are unable to regenerate.²⁸⁸¹ It should be noted that due to the feedback between fire severity and fuel level, a period of more frequent, severe fires will not persist (more frequent removal of fuels means less fuel, which means lower severity fires).²⁸⁸² Removal of fuels to alter fire behavior and severity to reduce carbon emissions would, in most cases, lead to substantial losses of carbon stores as the amount of carbon needed to be removed to alter fire severity exceeds the amount released by fires at least 10-fold.²⁸⁸³ Using removed fuels as a biofuels feedstock or for wood products narrows the carbon cost of fuel treatments, but it does not entirely eliminate the carbon debts created by these treatments.²⁸⁸⁴

²⁸⁷² Verbatim from Littell et al. (2010, p. 150-151)

²⁸⁷³ Verbatim from Littell et al. (2010, p. 151)

²⁸⁷⁴ Nearly verbatim from Dale et al. (2008, p. 730)

²⁸⁷⁵ Verbatim from Spies et al. (2010, p. 1192). Spies et al. cite Thomas et al. (1999) for this information.

²⁸⁷⁶ Verbatim from Spies et al. (2010, p. 1192)

²⁸⁷⁷ Verbatim from Spies et al. (2010, p. 1192)

²⁸⁷⁸ Verbatim from Spies et al. (2010, p. 1192)

²⁸⁷⁹ Verbatim from Littell et al. (2010, p. 151)

²⁸⁸⁰ Nearly verbatim from Dale et al. (2008, p. 730)

²⁸⁸¹ Nearly verbatim from Shafer et al. (2010, p. 191)

²⁸⁸² Verbatim from Shafer et al. (2010, p. 191)

²⁸⁸³ Verbatim from Shafer et al. (2010, p. 191). Shafer et al. cite Mitchell et al. (2009) for this information.

²⁸⁸⁴ Verbatim from Shafer et al. (2010, p. 191)

Assuming fuel removal continues to produce biofuels, it may take many decades to centuries to pay back the carbon debts incurred.²⁸⁸⁵

Use wildfires to facilitate establishment of climate-adapted species and communities

While increased wildfires can be a threat to biodiversity, especially in landscapes where habitat has been altered by logging and land-use change, they also provide a benefit by creating diverse early successional conditions and opportunities for natural or artificial regeneration of new genotypes and species that may be better adapted to the climate than those in existing stands.²⁸⁸⁶ The challenge to planners and managers is deciding when and where to allow fires to burn and what to do afterwards.²⁸⁸⁷ Planting with new species mixes or new genotype combinations, or assisting development of new animal habitats after disturbance, are examples of actions that can be taken after a disturbance.²⁸⁸⁸ The challenge is especially great where federal lands border state and private lands where wildfires can threaten commercial timber crops and homes.²⁸⁸⁹

Align significantly disrupted systems to likely future conditions

Realigning significantly disrupted ecological conditions to current and future climates may be a preferred choice when resilience thresholds are exceeded and restoration to historic pre-disturbance conditions is considered too environmentally challenging, too expensive or not politically feasible.²⁸⁹⁰ This type of adaptation was implemented for Mono Lake, California; after court-ordered mediation among stakeholders, restoration goals were revised to take into account current climate and future climate uncertainties to determine the most appropriate lake level for present and anticipated future conditions.²⁸⁹¹

Additional options

The following adaptation option for restoring, creating, or maintaining climate-resilient habitat was found in the literature, but was not discussed in detail, or is described elsewhere in this report:

- ***Use diverse genetic stocks when replanting:*** It has been suggested that replanting efforts and restoration efforts in general make use of diverse genetic stocks instead of relying on local genotypes.²⁸⁹² *For additional information on preserving and restoring genetic diversity, please see section “Preserve and restore genetic diversity.”*

²⁸⁸⁵ Verbatim from Shafer et al. (2010, p. 191). Shafer et al. cite Mitchell et al. (2009) for this information.

²⁸⁸⁶ Verbatim from Spies et al. (2010, p. 1192)

²⁸⁸⁷ Verbatim from Spies et al. (2010, p. 1192)

²⁸⁸⁸ Verbatim from Peterson et al. (2011, p. 62)

²⁸⁸⁹ Verbatim from Spies et al. (2010, p. 1192)

²⁸⁹⁰ Verbatim from Blate et al. (2009, p. 61)

²⁸⁹¹ Verbatim from Blate et al. (2009, p. 61). Blate et al. cite Millar, Stephenson, & Stephens (2007) for this information.

²⁸⁹² Nearly verbatim from Stein et al. (2012, p. 6-22). Stein et al. cite Glick & others (2009) for this information.

Maintain, restore, or create prairie, oak woodland, savanna, and grassland habitats

In the context of climate change, developing new conservation strategies should focus on taking advantage of opportunities (e.g., warmer, longer and drier summers) and facilitate the minimization of long-term land management and management expenses.²⁸⁹³ Conservation of prairies and savannas should also take into account other threats besides climate change.²⁸⁹⁴ Several of these threats (e.g., land conversion, landscape fragmentation) are likely to be of more immediate consequence to grassland species than is climate change.²⁸⁹⁵ Therefore, effective conservation strategies need to assess how climate change may exacerbate the impacts of these other threats, for example, impacts due to likely human immigration from warmer and drier areas.²⁸⁹⁶

Utilize the full geographic and climatic range of prairies and oak savannas

In Washington and Oregon, taking advantage of the 497 mile (800 km) north-south range of prairies and oak savannas in the Willamette Valley-Puget Sound ecoregion is crucial for conservation actions to mitigate local constraints.²⁸⁹⁷ Despite its controversial aspect, assisted colonization and similar translocations within the ecoregion may become critical to ensure the conservation of at-risk individual species or plant assemblages that support target faunal communities.²⁸⁹⁸ For example, conservation efforts to translocate western bluebirds from the Puget Sound, where they are threatened by habitat loss and nesting competition, northward to the San Juan Islands have been very successful.²⁸⁹⁹ Consideration is now underway to extend this translocation into British Columbia.²⁹⁰⁰

Adaptation in Action

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.

Source: Conservation Biology Institute (n.d.)

Establishing and enhancing connectivity between sites will also become increasingly important.²⁹⁰¹ This will place a high priority on identifying and protecting parcels that occupy critical locations to provide essential linkages.²⁹⁰² These parcels may not contain prairie/oak ecosystems at present, and may not even

²⁸⁹³ Verbatim from Bachelet et al. (2011, p. 420)

²⁸⁹⁴ Verbatim from Bachelet et al. (2011, p. 420)

²⁸⁹⁵ Verbatim from Bachelet et al. (2011, p. 420)

²⁸⁹⁶ Verbatim from Bachelet et al. (2011, p. 420)

²⁸⁹⁷ Nearly verbatim from Bachelet et al. (2011, p. 420)

²⁸⁹⁸ Verbatim from Bachelet et al. (2011, p. 420). Bachelet et al. cites Stone (2010) for information on the controversial aspect of assisted colonization.

²⁸⁹⁹ Verbatim from Bachelet et al. (2011, p. 420-421). Bachelet et al. cite Slater & Altman (2011) for this information.

²⁹⁰⁰ Verbatim from Bachelet et al. (2011, p. 421)

²⁹⁰¹ Verbatim from Dunwiddie & Bakker (2011, p. 87). *The future of restoration and management of prairie-oak ecosystems in the Pacific Northwest.*

²⁹⁰² Verbatim from Dunwiddie & Bakker (2011, p. 87)

have supported them in the past.²⁹⁰³ Invasive species may be rampant, and the soil structure, nutrients, and microfauna may be very different from that in a prairie/oak ecosystem.²⁹⁰⁴ Restoration of these types of sites has scarcely been attempted in this region, and presents enormous challenges in terms of both cost and feasibility.²⁹⁰⁵

Use habitat heterogeneity to sustain populations and functions in place

This may mean facilitating species shifts into new microhabitat types or even new community types.²⁹⁰⁶ For example, some plant species currently found in upland prairies may need to shift their distribution to wetland prairies or vernal pools under increased summer drought stress.²⁹⁰⁷ Similarly, tree shade in oak savannas and the presence of microtopographic heterogeneity, such as mounds and swales, affect the distribution of prairie species which may allow some to persist under a warmer, drier, climate, and also extend the flowering period of plants, potentially helping to maintain key plant-pollinator interactions.²⁹⁰⁸ Managers working to conserve grassland species may also find it necessary to shift their attention from the hot, dry south-facing slopes that currently support much of the remnant prairie and savanna habitat to include the adjacent, cooler northern aspects that are currently dominated by Douglas-fir, especially if Douglas-fir should begin to decline on these sites.²⁹⁰⁹

Manage current sites adaptively and strategically expand prairie conservation areas

Adding certain species or functional groups, as well as increasing population sizes, may facilitate changes in community composition and phenology that still support conservation goals.²⁹¹⁰ For instance, in several South Puget Sound prairies, conservation practitioners have begun to increase the amount of annual forbs and non-native plant species that can fill the need for early season food, especially in cool wet springs, for larvae of the Taylor's checkerspot butterfly.²⁹¹¹ These efforts can be combined with the reintroduction of local species to either historical sites or to new, more favorable sites that can help boost local populations.²⁹¹²

Management of existing sites will need to counter the twin threats of invasive species and encroaching woody vegetation.²⁹¹³ Although future climate change may influence the relative importance of these threats, both will remain management issues.²⁹¹⁴ Early detection of these new invasive species, combined

²⁹⁰³ Verbatim from Dunwiddie & Bakker (2011, p. 87)

²⁹⁰⁴ Verbatim from Dunwiddie & Bakker (2011, p. 87)

²⁹⁰⁵ Verbatim from Dunwiddie & Bakker (2011, p. 87)

²⁹⁰⁶ Verbatim from Bachelet et al. (2011, p. 421)

²⁹⁰⁷ Verbatim from Bachelet et al. (2011, p. 421)

²⁹⁰⁸ Verbatim from Bachelet et al. (2011, p. 421). Bachelet et al. cite del Moral & Deardoff (1976) for information on the factors affecting the distribution of prairie species.

²⁹⁰⁹ Verbatim from Bachelet et al. (2011, p. 421)

²⁹¹⁰ Verbatim from Bachelet et al. (2011, p. 421)

²⁹¹¹ Verbatim from Bachelet et al. (2011, p. 421). Bachelet et al. cite Fimbel et al. (2010) for this information.

²⁹¹² Verbatim from Bachelet et al. (2011, p. 421)

²⁹¹³ Verbatim from Dunwiddie & Bakker (2011, p. 87)

²⁹¹⁴ Verbatim from Dunwiddie & Bakker (2011, p. 87)

with rapid and effective control actions before they become extensive and difficult to eradicate, is already a widely embraced strategy and will become increasingly urgent in years to come.²⁹¹⁵

Intensive management techniques used to restore prairies and oak savannas on severely degraded sites that have been cultivated are invaluable to both increase the number of prairie habitat sites and alleviate landscape fragmentation.²⁹¹⁶ Additionally, and maybe more controversially, managers may want to consider using prescribed fire to pre-adapt areas to projected increases in fire frequency.²⁹¹⁷ Prescribed fire is only now beginning to be widely utilized in prairies and oak savannas.²⁹¹⁸ Fire managers may wish to consider higher fire frequencies on small portions of protected sites to help promote projected changes in communities, while still protecting fire-sensitive target species such as butterflies.²⁹¹⁹ Similarly, managers might consider altering the timing of fires to reflect the increased likelihood of summertime fires in the future.²⁹²⁰

Establish new prairies and oak savannas on lands that become suitable due to climate change

Prairies and oak savannas are likely to tolerate the impacts of climate change better than lowland Douglas-fir forest or floodplain agriculture.²⁹²¹ This could create an opportunity to expand prairie and oak savanna habitat where more susceptible communities have been displaced.²⁹²² In fact, a climate-driven expansion of prairie habitat may reverse trends that have decreased the extent of prairie and oak savannas from the recent past.²⁹²³ For example, scenarios where both drier upland fields and wetter alluvial soils become unsuitable for productive agriculture are plausible.²⁹²⁴ Establishing natural prairie and oak savanna habitats in these less productive areas may be an ecologically sensible alternative.²⁹²⁵

Enhance opportunities for conservation and restoration by using ecosystem services from prairies and oak savannas

Because terrestrial carbon sequestration will be an important component of both current and future carbon markets, the restoration of prairies and savannas offers the opportunity to take advantage of financial incentives to fund conservation efforts.²⁹²⁶ Some prairies and oak savannas contribute to buffering hydrological flows.²⁹²⁷ For instance, wetland prairies in the WPG ecoregion can play a role in moderating potential high-water spates that are projected for the region.²⁹²⁸ In some areas such as Eugene, Oregon,

²⁹¹⁵ Verbatim from Dunwiddie & Bakker (2011, p. 87). Dunwiddie & Bakker cite Dennehy et al. (2011) for information on early detection and rapid and effective control actions as a widely embraced strategy.

²⁹¹⁶ Verbatim from Bachelet et al. (2011, p. 422). Bachelet et al. cite Bakker et al. (2010) for this information.

²⁹¹⁷ Verbatim from Bachelet et al. (2011, p. 422)

²⁹¹⁸ Verbatim from Bachelet et al. (2011, p. 422). Bachelet et al. cite Hamman et al. (2011) for this information.

²⁹¹⁹ Verbatim from Bachelet et al. (2011, p. 422)

²⁹²⁰ Verbatim from Bachelet et al. (2011, p. 422)

²⁹²¹ Verbatim from Bachelet et al. (2011, p. 422)

²⁹²² Verbatim from Bachelet et al. (2011, p. 422)

²⁹²³ Verbatim from Bachelet et al. (2011, p. 422)

²⁹²⁴ Verbatim from Bachelet et al. (2011, p. 422). Bachelet et al. cite Vynne et al. (2011) for this information.

²⁹²⁵ Verbatim from Bachelet et al. (2011, p. 422)

²⁹²⁶ Verbatim from Bachelet et al. (2011, p. 422)

²⁹²⁷ Verbatim from Bachelet et al. (2011, p. 422)

²⁹²⁸ Verbatim from Bachelet et al. (2011, p. 422)

they are already being harnessed to the service of infiltrating peak stormwater flows from urban impervious surfaces.²⁹²⁹

Monitor climate and threshold responses of biological communities

Since local climate and impacts will differ, monitoring may need to be customized to particular subregions and their projected changes.²⁹³⁰ For instance, extreme events such as drought may affect important plant species, such as Garry Oak or the native bunchgrass, Roemer's fescue, at the southern extent of prairies and oak savannas, whereas drought in the northern range may not have sufficient intensity to produce similar effects on core species.²⁹³¹ Monitoring programs should include information from adjacent agricultural land and timberlands, especially those that may become susceptible to abandonment or dieback as water availability decreases during the growing season.²⁹³² If productivity becomes too low to be commercially viable on parts of the landscape that are currently zoned for agriculture or forestry, programs could be promoted to support conversion to prairie or oak savanna on such lands.²⁹³³

Maintain, restore, or create terrestrial connectivity

Static protected areas will not be sufficient to conserve biodiversity in a changing climate, requiring an emphasis on landscape-scale conservation, connectivity among protected habitats, and sustaining ecological functioning of working lands and waters.²⁹³⁴ Dispersal corridors are vital for species to track changes in climatic conditions.²⁹³⁵

Intact natural landscapes constitute the best options for wildlife survival during climate change because they provide functional matrices or corridors for migration and moderated microclimates for short-term persistence and longer-term adaptation.²⁹³⁶ More specifically, intact ecosystems can soften the impact of climate change to wildlife by slowing the rate of landscape change, moderating microclimates, and providing alternative habitats.²⁹³⁷ Strategies to reduce adaptive constraints include enhancing connectivity through fragmented landscapes by encouraging compatible land uses and maintaining or enhancing wildlife corridors.²⁹³⁸ Non-degraded, supportive habitat provides the best chance for the movement and transport of materials, nutrients, energy, and organisms, so planning should strive for:

- ***Very large core intact area*** complexes;
- ***Large intact mountain ranges***, to maintain their key laddering role across ecosystems and life zones;

²⁹²⁹ Verbatim from Bachelet et al. (2011, p. 422-423)

²⁹³⁰ Verbatim from Bachelet et al. (2011, p. 423)

²⁹³¹ Verbatim from Bachelet et al. (2011, p. 423)

²⁹³² Verbatim from Bachelet et al. (2011, p. 423)

²⁹³³ Verbatim from Bachelet et al. (2011, p. 423)

²⁹³⁴ Verbatim from Stein et al. (2012, p. 6-1)

²⁹³⁵ Verbatim from Heino, Virkkala and Toivonen. (2009, p. 49)

²⁹³⁶ Verbatim from Pojar (2010, p. 42). Pojar cites Groves (2003), Dobson et al. (1999), and Hilty et al. (2006) for this information.

²⁹³⁷ Nearly verbatim from Pojar (2010, p. 42). Pojar cites Noss (2001) for this information.

²⁹³⁸ Verbatim from Klausmeter et al. (2011, p. 12)

- *Spacious migration corridors/landscape linkages* – south-north, west-east (transmontane), upslope; and,
- *Supportive buffer areas.*²⁹³⁹

Protected area management to ensure adaptation to climate change may include restoration, focusing on resilient habitats, managing specifically for anticipated threats such as fire and pests, and addressing other threats (which can be exacerbated by climate change).²⁹⁴⁰ Restoration will be important both within protected areas and around them in targeted locations within the wider landscape.²⁹⁴¹ Future protected area management strategies and plans should also include options for carbon storage as well as reducing emissions from deforestation and degradation.²⁹⁴²

Expand or create new protected areas

Many strategies for improving habitat connectivity have focused on expanding protected areas to provide more space for species to shift, cover broader climatic conditions, or to span multiple biomes.²⁹⁴³ One such strategy that could be considered is for existing programs (for example, the National Wildlife Refuge system) to increase the number of functionally connected units, which may increase resilience to climate change for migratory species.²⁹⁴⁴ Larger reserves may help to protect more species for longer periods of time in a changing climate.²⁹⁴⁵ Similarly, reserves that span strong environmental gradients may facilitate range shifts within reserves by providing species access to areas where future suitable habitats may occur (for example, at higher elevations).²⁹⁴⁶ To best protect species in a changing climate, new reserves can be placed at the core of species environmental distributions, at elevational or poleward range limit of key species, or at transitions between major ecological systems or biomes.²⁹⁴⁷

More sophisticated approaches for locating new protected areas to address climate change have been suggested:²⁹⁴⁸

- ***Base protected areas on future species distributions:*** Recently, efforts have been made to locate new or expand existing protected areas based on projected shifts in species distributions under different climate scenarios.²⁹⁴⁹ The increase in specificity potentially makes this approach more

²⁹³⁹ Nearly verbatim from Pojar (2010, p. 43). Pojar cites Franklin & Lindenmeyer (2008) for information on non-degraded, supportive habitat providing the best chance for the movement and transport of materials, nutrients, energy, and organisms.

²⁹⁴⁰ Verbatim from Mansourian et al. (2009, p. 67). *The role of forest protected areas in adaptation to climate change.*

²⁹⁴¹ Verbatim from Mansourian et al. (2009, p. 67)

²⁹⁴² Verbatim from Mansourian et al. (2009, p. 68)

²⁹⁴³ Verbatim from Staudt et al. (2012, p. 5-20)

²⁹⁴⁴ Verbatim from Staudt et al. (2012, p. 5-20). Staudt et al. cite Griffith & others (2009) for this information.

²⁹⁴⁵ Verbatim from Stein et al. (2012, p. 6-20). Stein et al. cite Peters & Darling (1985) for this information.

²⁹⁴⁶ Verbatim from Stein et al. (2012, p. 6-20).

²⁹⁴⁷ Verbatim from Stein et al. (2012, p. 6-20). Stein et al. cite Araújo & others (2004) for information on placing reserves at the core of species environmental distributions, Peters & Darling (1985) for information on placing reserves at elevational or poleward range limits of key species, and Halpin (1997) for information on placing reserves at transitions between major ecological systems or biomes.

²⁹⁴⁸ Nearly verbatim from Stein et al. (2012, p. 6-20). Stein et al. cite Game & others (2011) for this information.

²⁹⁴⁹ Verbatim from Staudt et al. (2012, p. 5-20). Staudt et al. cite Game & others (2011), Hannah & others (2007), Vos & others (2008), Ackerly & others (2010), Williams & others (2005), and Rose & Burton (2009) as examples of locating new or expanded protected areas based on projected shifts in species distributions.

effective for the targeted species; however, it incorporates higher levels of uncertainty inherent in forecasting future climatic changes and the biotic responses to those changes.²⁹⁵⁰

- **Locate protected areas where underlying environmental gradients are protected:** Others have suggested placing reserves in areas that protect the underlying environmental gradients that largely determine patterns of biodiversity at broader scales.²⁹⁵¹ Although such approaches are theoretically justified, few studies have investigated their applicability.²⁹⁵²
- **Select protected areas that will serve as climatic refugia:** Climate refugia have been described both as areas that are projected to experience relatively small changes in climate and as areas projected to have suitable microclimates for given species.²⁹⁵³ Ashcroft (2010) also distinguishes between climate refugia at macro versus micro spatial scales, and whether climate refugia are located within a species' current distribution (*in situ*) or outside the current distribution (*ex situ*).²⁹⁵⁴ Protecting areas that are projected to change relatively little serves the purpose of protecting strongholds of current species, communities, and ecosystems.²⁹⁵⁵ Protecting areas that are generally projected to have cooler (or moister or drier) climates than those in the surrounding landscape serves the purpose of giving species in a region a place to go.²⁹⁵⁶ Locally cooler microclimates may occur at slightly higher elevations or be in areas with more vegetative cover or potential for vegetative cover.²⁹⁵⁷

Dispersal corridors

Longer-term adaptation options are needed that over time will help ecosystems and species to respond to climate change and that will help avoid dramatic and abrupt transitions from one ecosystem condition to another (e.g. forest to shrubland).²⁹⁵⁸ Ensuring that landscapes are connected to permit species migration and dispersal is considered fundamental in this regard.²⁹⁵⁹ Recent studies have highlighted alternative approaches to connecting landscapes to address climate change.²⁹⁶⁰ One such approach, uses climate projections to orient corridors and expand existing reserves in the direction of anticipated climatic changes.²⁹⁶¹ Others have suggested using projected shifts in species distributions to map potential routes that species might take to track shifting climates.²⁹⁶² Alternatively, Beier and Brost (2010) recommend using abiotic conditions or land facets (unique combinations of soil types, geologies, and topographies) to

²⁹⁵⁰ Verbatim from Stein et al. (2012, p. 6-20). Stein et al. cite Beier & Brost (2010) for this information.

²⁹⁵¹ Verbatim from Stein et al. (2012, p. 6-20). Stein et al. cite Anderson & Ferree (2010) and Beier & Brost (2010) for this information.

²⁹⁵² Verbatim from Stein et al. (2012, p. 6-20). Stein et al. cite Schloss & others (2011) for this information.

²⁹⁵³ Verbatim from Stein et al. (2012, p. 6-20 to 6-21). Stein et al. cite Saxon & others (2005), Hansen & others (2010), Dobrowski (2011), and Shoo & others (2011) for this information.

²⁹⁵⁴ Verbatim from Stein et al. (2012, p. 6-21)

²⁹⁵⁵ Verbatim from Stein et al. (2012, p. 6-21)

²⁹⁵⁶ Verbatim from Stein et al. (2012, p. 6-21)

²⁹⁵⁷ Verbatim from Stein et al. (2012, p. 6-21)

²⁹⁵⁸ Nearly verbatim from Blate et al. (2009, p. 61)

²⁹⁵⁹ Verbatim from Blate et al. (2009, p. 61). Blate et al. cite Halpin (1997), Holling (2001), and Noss (2001) for this information.

²⁹⁶⁰ Nearly verbatim from Stein et al. (2012, p. 6-21)

²⁹⁶¹ Verbatim from Stein et al. (2012, p. 6-21). Stein et al. cites Ackerly & others (2010) for this information.

²⁹⁶² Verbatim from Stein et al. (2012, p. 6-21). Stein et al. cites Williams & others (2005) and Rose & Burton (2009) for this information.

define movement corridors.²⁹⁶³ Yet another approach involves connecting warmer areas to cooler areas (or drier areas to wetter areas) along routes that avoid lands that are more heavily impacted by humans and paths that do not follow more gentle climate gradients.²⁹⁶⁴

Identifying migration corridors also has important practical applications for land use planning.²⁹⁶⁵ For example, areas that may not be of particular ecological importance at present and that may be considered for development could play a key role in the preservation of ecologically rich conditions in California as the climate changes.²⁹⁶⁶ In British Columbia, connectivity across the province's borders will also be key.²⁹⁶⁷ Transboundary connectivity and corridors for migration and ecological transport includes:

- Latitudinal movements – north from the U.S. (Washington, Oregon, Idaho, and Montana) to B.C., and from B.C. to Yukon, Northwest Territories, and Alaska;
- Longitudinal movements – east from southeast Alaska to B.C., and from B.C. to Alberta and the northern Great Plains;
- Transboundary rivers such as the Stikine, Taku, Alsek-Tatshenshini, Yukon, Liard, Peace, Columbia, Flathead, Okanagan; and,
- Physiographic lineaments or between-mountain corridors such as the Rocky-Columbia-Mackenzie Mountains, Cascade-Coast Mountains, Rocky Mountain-Tintina Trenches, Pacific coastal trough (Puget Sound-Georgia Basin-Hecate Depression-Alexander Depression).²⁹⁶⁸
- Altitudinal movements upslope within mountain ranges should also be considered.²⁹⁶⁹

Increase functional connectivity

Measuring functional connectivity using the movements of individual organisms can be logistically complicated.²⁹⁷⁰ Even the largest studies using the most appropriate technologies can track only relatively few individuals over modest time periods, and controlled experiments addressing movements and dispersal at relevant scales are extremely difficult to implement.²⁹⁷¹ One way to address this difficulty is to measure gene flow, which may more accurately and efficiently reflect functional connectivity across large landscapes.²⁹⁷² Genetic studies avoid the logistic and financial costs of tracking individual animals and integrate only those movements that produce meaningful population impacts – dispersals that result in breeding or emigration.²⁹⁷³ A shortcoming of this approach is that current genetic patterns may not reflect the impact of current landscape features, especially for species with large population sizes or long generation times, or species affected by unobserved events, such as genetic bottlenecks caused by past

²⁹⁶³ Verbatim from Stein et al. (2012, p. 6-21)

²⁹⁶⁴ Verbatim from Stein et al. (2012, p. 6-21). Stein et al. cites Nuñez & others (written communication, 2012) for this information.

²⁹⁶⁵ Nearly verbatim from Moser et al. (2012, p. 12)

²⁹⁶⁶ Nearly verbatim from Moser et al. (2012, p. 12)

²⁹⁶⁷ Nearly verbatim from Pojar (2010, p. 71)

²⁹⁶⁸ Nearly verbatim from Pojar (2010, p. 71-72)

²⁹⁶⁹ Verbatim from Pojar (2010, p. 72)

²⁹⁷⁰ Verbatim from Rudnick et al. (2012, p. 6). *The role of landscape connectivity in planning and implementing conservation and restoration priorities.*

²⁹⁷¹ Verbatim from Rudnick et al. (2012, p. 6)

²⁹⁷² Verbatim from Rudnick et al. (2012, p. 6)

²⁹⁷³ Verbatim from Rudnick et al. (2012, p. 6)

epidemics or human persecution.²⁹⁷⁴ In addition, genetic connectivity may be masked in some instances by local adaptation, which can drive genetic distinctiveness even in a well-connected landscape, by selecting for particular characteristics of the local environment.²⁹⁷⁵

Networks of protected areas

- Extensive networks of protected areas provide the most efficient way of conserving biodiversity in the face of climate change.²⁹⁷⁶ Reserve networks will only be effective at protecting biodiversity in a changing climate if species are able to move among the reserves.²⁹⁷⁷ *For additional information on enabling species movement among reserves, please see sub-section “Dispersal corridors.”*
- A well-planned protected area network is necessary if species that are present in few fragmented patches of habitat, in small numbers or at the limits of their range are to adapt to climate-related changes.²⁹⁷⁸ Size, shape and altitudinal gradients all contribute to a protected area’s resilience to climate change and to species’ freedom of movement.²⁹⁷⁹ Optimally designed protected area networks should reduce barriers and obstacles between protected areas.²⁹⁸⁰ They should incorporate buffers, connections, corridors and stepping stones for the movement of animal species across the landscape and abundant good habitat across a vast range of altitudes, so that in times of stress species can move to more favorable environments within the relative safety of a protected area.²⁹⁸¹
- An integrated approach for both freshwater and terrestrial ecosystems is likely to be the most fruitful avenue for conserving wholesale biodiversity in reserve networks.²⁹⁸² Given that currently protected areas are typically delineated based on the representation of terrestrial ecosystems and a low number of taxonomic groups (e.g. vascular plants and terrestrial vertebrates), it is unclear if freshwater biodiversity is adequately protected in current protected areas network, and if future

Adaptation in Action

To supplement and inform a state-wide connectivity assessment, the **Washington Wildlife Habitat Connectivity Working Group’s Climate Change Subgroup** used information on current climatic gradients, land-use patterns, and topography to identify climate-smart connectivity areas across the state. These areas represent a likely network of patches and corridors across which species may move in response to a changing climate.

The subgroup has also developed finer scale analyses for the Columbia Plateau Ecoregion and transboundary areas of Washington and British Columbia, and is working to identify core habitat areas and linkages that may persist in a changing climate.

Sources: Krosby et al. (20#), Nuñez et al. (2013), WWHCWG (2013)

²⁹⁷⁴ Verbatim from Rudnick et al. (2012, p. 6)

²⁹⁷⁵ Verbatim from Rudnick et al. (2012, p. 6)

²⁹⁷⁶ Verbatim from Heino, Virkkala and Toivonen. *Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions.* (2009, p. 49)

²⁹⁷⁷ Verbatim from Stein et al. (2012, p. 6-21)

²⁹⁷⁸ Verbatim from Mansourian et al. (2009, p. 66)

²⁹⁷⁹ Verbatim from Mansourian et al. (2009, p. 66)

²⁹⁸⁰ Verbatim from Mansourian et al. (2009, p. 66)

²⁹⁸¹ Verbatim from Mansourian et al. (2009, p. 66-67)

²⁹⁸² Nearly verbatim from Heino, Virkkala and Toivonen. (2009, p. 49). The authors cite Abell (2002) for this information.

shifts in freshwater species' ranges could be accommodated by these areas.²⁹⁸³ *For additional information on conserving freshwater diversity in reserve networks, please see the cited companion report.*²⁹⁸⁴

Management of the matrix between protected areas

Although much of the research and discussion of connectivity focuses on corridors for connecting landscapes, there are other, likely more cost effective approaches that are potentially more applicable to a wider range of species.²⁹⁸⁵ Furthermore, data show that the type of land cover between protected areas strongly affects the sensitivity of species to the impacts of living in small isolated patches of protection.²⁹⁸⁶

For example, increasing the permeability of the landscape (that is, the degree to which a landscape is conducive to wildlife movement) by managing lands to facilitate species' movements will likely also be an effective method of increasing connectivity.²⁹⁸⁷ Connectivity of native forest habitats can facilitate movement of desirable organisms and impede movement of undesirable organisms (e.g. exotic plants).²⁹⁸⁸ However, increased connectivity of dense forests in fire prone landscapes can also facilitate the spread of fire and insects.²⁹⁸⁹ Increasing connectivity to facilitate movement of species in response to climate change can come by promoting old-forest habitats (e.g. thinning to promote the development of large trees in plantations, and fire management to protect existing old forests) and structures, increasing the extent of riparian buffers, especially on non-federal lands where buffers are currently limited, and increasing connections across ridgelines to promote dispersal of headwater species.²⁹⁹⁰ On the other hand, reducing connectivity by breaking up contiguous patches of dense fuels in dry forest types or introducing heterogeneity into monocultures can reduce spread of fire and insects.²⁹⁹¹

To increase landscape area devoted to providing critical habitats and resilient ecosystem types, another option is to increase the safety margin against the loss of valued habitats (e.g. northern spotted owl and other old-forest associated species) to high-severity disturbances.²⁹⁹² For example, on U.S. federal forests an option may be to manage the matrix lands (land currently intended for timber production, about 20% of total federal land) to increase area devoted to producing critical habitats and climate and fire-resilient forests.²⁹⁹³ Selective harvest or retention cuts, tree-planting, alternative zoning, and rotational grazing may provide enough permeability to facilitate range expansions for many species.²⁹⁹⁴

²⁹⁸³ Verbatim from Heino, Virkkala and Toivonen. (2009, p. 49)

²⁹⁸⁴ Tillmann & Siemann (2011b)

²⁹⁸⁵ Verbatim from Stein et al. (2012, p. 6-21)

²⁹⁸⁶ Nearly verbatim from Pojar (2010, p. 47)

²⁹⁸⁷ Verbatim from Stein et al. (2012, p. 6-21). Stein et al. cite Franklin & Lindenmayer (2009) for this information.

²⁹⁸⁸ Verbatim from Spies et al. (2010, p. 1191)

²⁹⁸⁹ Verbatim from Spies et al. (2010, p. 1191)

²⁹⁹⁰ Verbatim from Spies et al. (2010, p. 1191). Spies et al. cite Olsen & Burnett (2009) for this information.

²⁹⁹¹ Verbatim from Spies et al. (2010, p. 1191)

²⁹⁹² Nearly verbatim from Spies et al. (2010, p. 1191)

²⁹⁹³ Nearly verbatim from Spies et al. (2010, p. 1191)

²⁹⁹⁴ Verbatim from Stein et al. (2012, p. 6-21 to 6-22). Stein et al. cite Kohm & Franklin (1997) and Manning & others (2009) for this information.

Land exchange and acquisition

A land exchange program, such as a conservation easement, typically transfers some development and management options – such as the right to subdivide or to cut trees – from the landowner to a nonprofit or governmental organization that holds those rights.²⁹⁹⁵ The landowner reserves certain rights, such as the right to build additional homes or add roads and also continues to own the property and manage it within the bounds set by the easement.²⁹⁹⁶ The easement holder is responsible for monitoring and enforcing easement specifications.²⁹⁹⁷ A conservation easement program is likely to be most effective when it has strong planning and outreach components that identify lands that would benefit from easements and inform property owners about easements and their benefits.²⁹⁹⁸

Landowners who donate their easement may be eligible for federal or state tax breaks.²⁹⁹⁹ Easements typically apply in perpetuity and are passed on from owner to owner.³⁰⁰⁰ Most are placed on individual properties, but they may also be placed on subdivisions or coordinated at a regional scale (e.g., to more effectively manage a strip of land or accommodate wetland migration).³⁰⁰¹

New land designations and/or tenures will likely be required to guide management of an expanded conservation network that falls outside of existing protected areas.³⁰⁰²

Specific options for migratory species

Habitat fragmentation impedes the ability of broad-front migrants to adapt their migratory routes and may create new ecological barriers, although this could be reduced by using fragments of natural and semi-natural habitat in a matrix of low intensity land-use to create a permeable landscape surrounding these “stepping stones.”³⁰⁰³ For other species, maintenance of an ecologically coherent network of stopover sites will be required, and identification of such networks is urgently required to provide a strategic,

A conservation easement is a legal agreement between a landowner and a land trust or government agency that can be used to restrict development in sensitive and hazard-prone areas. A conservation easement program is likely to be most effective when it has strong planning and outreach components that identify lands that would benefit from easements and inform property owners about easements and their benefits.

Source: NOAA (2010)

²⁹⁹⁵ Nearly verbatim from Merenlender et al. *Land trusts and conservation easements: Who is conserving what for whom?* (2004, p. 67)

²⁹⁹⁶ Nearly verbatim from Merenlender et al. (2004, p. 67)

²⁹⁹⁷ Verbatim from Merenlender et al. (2004, p. 67)

²⁹⁹⁸ Verbatim from NOAA. (2010, p. 68)

²⁹⁹⁹ Verbatim from NOAA. (2010, p. 68)

³⁰⁰⁰ Verbatim from NOAA. (2010, p. 68)

³⁰⁰¹ Verbatim from NOAA. (2010, p. 68)

³⁰⁰² Nearly verbatim from Pojar (2010, p. 71)

³⁰⁰³ Verbatim from Robinson et al. (2008, p. 95). Robinson et al. cite Travis (2003) and Opdam & Wascher (2004) for information on the effects of habitat fragmentation on migrants.

international overview of site protection priorities.³⁰⁰⁴ Measures are likely to be necessary throughout the species range, particularly when there is a high degree of population structuring in migratory routes.³⁰⁰⁵

A major challenge in the conservation of migratory species is the shifting of migratory routes.³⁰⁰⁶ Thus, it will be important to protect areas that may be used in the future, and to recognise shifts away from currently used sites, as seen for shorebirds wintering in western Europe.³⁰⁰⁷ Future changes may also remove sites from the network (either because of habitat loss, or because latitudinal shifts in habitat mean that journeys become too long), causing the network to collapse.³⁰⁰⁸ A novel approach to these problems is exemplified by the creation of “zakazniks” (reserves which limit hunting and disturbance), which follow the annual migration of saiga antelope, rather than being limited to particular sites.³⁰⁰⁹

Preserve and restore genetic diversity

A common recommendation for enhancing the adaptive capacity of terrestrial ecosystems, particularly forested systems, is to broaden the genetic variability and the species diversity of managed sites.³⁰¹⁰ The restoration of as much biodiversity and redundancy as possible may contribute to sufficient genetic diversity for thermal adaptation by many species.³⁰¹¹ Conserving genetic diversity may occur by maintaining adaptive potential and reducing disturbance probability and intensity in native stands (*in situ* conservation) and by collection and storage of the most vulnerable populations (*ex situ* conservation).³⁰¹² Species-based adaptation approaches could include efforts to identify and manage for populations with higher genetic diversity, or promote populations with more plastic behaviors and morphologies.³⁰¹³ *Ex-situ* conservation may be a necessary alternative to assisted colonization or some species whose ranges or populations are dramatically reduced by climate impacts.³⁰¹⁴ Such actions could include seed banking and captive breeding to ensure the long-term survival of a species.³⁰¹⁵

Gather, maintain, and evaluate information on genetic diversity

Options to gather, maintain, and evaluate information on genetic diversity include:

- ***Review the state of the knowledge of seed collection and storage*** for key species, as well as propagation and planting requirements.³⁰¹⁶ Develop plant collection and nursery propagation protocols for new or difficult-to-grow species that may have an increased emphasis in future

³⁰⁰⁴ Verbatim from Robinson et al. (2008, p. 95)

³⁰⁰⁵ Verbatim from Robinson et al. (2008, p. 95). Robinson et al. cite Martin et al. (2007) for this information.

³⁰⁰⁶ Verbatim from Robinson et al. (2008, p. 95)

³⁰⁰⁷ Verbatim from Robinson et al. (2008, p. 95). Robinson et al. cite Austin & Rehfisch (2005) for this information.

³⁰⁰⁸ Verbatim from Robinson et al. (2008, p. 95)

³⁰⁰⁹ Verbatim from Robinson et al. (2008, p. 95). Robinson et al. cite Gordon et al. (2004) for this information.

³⁰¹⁰ Verbatim from Lawler (2009, p. 88). Lawler cites Harris et al. (2006) and Millar et al. (2007) for this information.

³⁰¹¹ Verbatim from Senos et al. (2006, p. 420)

³⁰¹² Nearly verbatim from Shafer et al. (2010, p. 193)

³⁰¹³ Nearly verbatim from Stein et al. (2012, p. 6-22)

³⁰¹⁴ Verbatim from Stein et al. (2012, p. 6-22). Stein et al. cite Li & Pritchard (2009) for this information.

³⁰¹⁵ Verbatim from Stein et al. (2012, p. 6-22)

³⁰¹⁶ Verbatim from Erickson et al. (2012, p. 12). *Genetic resource management and climate change: genetic options for adapting national forests to climate change.*

reforestation practices due to changing climate.³⁰¹⁷ Consider both commercial and non-commercial species, and species that are now regenerated naturally but may need to be augmented or moved outside their current ranges in the future.³⁰¹⁸

- **Acquire and maintain historical provenance data and share broadly** so that the NFS (i.e., the National Forest System Genetic Resource Management Program) and others can collaboratively use it to predict responses to climate change and choose appropriate seed sources.³⁰¹⁹ For example, the Pacific Northwest Research Station has collaborated with Oregon State University in a simple Web-based data management system, called the Center for Forest Provenance Data.³⁰²⁰ The systems may be used for archiving provenance data and make it available for others (see <http://cenfor.gen.forestry.oregonstate.edu/index.php>).³⁰²¹
- **Maintain detailed spatial information on seed source locations** (such as latitude, longitude, and elevation) in seed inventory management systems (such as the Nursery Management Information System), continued support of seed transfer expert systems, and development of GIS applications to track seedlot origin and use and to facilitate seed sharing in the future.³⁰²² When seed sources are combined, consider bulking seed across smaller geographic scales and elevation bands to facilitate the creation of custom seedlots and provide flexibility in deployment decisions in the future.³⁰²³ For example, buffer possible changes in seed movement guidelines in the future by adding a percentage of seed from outside the current seed zone or recommended elevation band, with emphasis on areas that could be reasonable analogs for the future.³⁰²⁴
- **Evaluate seed production capacity, seed storage, and nursery capacity** to determine whether they are adequate to meet long-term needs or whether additional focused investments are required.³⁰²⁵
- **Assess needs for additional seed orchards and cutting orchards** for long-term plant material sources for new species or geographic areas where there is likely to be greater demand in the future (approximately 50–80 years from now).³⁰²⁶ Plant material suited to these future climates may not currently exist on National Forest System lands, and may need to be obtained from other land ownerships.³⁰²⁷ Seed orchards established with this material could be designed to also perform as assisted migration trials to evaluate plant adaptation to novel environments.³⁰²⁸
- **Install common garden studies in multiple climates** to help choose seed sources for species and geographic areas where this information is lacking.³⁰²⁹ Many key species currently lack even the most basic information on adaptive genetic variation.³⁰³⁰ In these situations, consider available climate-based tools such as SeedZone Mapper

³⁰¹⁷ Verbatim from Erickson et al. (2012, p. 12)

³⁰¹⁸ Verbatim from Erickson et al. (2012, p. 12)

³⁰¹⁹ Nearly verbatim from Erickson et al. (2012, p. 12)

³⁰²⁰ Verbatim from Erickson et al. (2012, p. 12)

³⁰²¹ Verbatim from Erickson et al. (2012, p. 12)

³⁰²² Verbatim from Erickson et al. (2012, p. 12)

³⁰²³ Verbatim from Erickson et al. (2012, p. 12)

³⁰²⁴ Verbatim from Erickson et al. (2012, p. 12)

³⁰²⁵ Verbatim from Erickson et al. (2012, p. 12)

³⁰²⁶ Nearly verbatim from Erickson et al. (2012, p. 11)

³⁰²⁷ Nearly verbatim from Erickson et al. (2012, p. 11)

³⁰²⁸ Nearly verbatim from Erickson et al. (2012, p. 11)

³⁰²⁹ Verbatim from Erickson et al. (2012, p. 12)

³⁰³⁰ Verbatim from Erickson et al. (2012, p. 12)

(http://www.fs.fed.us/wwetac/threat_map/SeedZones_Intro.html) and the Seedlot Selection Tool (<http://sst.forestry.oregonstate.edu/PNW/index.html>) to identify the best locations to obtain and deploy plant materials.³⁰³¹ Support the refinement and development of these and other decision tools to better predict and plan for where to obtain seed that will be optimal for future climates.³⁰³²

- ***Collaborate with researchers*** to establish and maintain common garden and provenance studies, as well as assisted migration trials for key species.³⁰³³

Enhance the potential for natural adaptation

Boosting population sizes, protecting or restoring multiple examples of ecosystems and promoting heterogeneous, multiple-age forest stands will increase biological diversity at multiple levels of organization (from genes to landscapes), and hence the potential for natural adaptation.³⁰³⁴ Specific options to create opportunities for rapid natural selection for species, habitats, and geographic areas with high observed or predicted potential for adverse impacts due to climate change include:³⁰³⁵

- ***Promote abundant regeneration, mixing of appropriate genotypes and seed sources***, and possibly also shortened generation times if appropriate and feasible.³⁰³⁶
- When prescribing species and seed sources in reforestation programs, ***ensure that any changes to established practices are based on a variety of robust and reliable data sources*** such as common garden studies and reciprocal transplant experiments, climate model projections, remote sensing, dendroclimatology, and other empirical research and forest health and productivity monitoring approaches.³⁰³⁷ This approach very much aligns with current, robust and scientifically derived guidelines for plant material selection.³⁰³⁸ To minimize the high degree of uncertainty and risk associated with longer-term climate projections, develop adaptation strategies with a relatively short timeframe, such as a 10–20-year planning horizon.³⁰³⁹ This will promote the planting of species and genotypes that will be optimally adapted to predicted climates during the highly vulnerable seed and sapling stage.³⁰⁴⁰
- ***Implement mechanisms for tracking reforestation success*** and the growth and health of forest stands to allow for recursive improvements to species and seed source prescriptions over the long term.³⁰⁴¹

³⁰³¹ Verbatim from Erickson et al. (2012, p. 12)

³⁰³² Verbatim from Erickson et al. (2012, p. 12)

³⁰³³ Verbatim from Erickson et al. (2012, p. 12)

³⁰³⁴ Nearly verbatim from Blate et al. (2009, p. 61)

³⁰³⁵ Nearly verbatim from Erickson et al. (2012, p. 13)

³⁰³⁶ Verbatim from Erickson et al. (2012, p. 13)

³⁰³⁷ Verbatim from Erickson et al. (2012, p. 13)

³⁰³⁸ Nearly verbatim from Erickson et al. (2012, p. 13)

³⁰³⁹ Verbatim from Erickson et al. (2012, p. 13)

³⁰⁴⁰ Verbatim from Erickson et al. (2012, p. 13)

³⁰⁴¹ Verbatim from Erickson et al. (2012, p. 13)

Create and maintain seed banks

For forest trees, four specific options are:

- ***Partner with other land managers to create a virtual cooperative tree seed bank:*** This would increase the likelihood that appropriate seed will be available for reforestation after large-scale disturbances such as fire or insect outbreaks.³⁰⁴² Landowners can maintain their own seed inventories, but enter in cooperative agreements to share seed in the event of a major disturbance.³⁰⁴³ As a first step, one suggestion from western Washington is that Forest Service personnel should form a partnership with silviculturists, geneticists, and seed managers from the Washington Department of Natural Resources and the National Park Service and others to develop an approach for sharing information and seed.³⁰⁴⁴
- ***Maintain an inventory of high-quality seed for tree species that are likely to be needed over the next twenty years:*** Expand operational seed banks to include a wider array of species, seed zones, and elevation bands.³⁰⁴⁵ Place a priority on species whose seeds store well and have good post-disturbance establishment capabilities.³⁰⁴⁶ To accomplish this, one example from western Washington is to assess the viability of seed stored at the Forest Service storage facility at JH Stone Nursery, retest viability as needed, discard non-viable seed, and update Seed Procurement Plans to include new and replacement collections.³⁰⁴⁷
- ***Conduct comprehensive risk and seed need assessments,*** for example, by assessing genetic diversity of existing inventories and by overlaying seed zones with climate change and disturbance threat maps (e.g., WWETAC ThreatMapper, http://www.fs.fed.us/wwwetac/threat_map, see map sidebar).³⁰⁴⁸ Also, evaluate seed inventories and replenish low seed stores for species, habitats, and geographic areas most likely to experience climate change effects, especially large-scale disturbance.³⁰⁴⁹
- ***Protect and maintain existing seed orchards, breeding orchards, and clone banks*** to serve as the most efficient and cost effective source of high-quality seed for reforestation.³⁰⁵⁰ Characterize the mean and range of climates for the germplasm (i.e., genetic variability of a population) and deployment zones of existing orchards to better understand where that material may be appropriately used in the future.³⁰⁵¹ In western Washington, specific suggestions are to maintain the Dennie Ahl seed orchard in Olympic National Forest (which serves as a gene conservation area and is the forest's most efficient source of high quality tree seed for Douglas-fir, Pacific silver fir, and rust resistant western white pine), the White Salmon, Planting Creek, Coyote, Cispus and French Butte seed orchards in Gifford Pinchot National Forest (which serves as a

³⁰⁴² Verbatim from Aubry et al. (2011, Table 29, p. 91)

³⁰⁴³ Verbatim from Aubry et al. (2011, Table 29, p. 91)

³⁰⁴⁴ Nearly verbatim from Aubry et al. (2011, Table 29, p. 91)

³⁰⁴⁵ Verbatim from Erickson et al. (2012, p. 10)

³⁰⁴⁶ Verbatim from Erickson et al. (2012, p. 10)

³⁰⁴⁷ Nearly verbatim from Aubry et al. (2011, Table 29, p. 91)

³⁰⁴⁸ Verbatim from Erickson et al. (2012, p. 10-11)

³⁰⁴⁹ Nearly verbatim from Erickson et al. (2012, p. 10)

³⁰⁵⁰ Nearly verbatim from Erickson et al. (2012, p. 11)

³⁰⁵¹ Nearly verbatim from Erickson et al. (2012, p. 11)

gene conservation area and is the forest’s most efficient source of high quality tree seed for Douglas-fir, noble fir, and rust resistant western white pine), and the McCullough seed orchard in Mt. Baker-Snoqualmie National Forest (which serves as a gene conservation area and is the forest’s most efficient source of high quality tree seed for Douglas-fir, noble fir, and rust resistant western white pine).³⁰⁵²

For dry grasslands (includes native prairies, balds, and Oregon white oak savannas and woodlands), target both rare and “workhorse” species for gene conservation and restoration purposes.³⁰⁵³ Collect seeds and, if needed, increase seed of native grassland plants, including grasses.³⁰⁵⁴ *For additional information on adaptation options for native prairies, balds, and Oregon white oak savanna and woodlands, please see the section “Maintain, restore, or create prairie, oak woodland, savanna, and grassland habitats.”*

Preserve representative samples of species and populations

Conservation of genetic resources can be accomplished through a variety of *in situ* and *ex situ* approaches.³⁰⁵⁵ *In situ* methods protect plants in their native habitats where they are subject to natural evolutionary processes.³⁰⁵⁶ *Ex situ* methods involve storing genetic material in off-site locations such as seed banks, genetic resource plantations (such as provenance and progeny tests), and seed and breeding orchards.³⁰⁵⁷ A robust gene conservation strategy combines elements of both approaches and is based on knowledge of the genetic structure of a species and the perceived threat to a species—whether from natural disturbance processes, introduced insect and pathogens, or sensitivity to changing climate.³⁰⁵⁸ These strategies are underpinned by effective management policies.³⁰⁵⁹

Options to preserve representative samples include:

- ***Develop and evaluate tools*** for assessing the vulnerability of species and populations to changes in climate.³⁰⁶⁰ Give focus to both rare and common species.³⁰⁶¹
- ***Conduct monitoring*** to identify species and populations for which gene conservation is most urgent because of climate change, and prioritize them by importance and urgency.³⁰⁶² Include both rare and common species in monitoring efforts.³⁰⁶³
- ***Develop and implement gene conservation plans*** for protecting a representative sample of genes from vulnerable species and populations, including long-term storage at Forest Service nurseries and extractories, regional genetic resources centers, the Forest Service National Seed Laboratory, and the Agricultural Research Service National Center for Genetic Resources Preservation.³⁰⁶⁴

³⁰⁵² Nearly verbatim from Aubry et al. (2011, Table 29, p. 91)

³⁰⁵³ Nearly verbatim from Aubry et al. (2011, Table 29, p. 94)

³⁰⁵⁴ Nearly verbatim from Aubry et al. (2011, Table 29, p. 94)

³⁰⁵⁵ Verbatim from Erickson et al. (2012, p. 13). Erickson et al. cite St. Clair & Howe (2011) for this information.

³⁰⁵⁶ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁵⁷ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁵⁸ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁵⁹ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁶⁰ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁶¹ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁶² Verbatim from Erickson et al. (2012, p. 14)

³⁰⁶³ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁶⁴ Nearly verbatim from Erickson et al. (2012, p. 14)

- **Protect and maintain existing seed orchards, breeding orchards, clone banks, and provenance and progeny test sites** to serve as *ex situ* gene conservation areas.³⁰⁶⁵ Protect and maintain the network of designated plus trees as *in situ* conservation.³⁰⁶⁶ *For additional information on nurseries, please see the previous sub-section.*
- **Develop techniques for ex situ preservation of novel species** (for example, how to preserve large-seeded, recalcitrant species that do not store well, such as oak acorns, or American chestnut or butternut nuts).³⁰⁶⁷
- **Evaluate the need for additional infrastructure** for *ex situ* gene conservation; for example, additional freezers to house working collections.³⁰⁶⁸

Additional options

The following adaptation options for preserving and restoring genetic diversity were found in the literature, but were not discussed in detail, or they are described elsewhere in this report. The selection and adaptation of plant populations in new environments may be facilitated by managing the genetic diversity inherent among and within plant populations by:³⁰⁶⁹

- **Assisted migration:** Plant species and populations in new locations in which they may be expected to be adapted in the future.³⁰⁷⁰ *Please see the section “Maintain, restore, or create habitat for vulnerable species” for additional information on assisted migration.*
- **Establish genetic outposts:** These are genetically divergent planted stands that may facilitate gene flow for adaptive variation into adjacent native stands.³⁰⁷¹ *Please see the section “Address invasive and non-native species, insects, and pathogens” for information on genetic outposts.*
- **Breeding programs:** Breeding programs for forest trees can promote genetic diversity, disease resistance, and tolerance to environmental stresses.³⁰⁷² Use breeding programs to enhance adaptive traits such as drought hardiness, cold hardiness (for reasons of increased climatic variability and starting to move populations upslope), and pest resistance or tolerance.³⁰⁷³
- **Where appropriate, actively manage stands using a variety of silvicultural and restoration tools** (planting, seeding, prescribed fire, thinning, etc.) to promote establishment, growth, and survival of desirable species and genotypes.³⁰⁷⁴ Consider the need for artificial regeneration, especially for species that are highly vulnerable to climate change effects and in areas of rapidly changing climate where natural regeneration has been the traditional method of reforestation.³⁰⁷⁵ *For additional information on modifying forestry practices, please see the section “Reduce fuel loads.”*

³⁰⁶⁵ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁶⁶ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁶⁷ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁶⁸ Verbatim from Erickson et al. (2012, p. 14)

³⁰⁶⁹ Verbatim from Shafer et al. (2010, p. 193)

³⁰⁷⁰ Nearly verbatim from Shafer et al. (2010, p. 193)

³⁰⁷¹ Nearly verbatim from Shafer et al. (2010, p. 193)

³⁰⁷² Verbatim from Sturrock et al. (2011, p. 142)

³⁰⁷³ Nearly verbatim from Shafer et al. (2010, p. 193)

³⁰⁷⁴ Verbatim from Erickson et al. (2012, p. 12)

³⁰⁷⁵ Verbatim from Erickson et al. (2012, p. 12)

- ***Ensure that seed planted on national forests includes offspring from an adequate number of parents.***³⁰⁷⁶ Use multiple species and a diverse mix of appropriate seed sources; consider the need to add germplasm (i.e., genetic variability in a population) from warmer/drier geographic areas that may be more suited to trending future climates (10–20 year timeframe).³⁰⁷⁷ Emphasize under-represented species species in both planting and thinning prescriptions.³⁰⁷⁸ Increase genetic diversity within stands and across landscapes by planting mixtures of populations, and allowing for natural and human selection within diverse stands by planting at higher densities with the possibility of thinning.³⁰⁷⁹ More specifically, consider the need for increased planting densities to allow for enhanced natural selection opportunities and/or human mediated selection via thinning to remove maladapted phenotypes.³⁰⁸⁰ Conversely, if drought conditions or highly altered moisture regimes are projected, lower planting densities may be prescribed to reduce stress and inter-plant competition.³⁰⁸¹

Maintain, restore, or create habitat for vulnerable species

Monitor to determine when and what changes are occurring

Since many organisms respond to climatic variability and trends, some of these responses may be useful as indicators of climate change.³⁰⁸²

Beyond categorization of existing biological indicators as sensitive/insensitive to climate change effects, there are biological metrics that could be considered for incorporation into bioassessment programs that are not currently measured on a routine basis in most existing programs.³⁰⁸³ Such “novel” indicators are considered specifically because of their sensitivity to climate change effects – most have been predicted or observed in the literature as biological responses to directional climate change, especially increases in water temperature.³⁰⁸⁴ U.S. EPA (2008b) summarizes examples of such “novel” biological indicators.³⁰⁸⁵ Considerations for ongoing evaluation of potential novel indicators and their role in adaptation of bioassessment programs include:

- Many of the metrics are more difficult or time- and resource-consuming to measure, especially on a routine basis.³⁰⁸⁶
- Some metrics require sampling techniques and timing or frequency of sampling that are quite different from the commonly applied bioassessment approaches.³⁰⁸⁷

³⁰⁷⁶ Verbatim from Erickson et al. (2012, p. 12)

³⁰⁷⁷ Verbatim from Erickson et al. (2012, p. 12)

³⁰⁷⁸ Verbatim from Erickson et al. (2012, p. 12)

³⁰⁷⁹ Nearly verbatim from Shafer et al. (2010, p. 193)

³⁰⁸⁰ Nearly verbatim from Erickson et al. (2012, p. 12)

³⁰⁸¹ Verbatim from Erickson et al. (2012, p. 12)

³⁰⁸² Verbatim from U. S. EPA. (2008b, p. 1-9)

³⁰⁸³ Verbatim from U. S. EPA. (2008b, p. 3-5)

³⁰⁸⁴ Verbatim from U. S. EPA. (2008b, p. 3-5)

³⁰⁸⁵ U. S. EPA. (2008b, p. 3-5)

³⁰⁸⁶ Nearly verbatim U. S. EPA. (2008b, p. 3-8)

³⁰⁸⁷ Nearly verbatim U. S. EPA. (2008b, p. 3-8)

- The potential sensitivity to other (conventional) stressors, in addition to their responsiveness to climate change, will affect how they might be incorporated into a monitoring design and analysis approach.³⁰⁸⁸
- If faced with enough external change, species and systems will exceed their adaptive capacity (even with the benefit of targeted adaptation actions), cross ecological thresholds, and undergo regime shifts.³⁰⁸⁹ Although development of indicators to predict regime shifts is an active area of research, ecological thresholds are notoriously difficult to forecast, and tend to be recognized only once they have been exceeded.³⁰⁹⁰

Alter microclimate

Species-based approaches may include altering microclimates of artificial nest-boxes for rare birds by painting boxes white or locating them on north-exposed slopes and supplemental watering of key plant species in drought years.³⁰⁹¹

Focus conservation resources on species that might become extinct

This strategy would invest resources in the maintenance and continued survival of those species that are most likely to become extinct as a result of global climate change.³⁰⁹² From a management perspective, climate change may provide opportunities for innovative approaches, such as the scheme described by Kilpatrick (2006) to accelerate the evolution of resistance to avian malaria in native Hawaiian birds.³⁰⁹³ Traditional endangered species

Adaptation in Action

Derived from the North Cascadia Adaptation Partnership process, adaptation options for **alpine and subalpine habitats** in Mount Rainier National Park and the North Cascades Park Complex include:

- **Expand current monitoring** over time and to new or revised areas of focus such as the phenology of focal species, interannual patterns in species abundance, demographics and productivity of high-elevation populations, tracking of species at their range extremes, and an assessment of the genetic and physiological adaptive capacity of high-elevation species.
- **Coordinate to ensure resources for whitebark pine are used strategically**, for example on long-term permanent plots to monitor trends in infection and mortality from white pine blister rust and mountain pine beetle or on continuation of current management practices (e.g., planting blister rust resistant seedling, using anti-aggregation pheromones).
- **Establish baseline information on the extent and distribution of high-elevation wetlands.**
- **Consider active management** such as tree removal and prescribed fire if trees begin to encroach on huckleberry habitat, which is a food source for wildlife and culturally important for Native Americans.

Source: Littell et al. (2013)

³⁰⁸⁸ Nearly verbatim U. S. EPA. (2008b, p. 3-8)

³⁰⁸⁹ Verbatim from Stein et al. (2012, p. 6-29). Stein et al. cite CCSP (2009) for this information.

³⁰⁹⁰ Verbatim from Stein et al. (2012, p. 6-29). Stein et al. cite Brock & Carpenter (2006) and Scheffer & others (2009) for information on developing indicators to predict regime shifts. Stein et al. cite Groffman & others (2006) and CCSP (2009) for information on the difficulty of forecasting ecological thresholds and for information on thresholds typically being recognized only once they have been exceeded.

³⁰⁹¹ Verbatim from Stein et al. (2012, p. 6-22). Stein et al. cite Catry & others (2011) for information on altering artificial nest boxes and Pavlik & others (2002) for information on supplemental watering of key plant species.

³⁰⁹² Nearly verbatim from Heinz Center (2008, p. 26)

³⁰⁹³ Verbatim from Heinz Center (2008, p. 26)

management can also be extraordinarily expensive.³⁰⁹⁴ Unless significant new sources of funding are developed, resources will simply not be available for comprehensive conservation actions targeting every species imperiled by climate change.³⁰⁹⁵

Reduce pressures on species from sources other than climate change

This strategy seeks to remove other, non-climate stressors from wildlife species, to give wildlife species the maximum flexibility possible to evolve responses to climate change.³⁰⁹⁶ The strategy recognizes the obvious fact that species experience multiple stressors, and that the removal of these other stressors may give individual species additional flexibility in adapting to climate change.³⁰⁹⁷ However, there are a very broad spectrum of other stressors affecting species and only limited resources at present to address this broad suite of stressors.³⁰⁹⁸ Given these circumstances, there is potential for a loss in focus and much diffuse action across a broad range of threats, rather than targeted action to address a few key threats.³⁰⁹⁹

Assisted migration

This strategy (i.e., assisted migration, also known as managed translocation and assisted colonization) involves the human movement of species outside their native range in order to facilitate their movement in response to climate change.³¹⁰⁰ To the extent that there are no similar suitable habitats nearby that species can reach on their own, managers may need to assist them in relocating to new suitable environments.³¹⁰¹ These translocations would include both movements among currently occupied populations, as well as introductions from extant populations into unoccupied habitat within the species' broad geographic ranges.³¹⁰²

Frameworks for developing policies and making informed decisions for managed translocation have been developed.³¹⁰³ Population response curves should be used to predict the maximum extent to which seed can be moved from milder to colder climates for reforestation in the short term and tree growth in the longer term, and seed transfer guidelines should be changed accordingly.³¹⁰⁴

A range of specific options for assisted migration are available:

- Initially one could consider moving and planting genotypes within the current range of the species.³¹⁰⁵ This certainly could occur when new plantations are established or when replanting

³⁰⁹⁴ Verbatim from Mawdsley et al. (2009, p. 1084). Mawdsley et al. cite Canadian Wildlife Service & U.S. Fish and Wildlife Service (2005) for this information.

³⁰⁹⁵ Verbatim from Mawdsley et al. (2009, p. 1084)

³⁰⁹⁶ Verbatim from Heinz Center (2008, p. 28). The Heinz Center cites Inkley et al. (2004), Lovejoy (2005), and Robinson et al. (2005) for this information.

³⁰⁹⁷ Verbatim from Heinz Center (2008, p. 28)

³⁰⁹⁸ Verbatim from Heinz Center (2008, p. 28). The Heinz Center cites IUCN-CMP (2006a) for information on the broad spectrum of other stressors affecting species.

³⁰⁹⁹ Verbatim from Heinz Center (2008, p. 28)

³¹⁰⁰ Nearly verbatim from Stein et al. (2012, p. 6-22)

³¹⁰¹ Verbatim from Moser et al. (2012, p. 12)

³¹⁰² Verbatim from Running & Mills (2009, p. 26)

³¹⁰³ Verbatim from Stein et al. (2012, p. 6-22). Stein et al. cite Hoegh-Guldberg & others (2008) and Richardson & others (2009) for this information.

³¹⁰⁴ Verbatim from Aitken et al. (2008, p. 108)

³¹⁰⁵ Verbatim from Spies et al. (2010, p. 1192)

after wildfire.³¹⁰⁶ The USDA Forest Service is already beginning to plant more southern ecotypes of trees on the lands that are being manually replanted.³¹⁰⁷

- Establishment of new genotypes and species often requires creating canopy openings in existing forests that are large enough to meet the light requirements of species.³¹⁰⁸ On federal lands, these management actions could be done within existing plantations and other younger forests.³¹⁰⁹
- Additionally, experimental populations could be established outside the current ranges of the species as sources of seed and genetic material to facilitate natural gene flow and population migration.³¹¹⁰
- A specific example of a place-based adaptation strategy involves planting climate-resistant species or ecotypes.³¹¹¹ These species or ecotypes could be used to establish “neo-native forests” – forests consisting of species that existed in that location in the past, but that are not currently found there.³¹¹²

The effectiveness of assisted migration for genotypes and species is not well understood and is controversial in the scientific community.³¹¹³ Thus, assisted colonization has become a hotly debated topic with proponents highlighting the need to move species that will be unable to keep pace with climate change and opponents highlighting the potential for negative, ecological, evolutionary, and economic impacts, as well as ethical concerns.³¹¹⁴

Facilitated or assisted migration of trees may be an effective and cost-effective strategy to increase the probability of persistence of populations or species.³¹¹⁵ In some cases, genotypes and species currently present in those areas are believed to be unlikely to persist as climate changes.³¹¹⁶ Translocations of populations for reforestation from milder to colder environments may eventually provide a source of pre-adapted alleles into conservation populations through gene flow, once planted areas reach reproductive maturity.³¹¹⁷ Facilitated migration may be emphasized for species with narrow resource requirements or poor dispersal ability.³¹¹⁸ Additionally, species with small populations, fragmented ranges, low fecundity, or suffering declines due to introduced insects or diseases should be candidates for facilitated migration.³¹¹⁹ An assisted introduction can facilitate a climate change-induced range shift when the movement pathway is blocked, and assisted colonization from one population to another may increase adaptive genetic variation to respond to climate change in the receiving population.³¹²⁰

³¹⁰⁶ Verbatim from Spies et al. (2010, p. 1192)

³¹⁰⁷ Verbatim from Running & Mills (2009, p. 24)

³¹⁰⁸ Verbatim from Spies et al. (2010, p. 1192)

³¹⁰⁹ Verbatim from Spies et al. (2010, p. 1192)

³¹¹⁰ Verbatim from Spies et al. (2010, p. 1192)

³¹¹¹ Nearly verbatim from Stein et al. (2012, p. 6-22). Stein et al. cite Glick & others (2009) for this information.

³¹¹² Verbatim from Stein et al. (2012, p. 6-22). Stein et al. cite Millar & others (2007) for this information.

³¹¹³ Verbatim from Spies et al. (2010, p. 1192). Spies et al. cite Marris et al. (2009) for this information.

³¹¹⁴ Verbatim from Stein et al. (2012, p. 6-22). Stein et al. cite Ricciardi & Simberloff (2009), Sax & others (2009), and Schwartz & others (2009) for this information.

³¹¹⁵ Nearly verbatim from Sturrock et al. (2011, p. 142). Sturrock et al. cite Woods et al. (2010) for this information.

³¹¹⁶ Nearly verbatim from Sturrock et al. (2011, p. 142)

³¹¹⁷ Verbatim from Aitken et al. (2008, p. 108)

³¹¹⁸ Verbatim from Sturrock et al. (2011, p. 142). Sturrock et al. cite Warren et al. (2001) for this information.

³¹¹⁹ Nearly verbatim from Aitken et al. (2008, p. 95)

³¹²⁰ Nearly verbatim from Running & Mills (2009, p. 26)

Facilitated migration can have unintended consequences.³¹²¹ Intentional translocations via assisted colonization carry high cost and logistical challenges, as well as risks: ecological disasters from introductions are well-known, and translocations among different locally adapted genotypes can have unexpected negative effects on genetic structure.³¹²² For example, new pathogens may be introduced along with the target species (i.e., of trees).³¹²³ The introduced trees may have little immunity against diseases in the areas into which they are moved.³¹²⁴ Also, it is highly uncertain which pathogens will become more evident as climate changes.³¹²⁵ In addition, autumn temperatures are not increasing as fast as springtime temperatures; therefore, this approach does run some risks for frost damage from early autumn freezes.³¹²⁶

Establish captive populations of species that would otherwise go extinct

This approach would initiate captive maintenance programs for species that would otherwise become extinct due to climate change.³¹²⁷ Such an approach would necessarily serve as the strategy of last resort for species otherwise facing extinction.³¹²⁸ Rearing techniques and approaches to captive husbandry and propagation have been described for many animals and plants, and society has a whole industry (zoos, botanic gardens, and aquaria) that is already devoted to this approach.³¹²⁹ Nevertheless, given the resources required for captive maintenance programs, this is unlikely to be a viable long-term strategy for any more than a few species.³¹³⁰ Under extreme climate-change scenarios, ecosystem conditions may be so altered that the reintroduction of these species will be unfeasible, essentially making these species living fossils.³¹³¹

Support open-space preservation and conservation

Open space preservation and conservation can be accomplished through the management of lands dedicated as open space through a number of the measures, e.g. zoning, redevelopment restrictions, acquisition, easements, setbacks, and buffers.³¹³² While there are costs associated with the management of open space, the public expenditures may be lower than if the land was developed and the provision of full services was required.³¹³³ Management costs could be defrayed by transferring the title to a nonprofit conservation organization.³¹³⁴

³¹²¹ Nearly verbatim from Sturrock et al. (2011, p. 142)

³¹²² Verbatim from Running & Mills (2009, p. 26)

³¹²³ Nearly verbatim from Sturrock et al. (2011, p. 142)

³¹²⁴ Verbatim from Sturrock et al. (2011, p. 142)

³¹²⁵ Verbatim from Sturrock et al. (2011, p. 142)

³¹²⁶ Nearly verbatim from Running & Mills (2009, p. 24)

³¹²⁷ Verbatim from Heinz Center (2008, p. 28)

³¹²⁸ Verbatim from Heinz Center (2008, p. 28). The Heinz Center cites Hansen, Biringer & Hoffman (2003) for this information.

³¹²⁹ Nearly verbatim from Heinz Center (2008, p. 28). The Heinz Center cites Kleiman et al. (1997) for information on animals and Guerrant, Hayvens, & Maunder (2004) for information on plants.

³¹³⁰ Verbatim from Mawdsley et al. (2009, p. 1085). Mawdsley et al. cite Kleiman (1989) for information on the resources required for captive maintenance programs.

³¹³¹ Verbatim from Mawdsley et al. (2009, p. 1085)

³¹³² Verbatim from NOAA (2010, p. 86)

³¹³³ Verbatim from NOAA (2010, p. 86)

³¹³⁴ Verbatim from NOAA (2010, p. 86)

Open space management plans can be developed to guide the acquisition and use of open space in a manner that fulfills multiple community objectives (e.g., trails, athletic fields, campgrounds, community gardens, wildlife refuges, environmental education centers, etc.).³¹³⁵ Any such plan should consider the impacts and consequences of climate change, sea level rise and flooding in particular, to ensure that investments are wisely made (land purchase as well as use and amenity placement).³¹³⁶ Open space management should also consider the key role of open space in green infrastructure and wetland migration programs.³¹³⁷ *Please see the section “Modify infrastructure” for information on natural infrastructure.*

Protect large and environmentally heterogeneous areas

More heterogeneous protected areas, for example, in terms of mountainous and lowland areas would also provide possibilities for freshwater organisms to track suitable temperature conditions following climate change.³¹³⁸ *Please see the section “Maintain, restore, or create connectivity” for additional methods that may allow terrestrial organisms to track suitable temperature conditions.*

Address invasive and non-native species, insects, and pathogens

As with most forest management, management practices must be selected for the specific stand and objectives.³¹³⁹ Invasive species management strategies depend on the extent and magnitude to which the invasion has progressed.³¹⁴⁰ Before a disturbance occurs, forests can be managed to reduce vulnerability or to enhance recovery.³¹⁴¹ Some disturbances, such as fire, insects, disease, and drought, can be managed during the disturbance through preventive measures or manipulations that affect the intensity or frequency of the disturbance.³¹⁴² Alternatively, the disturbance can be managed to reduce its impact.³¹⁴³ For a wide variety of systems, invasions by nonnative species may be minimized through vigilance, early detection, and aggressive removal.³¹⁴⁴

Modify Early Detection and Rapid Response strategies

Responses include preventing the introduction of invasive species in the first place, early detection combined with rapid response, containing or minimizing the harmful effects of invasive species that are already established, and ecosystem restoration once the invasive species have been removed.³¹⁴⁵ These approaches will remain the foundation for dealing with invasive species, but the specific strategies may need to be revisited to consider the impacts of climate change.³¹⁴⁶ In particular, more intensive monitoring

³¹³⁵ Verbatim from NOAA (2010, p. 86-87)

³¹³⁶ Verbatim from NOAA (2010, p. 87)

³¹³⁷ Nealy verbatim from NOAA (2010, p. 87)

³¹³⁸ Verbatim from Heino, Virkkala and Toivonen. (2009, p. 49)

³¹³⁹ Verbatim from Klopfenstein et al. (2009, p. 8)

³¹⁴⁰ Verbatim from Staudt et al. (2012, p. 5-21)

³¹⁴¹ Verbatim from Dale et al. (2008, p. 730)

³¹⁴² Verbatim from Dale et al. (2008, p. 730)

³¹⁴³ Verbatim from Dale et al. (2008, p. 730)

³¹⁴⁴ Verbatim from Lawler (2009, p. 89). Lawler cites Hansen et al. (2003) and Baron et al. (2008) for this information.

³¹⁴⁵ Verbatim from Staudt et al. (2012, p. 5-21). Staudt et al. cite EPA (2008b) for this information.

³¹⁴⁶ Verbatim from Staudt et al. (2012, p. 5-21)

would help to detect invasive species as climate change will make it possible for species to establish in new locations, expand their range into new territories, and even become invasive in response to new conditions.³¹⁴⁷ For example, the State of Washington's Aquatic Invasive Species Plan identifies species such as the giant salvinia and the water hyacinth as species that should be monitored, even though temperatures in the State are currently too cold for these species.³¹⁴⁸

Plant trees resistant to disturbance from insects, pathogens, and invasive and non-native species

Trees can be planted that are less susceptible to disturbance.³¹⁴⁹ Species that promote disturbances can be removed.³¹⁵⁰ Managers can change species composition to reduce the vulnerability of forests to disturbances.³¹⁵¹ Tree species that are less vulnerable to fire, droughts, wind, insects, or pathogens can be planted or maintained.³¹⁵² For example, the colonization of phloem-feeding insects, such as bark beetles, is partially controlled by the ability of the tree to produce oleoresin, which is under genetic control.³¹⁵³ So, planting selected tree species and genotypes with relatively high oleoresin could limit insect outbreaks.³¹⁵⁴

For species facing the dual threats of damaging exotic pathogens and climate change (e.g., butternut, hemlock, ash, American chestnut, 5-needle pines), create openings specifically for establishment of disease-resistant stock, or augment natural regeneration with supplemental plantings for more effective utilization of resistant germplasm (i.e., genetic variability in a population) in species recovery and gene conservation efforts.³¹⁵⁵ In addition, initiate targeted outplantings to increase frequency of desirable genotypes and representation of at-risk species throughout their range (e.g., plant blister-rust-resistant western white pine or whitebark pine in gaps or openings created by planned and unplanned disturbances such as wildfires or pre-commercial thinning).³¹⁵⁶

Additional options for considering climate change when determining plans and priorities for disease and insect resistance selection and breeding programs include:

- Assess existing selective breeding programs to determine if ongoing efforts (species and geographic areas) are in alignment with potential shifts in host species and insects/diseases due to climate change.³¹⁵⁷
- Develop an understanding of the dynamics that would create these situations (i.e., novel combinations of hosts and insects or disease, and the potential for more widespread and damaging outbreaks), and evaluate the need, cost, and effectiveness of new selective breeding programs to mitigate risk.³¹⁵⁸

³¹⁴⁷ Verbatim from Staudt et al. (2012, p. 5-21). Staudt et al. cite EPA (2008b) for this information.

³¹⁴⁸ Nearly verbatim from Staudt et al. (2012, Table 5-2, p. 5-23). Staudt et al. cite Bierwagen & others (2008) for this information.

³¹⁴⁹ Verbatim from Dale et al. (2008, p. 730)

³¹⁵⁰ Verbatim from Dale et al. (2008, p. 730)

³¹⁵¹ Verbatim from Dale et al. (2008, p. 730)

³¹⁵² Verbatim from Dale et al. (2008, p. 730)

³¹⁵³ Verbatim from Dale et al. (2008, p. 730)

³¹⁵⁴ Verbatim from Dale et al. (2008, p. 730)

³¹⁵⁵ Verbatim from Erickson et al. (2012, p. 13)

³¹⁵⁶ Nearly verbatim from Erickson et al. (2012, p. 13)

³¹⁵⁷ Verbatim from Erickson et al. (2012, p. 13)

³¹⁵⁸ Nearly verbatim from Erickson et al. (2012, p. 13)

- For additional information, see the section “Preserve and restore genetic diversity.”

However, prospects for developing resistance to new pests or diseases through traditional breeding programmes appear limited.³¹⁵⁹ After some fifty years of tree breeding, few gains have been made in this regard, except for major diseases in a few commercially important species, e.g. leaf rust in poplars.³¹⁶⁰

Specific options for *Armillaria* root disease

Regarding the *Armillaria* root disease example, a number of management options are available depending on the situation and management objectives.³¹⁶¹ These options could include:

- Selectively removing species that are maladapted or predicted to become maladapted;
- Planting with seed-sources that are well-adapted to the predicted climate during the tree’s lifespan;
- Selectively favoring seral species (e.g., pine or larch species) that are more tolerant of *Armillaria* root disease and adapted to the predicted climate;
- Avoiding wounding of trees, which may facilitate pathogen infection;
- Employing treatments that reduce or do not exacerbate tree stress;
- Applying treatments that minimize woody substrates that can serve to build up the inoculum potential; or,
- Other less developed practices, such as fostering biological control.³¹⁶²

Additional options

The following adaptation options for addressing invasive and non-native species, insects, and pathogens were found in the literature, but were not discussed in detail, or are described elsewhere in this report:

- **Biofuel harvest:** In some situations there may be opportunities for biofuel harvest of some of these invasives that could also help restore the native ecosystems.³¹⁶³
- **Remove beetle-damaged trees:** A common way to control outbreaks of the southern bark beetle is to be on the alert for sites experiencing some beetle damage, then to cut those trees quickly to reduce the size of the area affected.³¹⁶⁴

³¹⁵⁹ Nearly verbatim from Bernier & Stone (2009, p. 9)

³¹⁶⁰ Verbatim from Bernier & Stone (2009, p. 9). Bernier & Stone cite Yanchuk & Allard (2009) for this information.

³¹⁶¹ Verbatim from Klopfenstein et al. (2009, p. 8)

³¹⁶² Nearly verbatim from Klopfenstein et al. (2009, p. 8)

³¹⁶³ Verbatim from Running & Mills (2009, p. 24)

³¹⁶⁴ Verbatim from Dale et al. (2008, p. 730)

X. Appendices

Appendix 1. Common and scientific names of the species mentioned in this report

ABC

Acorn woodpecker, *Melanerpes formicivorus*

Alaska cedar, *see* Yellow-cedar

Alaska marmot, *Marmota broweri*

Alaskan moose, *Alces alces gigas*

Alder, *Alnus* spp.

Alpine aster, *Aster alpigenus*

Alpine buckwheat, *Eriogonum pyrolae*

American avocet, *Recurvirostra americana*

American bittern, *Botaurus lentiginosus*

American elm, *Ulmus Americana*

American marten, *Martes americana*

American pipit, *Anthus rubescens*

Anise swallowtail, *Papilio zelicaon*

Anna's hummingbird, *Calypte anna*

Armillaria root disease, *Armillaria* spp.

Ash-throated flycatcher, *Myiarchus cinerascens*

Aspen, *Populus tremuloides*

Baird's shrew, *Sorex bairdi*

Baker's cypress, *Cupressus bakeri*

Bald eagle, *Haliaeetus leucocephalus*

Band-tailed pigeon, *Patagioenas fasciata*

Barn swallow, *Hirundo rustica*

Barred owl, *Strix varia*

Bay checkerspot butterfly, *Euphydryas editha bayensis*

Beard lichen, *Usnea filipendula*

Bufflehead, *Bucephala albeola*

Big sagebrush, *Artemisia tridentata*

Big-leaf maple, *Acer macrophyllum*

Birch, *Betula* spp.

Black sedge, *Carex nigricans*

Black bear, *Ursus americanus*

Black cottonwood, *Populus trichocarpa*

Black spruce, *Picea mariana*

Black tern, *Chlidonias niger*

Black-backed woodpecker, *Picoides arcticus*

Black-billed magpie, *Pica hudsonia*

Black-crowned night-heron, *Nycticorax nycticorax*

Black-headed grosbeak, *Pheucticus melanocephalus*

Black-necked stilt, *Himantopus mexicanus*

Black-tailed deer, *Odocoileus hemionus*

Black-throated gray warbler, *Dendroica nigrescens*

Blue grouse, *Dendragapus fuliginosus*

Blue oak, *Quercus douglasii*

Blue stain fungi, *Grosmannia clavigera*

Blue-gray gnatcatcher, *Poliptila caerulea*

Blueleaf huckleberry, *Vaccinium deliciosum*

Bobcat, *Lynx rufus*

Bog blueberry, *Vaccinium uliginosum*

Brewer sedge, *Carex breweri*

Brewer spruce, *Picea breweriana*
 Broadleaf lupine, *Lupinus latifolius*
 Brown bear, *Ursus arctos*
 Brown creeper, *Certhia americana*
 Brown-headed cowbird, *Molothrus ater*
 Bullock's oriole, *Icterus bullockii*
 Burrowing owl, *Athene cunicularia*
 California black oak, *Quercus kelloggii*
 California buckeye, *Aesculus californica*
 California fivespined ips, *Ips paraconfusus*
 California hazel, *Corylus cornuta* var. *californica*
 California white oak, *Quercus lobata*
 California vole, *Microtus californicus*
 Camas pocket gopher, *Thomomys bulbivorus*
 Canada geese, *Branta canadensis*
 Canada lynx, *Lynx canadensis*
 Canvasback, *Aythya valisineria*
 Canyon live oak, *Quercus chrysolepis*
 Caribou, *see* woodland caribou, woodland mountain caribou
 Cascade willow, *Salix cascadenis*
 Cassin's vireo, *Vireo cassinii*
 Checkered skipper, *Pyrgus ruralis*
 Cheatgrass, *Bromus tectorum*
 Chestnut-backed chickadee, *Parus rufescens*, also *Poecile rufescens*
 Chinquapin
 Chipping sparrow, *Spizella passerine*
 Cinnamon teal, *Anas cyanoptera*
 Clark's grebe, *Aechmophorus clarkii*
 Coast Douglas-fir, *Pseudotsuga menziesii* var. *menziesii*
 Coast redwood, *see* Redwood
 Coiled lousewort, *Pedicularis contorta*
 Colonial bentgrass, *Agrostis capillaris*
 Colorado piñon pine, *Pinus edulis*
 Columbian white-tailed deer, *Odocoileus virginianus leucurus*
 Common bushtit, *Psaltriparus minimus*
 Common goldeneye, *Bucephala clangula*
 Common merganser, *Mergus merganser*
 Common nighthawk, *Chordeiles minor*
 Common purple lilacs, *Syringa vulgaris* f. *purpurea*
 Common redpoll, *Carduelis flammea*
 Common shrew, *Sorex cinereus*
 Common witch's hair lichen, *Alectoria sarmentosa* and *Bryoria* spp.
 Cooley spruce gall adelgid, *Adelges cooleyi*
 Coral lichen, *Sphaerophorus globosus*
 Cougar, *Felis concolor*
 Coulter pine, *Pinus coulteri*
 Coyote, *Canis latrans*
 Cream mountain heath, *Phyllodoce glanduliflora*
 Creosote bush, *Larrea tridentate*
 Crowberry, *Empetrum nigrum*
 Cypress, *Cupressaceae* spp.
 Cytospora canker, *Cytospora umbrina*

DEF

Dark-eyed junco, *Junco hyemalis*
Dawson caribou, *Rangifer tarandus dawsoni*
Deer mouse, *Peromyscus maniculatus*
Dogwood anthracnose, *Discula destructiva*
Dothistroma needle blight, *Dothistroma septosporum* and *D. pini*
Douglas fir, *Pseudotsuga menziesii*; see also
Coast Douglas-fir, Rocky Mountain Douglas-
fir
Douglas-fir bark beetle, *Dendroctonus brevicomis*
Douglas-fir beetle, *Dendroctonus pseudotsugae*
Dunlin, *Calidris alpina*
Dusky grouse, *Dendragapus obscurus*
Dwarf mistletoe, *Arceuthobium* spp.
Eastern cottontail, *Sylvilagus floridanus*
Eastern gray squirrel, *Sciurus carolinensis*
Edith's checkerspot butterfly, *Euphydryas editha*
Elk, see Roosevelt elk
Engelmann spruce, *Picea engelmannii*
English ivy, *Hedera helix*
Erythraeid mites, *Balaustium* spp., *Erythraeus*
spp., *Leptus* spp.
European larch canker, *Lachnellula willkommii*
European mountain ash, *Sorbus aucuparia*
European starling, *Sturnus vulgaris*
Evergreen blackberry, *Rubus laciniatus*
False brome, *Brachypodium sylvaticum*
False hellebore, *Veratum viride*

Fanleaf cinquefoil, *Potentilla flabellifolia*
Field crescent butterfly, *Phyciodes pratensis*
Fir, *Abies* spp.
Fireweed, *Epilobium angustifolium*
Fenders blue butterfly, *Icaricia icarioides fender*
Fir engraver, *Scolytus ventralis*
Fisher marten, *Martes pennanti*
Flammulated owl, *Otus flammeolus*
Forster's tern, *Sterna forsteri*
Foxtail pine, *Pinus balfouriana*
Fremont's horsehair lichen, *Bryoria fremontii*
Fringed bat, *Myotis thysanodes*

GHI

Gall midge, *Lestodiplosis* spp.
Garlic mustard, *Alliaria petiolata*
Garry oak, see Oregon white oak
Giant conifer aphids, *Cinara* spp.
Golden-crowned kinglet, *Regulus satrapa*
Golden eagle, *Aquila chrysaetos*
Golden paintbrush, *Castilleja levisecta*
Goshawks, *Accipiter gentilis*
Grand fir, *Abies grandis*
Gray pine, *Pinus sabiniana*
Gray-tailed vole, *Microtus canicaudus*
Gray wolf, *Canis lupus*
Giant salvinia, *Salvinia molesta*
Grasshopper sparrow, *Ammodramus savannarum*

Gray-crowned rosy finch, *Leucosticte tephrocotis*
Green alder, *Alnus viridis*
Green fescue, *Festuca viridula*
Grizzly bear, *Ursus arctos horribilis*
Harvest mouse, *Reithrodontomys megalotis*
Hemlock, *Tsuga* spp.
Hemlock dwarf mistletoe, *Arceuthobium tsugense*
Hermit warbler, *Dendroica occidentalis*
Himalayan blackberry, *Rubus discolor*
Honeysuckle, *Lonicera* spp.
Hooded merganser, *Lophodytes cucullatus*
Horsehair lichen, *see* Common witch's hair lichen
House mouse, *Mus musculus*
House wren, *Troglodytes aedon*
Idaho fescue, *Festuca idahoensis*
Incense-cedar, *Calocedrus decurrens*
Indian paintbrush, *Castilleja* spp.

JKL

Jack pine, *Pinus banksiana*
Jeffrey pine, *Pinus jeffreyi*
Jeffrey pine beetle, *Dendroctonus jeffreyi*
Kidney lichens, *Nephroma* spp.
Kinnikinnick, *Arctostaphylos uva-ursi*
Knobcone pine, *Pinus attenuata*
Knotweed complex, *Fallopia* spp.
Kruckeberg's hollyfern, *Polystichum kruckebergii*

Lark sparrow, *Chondestes grammacus*
Lazuli bunting, *Passerine amoena*
Lettuce lung, *Lobaria oregana*
Lesser scaup, *Aythya affinis*
Lewis's woodpecker, *Melanerpes lewisii*
Lilac, *Syringa vulgaris*
Limber pine, *Pinus flexilis*
Little brown bat, *Myotis lucifugus*
Lodgepole pine, *Pinus contorta* var. *latifolia*
Long-billed curlew, *Numenius americanus*
Long-billed dowitcher, *Limnodromus scolopaceus*
Long-tailed vole, *Microtus longicaudus*
Luetkea, *Luetkea pectinata*
Lutz spruce, *Picea x lutzii*
Lynx, *see* Canada lynx

MNO

MacGillivray's warbler, *Oporornis tolmiei*
Madrone, *see* Pacific madrone
Maple, *Acer* spp.
Marbled murrelet, *Brachyramphus marmoratus*
Marten, *see* American marten
Mealybugs, Pseudococcidae family
Mink, *Neovison vison*
Monarch butterfly, *Danaus plexippus*
Monterey pine, *Pinus radiata*
Moose, *see* Alaskan moose, northwestern moose, Shiras' moose
Mountain alder, *Alnus crispa*

Mountain goat, *Oreamnos americanus*
Mountain hemlock, *Tsuga mertensiana*
Mountain holly fern, *Polystichum scopulinum*
Mountain larch, *see* Subalpine larch
Mountain lion, *see* Cougar
Mountain pine beetle, *Dendroctonus ponderosae*
Mule deer, *Odocoileus hemionus*
Mule deer musclemore, *Parelaphostrongylus odocoilei*
Muskrat, *Myocastor coypus*
Nashville warbler, *Vermivora ruficapilla*
Net-winged insects, Neuroptera order
North American river otter, *see* River otter
Northern flicker, *Colaptes auratus*
Northern flying squirrel, *Glaucomys sabrinus*
Northern goshawk, *Accipiter gentilis*
Northern shrike, *Lanius excubitor*
Northern spotted owl, *Strix occidentalis caurina*
Northern spruce engraver, *Ips perturbatus*
Northwestern deer mouse, *Peromyscus keeni*
Northwestern moose, *Alces alces andersoni*
Oak, *Quercus* spp.
Oceanspray, *Holodiscus discolor*
Olive-sided flycatcher, *Contopus cooperi*
Orange hawkweed, *Hieracium aurantiacum*
Orange-crowned warbler, *Vermivora celata*
Oregon ash, *Fraxinus latifolia*
Oregon giant earthworm, *Driloleirus macelfreshi*
Oregon lung lichen, *see* Lettuce lung

Oregon vesper sparrow, *Pooecetes gramineus affinis*

Oregon white oak, *Quercus garryana*

Osprey, *Pandion haliaetus*

PQR

Pacific dogwood, *Cornus nuttallii*

Pacific madrone, *Arbutus menziesii*

Pacific shrew, *Sorex pacificus*

Pacific water shrew, *Sorex bendirii*

Pacific silver fir, *Abies amabilis*

Pacific slope flycatcher, *Empidonax difficilis*

Pacific yew, *Taxus brevifolia*

Paddle worm, *Phyllodoce* spp.

Paper birch, *Betula papyrifera*

Pileated woodpecker, *Dryocopus pileatus*

Pine, *Pinus* spp.

Pine needle scale, *Chionaspis pinafoliae*

Pink mountainheath, *Phyllodoce empetriformis*

Piñon pine, *see* Colorado piñon pine, single-leaf piñon pine

Plantain, *Plantago* spp.

Poison oak, *Rhus diversiloba*

Ponderosa pine, *Pinus ponderosa*

Poplar, *Populus* spp.

Propertius duskywing, *Erynnis propertius*

Ptarmigan, *see* rock ptarmigan, white-tailed ptarmigan, or willow ptarmigan

Purple finch, *Carpodacus purpureus*

Purple reedgrass, *Calamagrostis purpurascens*

Raccoon, *Procyon lotor*
Ragged lichens, *Platismatia* spp.
Red alder, *Alnus rubra*
Red fir, *Abies magnifica*
Red fox, *Vulpes vulpes*
Red mountain heath, *Phyllodoce empetriformis*
Red squirrel, *Tamiasciurus hudsonicus*
Red tree vole, *Arborimus longicaudus*
Red-breasted merganser, *Mergus serrator*
Redwood, *Sequoia sempervirens*
Ring-necked duck, *Aythya collaris*
Ring-necked pheasant, *Phasianus colchicus*
River otter, *Lontra canadensis*
Rock ptarmigan, *Lagopus muta*
Rocky Mountain bristlecone pine, *Pinus aristata*
Rocky Mountain Douglas-fir, *Pseudotsuga menziesii* var. *glauca*
Roemer's fescue, *Festuca roemeri*
Roosevelt elk, *Cervus canadensis*
Ruby-crowned kinglet, *Regulus calendula*
Ruddy duck, *Oxyura jamaicensis*
Rufous hummingbird, *Selasphorus rufus*

STU

Sachem skipper, *Atalopedes campestris*
Sadler's oak, *Quercus sadleriana*
Saguaro, *Carnegiea gigantea*
Saiga antelope, *Saiga tatarica*
Salal, *Gaultheria shallon*
Sandhill crane, *Grus canadensis*
Say's phoebe, *Sayornis saya*

Scotch broom, *Cytisus scoparius*
Seaside juniper, *Juniperus maritima*
Seaside kidney, *Nephroma laevigatum*
Shasta red fir, *Abies magnifica* var. *shastensis*
Sheep moth, *Hemileuca eglanterina*
Shiras' moose, *Alces alces shirasi*
Shore pine, *Pinus contorta* var. *contorta*
Showy sedge, *Carex spectabilis*
Single-leaf piñon pine, *Pinus monophylla*
Sitka alder, *Alnus sinuata*
Sitka spruce, *Picea sitchensis*
Sitka valerian, *Valeriana sitchensis*
Slender-billed white-breasted nuthatch, *Sitta carolinensis aculeate*
Slide alder, *see* Sitka alder
Snow willow, *Salix nivalis*
Snowberry, *Symphoricarpos albus*
Snowbrush, *Ceanothus velutinus*
Snowy owl, *Bubo scandiacus*
Sooty grouse, *Dendragapus fuliginosus*
Sora, *Porzana carolina*
Specklebelly lichens, *Pseudocyphellaria* spp.
Spotted knapweed, *Centaurea maculosa*,
Centaurea stoebe
Spotted lichens, *Sticta* spp.
Spruce beetle, *Dendroctonus rufipennis* [Kirby]
Spurge-laurel, *Daphne laureola*
Squirreltail, *Elymus elymoides*
Streaked horned lark, *Eremophila alpestris strigata*
Song sparrow, *Melospiza melodia*

Sonora skipper, *Polites sonora*
Spruce, *Picea* spp.
Spruce (bark) beetle, *Dendroctonus rufipennis*
Stone's sheep, *Ovis dalli stonei*
Streaked horned lark, *Eromophila alpestris strigata*
Subalpine fir, *Abies lasiocarpa*
Subalpine larch, *Larix lyallii*
Sudden oak death, *Phytophthora ramorum*
Sugar pine, *Pinus lambertiana*
Sunflower, *Helianthus* spp.
Swainson's thrush, *Catharus ustulatus*
Sweetgale, *Myrica gale*
Swiss needle cast, *Phaeocryptopus gaeumannii*
Tanoak, *Notholithocarpus densiflorus*
Taylor's checkerspot butterfly, *Euphydryas editha taylora*
Therid spiders, Theridae family
Thinlead alder, *Alnus incana*
Timber danthonia, *Danthonia intermedia*
Tolmie saxifrage, *Saxifraga tolmiei*
Torrey pine, *Pinus torreyana*
Townsend's warbler, *Dendroica townsendi*
Trailing blackberry, *Rubus ursinus*
Tree swallows, *Tachycineta bicolor*
True fir, *Abies* spp.
Trumpeter swan, *Cygnus buccinator*
Tube lichens, *Hypogymnia* spp.
Tundra swan, *Cygnus columbianus*

VWXYZ

Vancouver island marmot, *Marmota vancouverensis*
Varied thrush, *Ixoreus naevius*
Vaux's swift, *Chaetura vauxi*
Vine maple, *Acer circinatum*
Virginia opossum, *Didelphis virginiana*
Virginia rail, *Rallus limicola*
Warbling vireo, *Vireo gilvus*
Water hyacinth, *Eichonria crassipes*
Western balsam bark beetle, *Dendroctonus confusus* Swaine
Western bluebird, *Sialia mexicana*
Western cassiope, *Cassiope mertensiana*
Western gray squirrel, *Sciurus griseus*
Western grebe, *Aechmophorus occidentalis*
Western hemlock, *Tsuga heterophylla*
Western kingbird, *Tyrannus verticalis*
Western larch, *Larix occidentalis*
Western meadowlark, *Sturnella neglecta*
Western moss heather, *Cassiope mertensiana*
Western pine beetle, *Dendroctonus brevicomis*
Western redcedar, *Thuja plicata*
Western scrub jay, *Apelocoma californica*
Western snowy plover, *Charadrius alexandrines nivosus*
Western spruce budworm, *Choristoneura occidentalis*
Western sword fern, *Polystichum munitum*
Western tanager, *Piranga ludoviciana*

Western white pine, *Pinus monticola*
 Western wood-pewee, *Contopus sordidulus*
 White fir, *Abies concolor*
 White mountain heather, *see* Western moss heather
 White pine blister rust, *Cronartium ribicola*
 White spruce, *Picea glauca*
 White sweetclover, *Melilotus alba*
 White-headed woodpecker, *Picoides albolarvatus*
 White-tailed deer, *Odocoileus virginianus*
 White-tailed kite, *Elanus leucurus*
 White-tailed ptarmigan, *Lagopus leucura*
 Whitebark pine, *Pinus albicaulis*
 Wild turkey, *Meleagris gallopavo*
 Williamson's sapsucker, *Sphyrapicus thyroideus*
 Willow, *Salix* spp.
 Willow flycatcher, *Empidonax traillii*
 Willow ptarmigan, *Lagopus lagopus*
 Willow scab, *Venturia saliciperda*
 Wilson's phalarope, *Phalaropus tricolor*
 Wilson's snipe, *Gallinago delicata*
 Wilson's warbler, *Wilsonia pusilla*
 Winter wren, *Troglodytes troglodytes*
 Wolf, *Canis lupus*
 Wolverine, *Gulo gulo*
 Woodland caribou, *Rangifer tarandus caribou*
 Woodland mountain caribou, *Rangifer tarandus montanus*
 Woodrat, *Neotoma* spp.
 Woolly everlasting, *Antennaria lanata*
 Wrangell Island red-backed vole. *Clethrionomys gapperi wrangeli*
 Yellow star thistle, *Centaurea solstitialis*
 Yellow warbler, *Dendroica petechia*
 Yellow-cedar, *Chamaecyparis nootkatensis*

Appendix 2. SRES Scenarios and Climate Modeling

The explanation of SRES scenarios is excerpted from the IPCC's AR4 Synthesis Report (p. 44). Figure 75 was accessed online at <http://sedac.ciesin.columbia.edu/ddc/sres/>, December 6, 2013.

SRES scenarios

SRES refers to the scenarios described in the IPCC Special Report on Emissions Scenarios (SRES, 2000). The SRES scenarios are grouped into four scenario families (A1, A2, B1 and B2) that explore alternative development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions. The SRES scenarios do not include additional climate policies above current ones. The emissions projections are widely used in the assessments of future climate change, and their underlying assumptions with respect to socio-economic, demographic and technological change serve as inputs to many recent climate change vulnerability and impact assessments. {WGI 10.1; WGII 2.4; WGIII TS.1, SPM}

The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change: fossil intensive (A1FI), non-fossil energy resources (A1T) and a balance across all sources (A1B). B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and

information economy. B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social, and environmental sustainability. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change. No likelihood has been attached to any of the SRES scenarios. {WGIII TS.1, SPM}

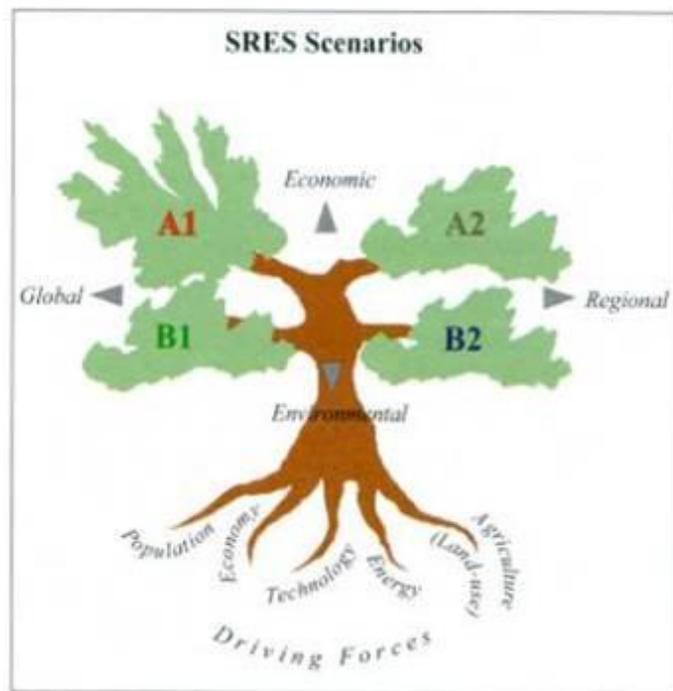


Figure 75. SRES Scenarios.

Climate modeling

Global Models

Envisioning global climate in a future with much higher greenhouse gases requires the use of physically based numerical models of the ocean, atmosphere, land, and ice, often called global climate models

(GCMs) or climate system models.³¹⁶⁵ A common set of simulations using 21 GCMs was coordinated through the Intergovernmental Panel on Climate Change (IPCC).³¹⁶⁶ These models typically resolve the atmosphere with between 6,000 and 15,000 grid squares horizontally, and with between 12 and 56 atmospheric layers.³¹⁶⁷

Simulations of 21st century climate require projections of future greenhouse gases and sulfate aerosols (which reflect sunlight and also promote cloud formation, thereby offsetting greenhouse gases locally), of which more than 40 were produced and six “marker” scenarios selected (B1, B2, A1, A1B, A1F1, A2) under the auspices of the IPCC.³¹⁶⁸ Three of these marker scenarios were commonly chosen for forcing the GCMs: B1, A1B, and A2.³¹⁶⁹ A2 produces the highest climate forcing by the end of the century, but before mid-century, none of the scenarios is consistently the highest.³¹⁷⁰ Though B1 is the lowest of the IPCC illustrative scenarios, it still produces changes in climate that many scientists call “dangerous” — a threshold that a growing number of political leaders have stated their intention to avoid.³¹⁷¹ At the high end, scenario A1FI results in even higher climate forcing by 2100 than A2 or A1B.³¹⁷² Mid-2000s global emissions of CO₂ exceeded even the A1FI scenario.³¹⁷³

Downscaled Climate Models

Note: While the information described here pertains to Washington State, it is often applicable for sub-global (e.g., regional, local) modeling elsewhere.

Global climate models do not account for the atmospheric processes that determine the unique spatially heterogeneous climatic features of Washington.³¹⁷⁴ Statistical downscaling is based on fine-scale data derived using assumptions about how temperature and precipitation vary over complex terrain in order to interpolate the sparse station network (about 50-km spacing) to a 0.0625° grid.³¹⁷⁵ Information simulated by the coarse-resolution global models (with output on a 100-to-300 km grid) is then used to project the future climate.³¹⁷⁶ This approach represents the mean climate and local regimes quite well but does not take into account how the terrain influences individual weather systems.³¹⁷⁷

Salathé, Jr. et al.’s (2010) results show that, with increased spatial resolution relative to global models, regional climate models can represent the local forcing from the complex terrain to produce more realistic spatial and temporal variability of temperature, precipitation, and snowpack in the State of

³¹⁶⁵ Verbatim from Mote and Salathé, Jr. (2010, p. 29)

³¹⁶⁶ Nearly verbatim from Mote and Salathé, Jr. (2010, p. 29-30)

³¹⁶⁷ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 30)

³¹⁶⁸ Verbatim from Mote and Salathé, Jr. (2010, p. 30)

³¹⁶⁹ Verbatim from Mote and Salathé, Jr. (2010, p. 30)

³¹⁷⁰ Verbatim from Mote and Salathé, Jr. (2010, p. 30)

³¹⁷¹ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 31). Mote and Salathé, Jr. cite Schellnhuber et al. (2006) for information on changes in climate that many scientists call dangerous.

³¹⁷² Verbatim from Mote and Salathé, Jr. (2010, p. 31).

³¹⁷³ Nearly verbatim from Mote and Salathé, Jr. (2010, p. 31). The authors cite Raupach et al. (2007) for information on mid-2000s emissions and state “...we must emphasize that the scenarios used here may not span the range of possibilities” (p. 31).

³¹⁷⁴ Verbatim from Salathé, Jr. et al. (2010, p. 52). *Regional climate model projections for the State of Washington*.

³¹⁷⁵ Verbatim from Salathé, Jr. et al. (2010, p. 52)

³¹⁷⁶ Verbatim from Salathé, Jr. et al. (2010, p. 52)

³¹⁷⁷ Verbatim from Salathé, Jr. et al. (2010, p. 52)

Washington.³¹⁷⁸ With the ability to resolve topographic effects, more robust changes in mountain snowpack and extreme precipitation emerge.³¹⁷⁹ These changes are consistent between the two regional simulations despite differences in seasonal precipitation and temperature changes in the global and regional model results.³¹⁸⁰ It is clear that changes in the seasonal climate and the frequency of extreme events may be locally much more intense than can be inferred from statistical methods.³¹⁸¹ The implication is that, while a valuable tool for regional climate impacts assessment, multi-model ensembles of global climate projections and statistical methods may under represent the local severity of climate change.³¹⁸²

³¹⁷⁸ Verbatim from Salathé, Jr. et al. (2009, p. 65). *Regional climate model projections for the State of Washington.*

³¹⁷⁹ Verbatim from Salathé, Jr. et al. (2009, p. 65)

³¹⁸⁰ Verbatim from Salathé, Jr. et al. (2009, p. 65)

³¹⁸¹ Verbatim from Salathé, Jr. et al. (2009, p. 65)

³¹⁸² Verbatim from Salathé, Jr. et al. (2009, p. 65)

Appendix 3. Major Climate Patterns in the NPLCC: ENSO and PDO

This explanation is excerpted from a webpage written by Nathan J. Mantua (Ph.D.) of the University of Washington's Joint Institute for the Study of the Atmosphere and Oceans and Climate Impacts Group. The webpage is not copied in its entirety; sections that explain climate variability and its impacts on climate in the NPLCC region are emphasized. The full-text can be accessed at http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm (accessed December 6, 2013).

Introduction

In addition to El Niño, there are other heavily researched climate patterns that exert important influences on regional climates around the world. For instance, many studies highlight the relative importance of the Pacific Decadal Oscillation and Arctic Oscillation/North Atlantic Oscillation in North American climate. Each of these major patterns--El Niño/Southern Oscillation, Pacific Decadal Oscillation, and Arctic Oscillation/North Atlantic Oscillation--has characteristic signatures in seasonally changing patterns of wind, air temperature, and precipitation; each pattern also has a typical life time for any given "event".

A PDO definition

The Pacific Decadal Oscillation, or PDO, is often described as a long-lived El Niño-like pattern of Pacific climate variability (Zhang et al. 1997). As seen with the better-known El Niño/Southern Oscillation (ENSO), extremes in the PDO pattern are marked by widespread variations in Pacific Basin and North American climate. In parallel with the ENSO phenomenon, the extreme phases of the PDO have been classified as being either *warm* or *cool*, as defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean.

Two main characteristics distinguish the PDO from ENSO. First, typical PDO "events" have shown remarkable persistence relative to that attributed to ENSO events - in this century, major PDO eras have persisted for 20 to 30 years (Mantua et al. 1997, Minobe 1997). Second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics - the opposite is true for ENSO. Several independent studies find evidence for just two full PDO cycles in the past century (e.g. Mantua et al. 1997, Minobe 1997): cool PDO regimes prevailed from 1890-1924 and again from 1947-1976, while warm PDO regimes dominated from 1925-1946 and from 1977 through (at least) the mid-1990's. Recent changes in Pacific climate suggest a possible reversal to cool PDO conditions in 1998, an issue that is discussed in more detail at the end of this article.

The North American climate anomalies associated with PDO warm and cool extremes are broadly similar to those connected with El Niño and La Niña (Latif and Barnett 1995, Latif and Barnett 1996, Zhang et al. 1997, Mantua et al. 1997). Warm phases of the PDO are correlated with North American temperature and precipitation anomalies similar to those correlated with El Niño (Figure 4): above average winter and spring time temperatures in northwestern North America, below average temperatures in the southeastern US, above average winter and spring rainfall in the southern US and northern Mexico, and below average precipitation in the interior Pacific Northwest and Great Lakes regions. Cool phases of the PDO are simply correlated with the reverse climate anomaly patterns over North America (not shown), broadly

similar to typical La Niña climate patterns. The PDO-related temperature and precipitation patterns are also strongly expressed in regional snow pack and stream flow anomalies, especially in western North America (see Cayan 1995, Mantua et al. 1997, Bitz and Battisti 1999, Nigam et al. 1999). A summary of major PDO climate anomalies are listed in Table 1.

Table 1: Summary of North American climate anomalies associated with extreme phases of the PDO.

<u>Climate Anomalies</u>	<u>Warm Phase PDO</u>	<u>Cool Phase PDO</u>
Ocean surface temperatures in the northeastern and tropical Pacific	Above average	Below average
October-March northwestern North American air temperatures	Above average	Below average
October-March Southeastern US air temperatures	Below average	Above average
October-March southern US/Northern Mexico precipitation	Above average	Below average
October-March Northwestern North America and Great Lakes precipitation	Below average	Above average
Northwestern North American spring time snow pack	Below average	Above average
Winter and spring time flood risk in the Pacific Northwest	Below average	Above average

An ENSO definition

This definition is excerpted from the Climate Impacts Group website [El Niño/Southern Oscillation](http://cses.washington.edu/cig/pnwc/aboutenso.shtml), available at <http://cses.washington.edu/cig/pnwc/aboutenso.shtml> (accessed December 6, 2013)

The El Niño/Southern Oscillation (ENSO) is the major source of inter-annual climate variability in the Pacific Northwest (PNW). ENSO variations are more commonly known as **El Niño** (the warm phase of ENSO) or **La Niña** (the cool phase of ENSO).

An El Niño is characterized by stronger than average sea surface temperatures in the central and eastern equatorial Pacific Ocean, reduced strength of the easterly trade winds in the Tropical Pacific, and an eastward shift in the region of intense tropical rainfall. A La Niña is characterized by the opposite – cooler than average sea surface temperatures, stronger than normal easterly trade winds, and a westward shift in the region of intense tropical rainfall. Average years, i.e., years where there is no statistically

significant deviation from average conditions at the equator, are called ENSO-neutral. Each ENSO phase typically lasts 6 to 18 months.

Although ENSO is centered in the tropics, the changes associated with El Niño and La Niña events affect climate around the world. ENSO events tend to form between April and June and typically reach full strength in December (hence the name El Niño, which is Spanish for “Little Boy” or “Christ Child”; La Niña means “Little Girl”). The ENSO influence on PNW climate is strongest from October to March; by summer, Northern Hemisphere wind patterns are such that they effectively trap ENSO-related disturbances in the tropics.

The CIG has demonstrated numerous linkages between changes in ENSO and variations in PNW climate and natural resources. El Niño winters, for example, tend to be warmer and drier than average with below normal snowpack and streamflow. La Niña winters tend to be cooler and wetter than average with above normal snowpack and streamflow. These linkages and the availability of ENSO forecasts a few months to one year in advance of the event’s maturation provide resource managers opportunity to consider how a particular ENSO forecast may affect resource management choices.

Interactions between ENSO and PDO

*This definition is excerpted from the Climate Impacts Group website *Impacts of Natural Climate Variability on Pacific Northwest Climate*, available at <http://ces.washington.edu/cig/pnwc/clvariability.shtml> (accessed December 6, 2013).*

The potential for temperature and precipitation extremes increases when ENSO and PDO are in the same phases and thereby reinforce each other. This additive effect is also seen in the region’s streamflow and snowpack. There is no evidence at this time to suggest that either PDO or ENSO dominates with respect to temperature and precipitation when the two climate patterns are in opposite phases (i.e., an El Niño during a cool phase PDO or a La Niña during a warm phase PDO). The opposite effects on temperature and precipitation can cancel each other out, but not in all cases and not always in the same direction. Similar effects are seen on regional streamflow.

Implications for climate predictions

This explanation is excerpted from a webpage written by Nathan J. Mantua (Ph.D.) of the University of Washington’s Joint Institute for the Study of the Atmosphere and Oceans and CIG. The full-text can be accessed at http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm (accessed December 6, 2013).

Recent studies suggest that ENSO teleconnections with North American climate are strongly dependent on the phase of the PDO, such that the "canonical" El Niño and La Niña patterns are only valid during years in which ENSO and PDO extremes are "in phase" (i.e. with warm PDO+El Niño, and cool PDO+La Niña, but not with other combinations) (Gershunov and Barnett 1999, Gershunov et al. 1999, McCabe and Dettinger 1999). Other studies have identified PDO connections with summer rainfall and drought in the US (Nigam et al. 1999), and the relative risks for winter and spring flood events in the Pacific Northwest (Hamlet and Lettenmeier, in press).

XI. Bibliography

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A Compilation of the Scientific
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Patricia Tillmann and Patty Glick

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National Wildlife Federation
Pacific Regional Center – Seattle

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

(206) 285-8707

(206) 285-8698 fax

